September 11–16 | 2016

HCI

Kielce, Poland

BOOK OF ABSTRACTS

18th International Conference Physics of Highly Charged Ions

Uniwersytet Jana Kochanowskiego w Kielcach

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SPECS™

18th International Conference on the Physics of Highly Charged Ions

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RL: Review Lectures	PR: Progress Reports
ST: Selected Topics	LR: Local Report

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RL: Review Lectures	PR: Progress Reports
ST: Selected Topics	LR: Local Report

REVIEW LECTURES

SPECTROSCOPY WITH ELECTRON BEAM ION TRAPS

P. Beiersdorfer

Physics Division, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

The first electron beam ion trap, now dubbed EBIT-I, was put into operation exactly 30 years ago in 1986. It is still operating at the Lawrence Livermore National Laboratory producing spectroscopic data of highly charged ions. In the meantime electron beam ion traps have been put to use at about a dozen additional locations on three continents, including in the USA, Canada, the UK, Germany, China, and Japan. The performance parameters of the different machines vary considerably. For example, Livermore's high-energy device, dubbed SuperEBIT, has been able to produce bare uranium, while low-energy devices, such as CoBIT and EBIT-LE, produce lower charge states of ions relevant to magnetic fusion and astrophysics. As a result, spectroscopic measurements have been possible that compete directly with those enabled by heavy-ion accelerators and storage rings. These include the most precise measurements of the two-loop Lamb shift in a highly charged ion, measurements of the hyperfine splitting of the 1s and 2s electronic levels in hydrogenlike and lithiumlike ions of heavy elements, and extremely precise determinations of radiative lifetimes. In addition, electron beam ion traps enable complementary experiments that include cross section determinations of electron-impact excitation, of dielectronic recombination, and of electron-impact ionization as well as x-ray polarization measurements. Electron beam ion trap measurements also have led to the discovery of magnetic-field induced x-ray transitions as well as of three- and four-electronic recombination involving highly charged ions. This presentation will highlight spectroscopic measurements performed at various facilities during the past three decades, including measurements applied magnetic fusion, atomic clock, and astrophysics research.

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HIGHLY CHARGED ATOMIC IONS IN COLLISIONS WITH ELECTRONS

S. Schippers

I. Physikalisches Institut, Justus-Liebig-Universität Gießen, 35392 Giessen, Germany

Recent progress in experimental studies of electron-ion collisions using (stored) ion beams [1,2] will be reviewed. This field of research is motivated twofold. First, electron-impact ionization of ions and electron-ion recombination are important atomic collision processes in plasmas governing the charge state distributions of the atomic species contained therein. Recently, attention has been given to tungsten ions [3,4] because of their prominent role in nuclear fusion plasmas. A particular challenge for theory is the complex electronic structure of these many-electron systems, particulary, if they have an open 4f shell. Benchmarking by experiment has lead to considerable advances in the theoretical understanding of electron-ion recombination of such complex atomic systems [5,6]. In addition, much work has been carried out with, e.g., astrophysically important iron ions [7,8]. A second motivation is provided by the fact that ionization and recombination resonances provide access to the atomic structure of highly charged ions where electron-ion collision spectroscopy is competitive with or sometimes even ahead of optical methods. Electron-ion collision spectroscopy of few-electron highly charged ions has been used for measuring atomic lifetimes [9], transition energies [e.g. 10], as well as nuclear properties [e.g. 11]. Perspectives for future studies with well cooled and state-prepared ions at CRYRING@ESR [12] and at the Heidelberg cryogenic storage ring CSR [13] will be pointed out.

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SPECTROSCOPY OF HIGHLY CHARGED IONS FOR EXTREME ULTRAVIOLET LITHOGRAPHY

Gerry O'Sullivan[a], Padraig Dunne[a], Fergal O'Reilly[a], Emma Sokell[c] and Takeshi Higashiguchi[b]

[a]School of Physics, University College Dublin, Belfield, Stilorgan Road, Dublin 4, Ireland

[b]Department of Electrical and Electronic Engineering, Faculty of Engineering, Utsunomiya University, Yoto 7-1-2, Utsunomiya, Tochigi 321-8585 Japan

The development of efficient sources for extreme ultraviolet lithography (EUVL) has posed a major scientific and technical challenge for many years. The most practical solution for the high volume production of microelectonic components, with dimensions of less than 10 nm has been identified as EUVL [1]. Sources must be capable of producing hundreds of watts of extreme ultraviolet (EUV) radiation within a wavelength bandwidth of 2% centred on 13.5 nm, based on the availability of Mo/Si multilayer mirrors (MLMs) with a reflectivity of ~70% at this wavelength. After initial studies to identify which ions are the strongest emitters at this wavelength it emerged that transitions of the type $4p^6 4d n - 4p54d^{n+1} + 4d^{n-1}4f$ from laser produced plasmas (LPPs) of tin, which overlap in a narrow wavelength range in the spectra of Sn IX to Sn XIV were the best candidates. However, because of plasma opacity, radiation transport is a major obstacle to be overcome. In order to maximise plasma emission the Sn ion density should be low enough to minimise absorption but the electron density should be sufficient to maximise the coupling of laser radiation into EUV emission. The current solution has been to irradiate tin droplets with a Nd:YAG pre-pulse which ionises the droplet and then reheat the resulting plasma with a CO_2 pulse when its density is close to the critical density for CO_2 radiation ~10^{19}cm^{-3} [2]. Currently the conversion efficiency of laser energy into in-band EUV radiation in such sources is close to 4% while significantly higher values have been predicted or reported from laboratory experiments. Work still remians to be done to optimise the emission from sources for high volume manufacturing.

Subsequently development of other sources at 6.X nm, where X ~ 0.7, has been identified for so-called Beyond EUVL (BEUVL), based on the availability of La/B based MLMs, with theoretical reflectance approaching 80% at this wavelength. Laser produced plasmas of Gd have been identified as a potential source, as $n = 4 - n = 4$ transitions in Gd ions emit strongly near this wavelength. However to date, the highest conversion efficiency (CE) obtained, for laser to BEUV energy emitted within the 0.6% wavelength bandwidth of the available mirrors is only 0.8%, [3]. This suggests a need to move to other sources, such as free electron lasers, if BEUVL is to become a reality..

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QUANTUM LOGIC SPECTROSCOPY OF TRAPPED IONS

Piet O. Schmidt[a,b]

[a]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
[b]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany

Precision spectroscopy is a driving force for the development of our physical understanding. However, only few atomic and molecular systems of interest have been accessible for precision spectroscopy in the past, since they miss a suitable transition for laser cooling and internal state detection. This restriction can be overcome in trapped ions through quantum logic spectroscopy. Coherent laser manipulation originally developed in the context of quantum information processing with trapped ions allows us to combine the special spectroscopic properties of one ion species (spectroscopy ion) with the excellent control over another species (logic or cooling ion). The logic ion provides sympathetic cooling and is used to control and read out the internal state of the spectroscopy ion. In my presentation I will provide an overview of different implementations of quantum logic spectroscopy suitable for narrow (long-lived) and broad (dipole-allowed) transitions. Applications range from highly accurate optical clocks based on aluminium ions [1], over precision spectroscopy of broad and non-closed transitions in calcium isotopes [2, 3], to non-destructive internal state detection and spectroscopy of molecular ions [4]. Prospects to extend quantum logic spectroscopy to highly charged ions and first steps towards this goal [5] will be discussed. Highly charged ions are among the most sensitive systems to probe for a variation of the fine-structure constant and hold the promise for high accuracy optical clocks.

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ION INTERACTIONS WITH FULLERENE AND PAH CLUSTERS

Henning Zettergren

Department of Physics, AlbaNova University Center, Stockholm University, Sweden

In this talk, I will review recent advances in our understanding of how pure and mixed clusters of fullerenes and Polycyclic Aromatic Hydrocarbons (PAHs) respond to singly and multiply charged keV-ion impact (see Fig. 1 for examples of molecular structures). I will highlight results from experimental and theoretical studies which show how the cluster environment plays a crucial role for the fate of the individual molecules (see e.g. Ref. 1 and references therein). These studies reveal how the projectile charge, mass, and velocity may be tuned to investigate, e.g., different cluster and monomer cooling processes [2], molecular heating by the Coulomb explosions of highly charged clusters [3], and impulse driven molecular growth processes [4,5]. I will also discuss recent observations of molecular growth in collisions with clusters of small hydrocarbon chains - a possible route for the formation of aromatic ring structures. The studies covered in this talk may contribute to a better understanding of energetic processing and formation of complex molecules in e.g. space [6], where PAHs and fullerenes are the largest molecules identified so far (or generally believed to be highly abundant) [6-8].

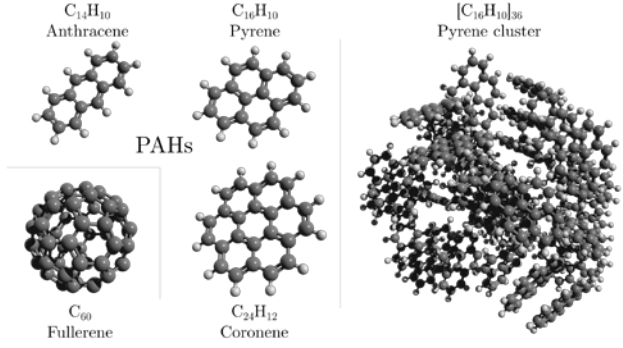

Figure 1: Examples of molecular structures for closed cage fullerenes (C_{60}), Polycyclic Aromatic Hydrocarbons (PAHs) and weakly bound PAH clusters ($[C_{16}H_{10}]_{36}$).

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PROGRESS REPORTS

FROM OPTICAL SPECTROSCOPIC ACCURACY TO FORBIDDEN-LINE SPECTROSCOPY

Tomas Brage[1], Jon Grumer[1], Wenxian Li[1,2,3], Xuelin Guo[1,3], Si Ran[1,3], Yang Yang[3], Xiao Jun[3], Per Jönsson[2], Roger Hutton[3] and Yaming Zou[2]

[1]Division of Mathematical Physics, Department of Physics, Lund University, Sweden
[2]Group of Material Science and Applied Mathematics, Malmö University, Sweden
[3]The Key Laboratory of Applied Ion Beam Physics, Ministry of Education, People's Republic of China

In this talk I will present some resent results from the collaboration between the theoretical groups of Lund and Malmö Universities, and the Modern Physics Institute of Fudan University in Shanghai. The first part will be concerned with the push for accurate calculations. Experimental results for atomic data, especially regarding transition energies and wavelengths in the optical and UV region, are often of unprecedented accuracy, leaving the theory far behind "in the dust". The general assumption is that only for simple, few-electron cases theory can compete – and even supersede experiment in accuracy for Helium-like systems, but then from methods geared towards these systems. The results for more general methods, such as the Multiconfiguration Dirac-Hartree-Fock used in this project, the accuracy is usually orders of magnitudes worse than from experiments, in the optical region. In this contribution we discuss a search for examples of systems where theory can achieve what we would label "optical spectroscopic accuracy", through large-scale and systematic modelling of these systems. This turns out to not only be of academic interest, but also opens up the possibility for tests of small and minute effects, such as transverse Breit and QED-corrections.

We will start by presenting results for systems with one electron outside a closed core, using the example of silver-like ions. Our results for the fine-structure, M1 transitions within the ground state rivals experiments in accuracy for wavelengths, but requires a large-scale investigation involving core-valence contributions with deep inner shells. Our final results agree with experiment to within 0.06 % accuracy, being accurate enough to allow for "single-line-spectroscopy" [1]. Even higher accuracy can be reached for systems without correlation in the first-order approximation. This is the case for systems with only one level for each J-value in the Layzer complex. We will exemplify this with systems with one single electron in the outermost shell, such as $2p^5$, $3d^9$ or $4f^{13}$. We will present results for F-like and Co-like ions, with the ground configuration of $2p^5$ and $3d^9$, respectively [2,3]. We will show that for these systems the computational accuracy rivals the experiment for the ground fine-structure and forbidden transition.

In the final part of the talk, I will discuss what we label as "Forbidden-line spectroscopy", with examples from Tungsten ions.

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POPULATION TRAPPING: THE MECHANISM FOR THE LOST RESONANCE LINES IN Pm-LIKE IONS

Daiji Kato[a,b] and Nobuyuki Nakamura[c]

[a]National Institute for Fusion Science, Toki, Gifu 509-5292, Japan
[b]Department of Fusion Science, Graduate University for Advanced Studies SOKENDAI, Toki, Gifu 509-5292, Japan
[c]Institue for Laser Science, The University of Electro-Communications, Chofu, Tokyo 182-8585, Japan

Promethium (Pm) has the 4f electron shell which is a loosely bound outermost orbital in a screened nuclear field. As the atomic number (Z) increases along the Pm isoelectronic sequence, the 4f orbital energy falls beneath the 5s orbital energy as in the hydrogenic system because screening of nuclear fields by ambient electrons in atomic systems becomes less significant for highly charged ions. Curtis and Ellis [1] predicted that the Pm sequence has the alkaline metal-like ground configuration: $4f^{14}5s$ for heavier elements of $Z > 73$ and should exhibit strong 5s-*n*p resonance line emissions in hot plasmas. However, there has yet to be a definite identification of the predicted resonance lines although many experimental and theoretical efforts have been devoted.

Here we report population kinetics studies on line emissions of the Pm sequence performed by using a collisional-radiative model. The present study reveals that population trapping in a long-lived excited configuration: $4f^{13}5s^2$ causes the loss of the 5s-*n*p resonance lines in emission spectra. The present calculations predict that emission lines of $5s^2$-5s5p resonance transitions are instead dominant in Extreme-Ultra-Violet (EUV) ranges at electron densities of 10^{10} cm^{-3} or higher. The calculated spectra are in good agreement with experimental spectra of Pm-like Bi^{22+} ions in a compact electron-beam ion trap (CoBIT) [2, 3]. The 5s-*n*p resonance lines become significant in calculated spectra if extremely low electron densities are assumed so that populations in the long-lived excited configuration can decay to the ground state via the electric octapole transition before subsequent electron collisions.

However, it is found that Sm-like Bi^{21+} ions exhibit strong resonance lines of the alkaline earth metal-like ground configuration: $4f^{14}5s^2\ ^1S_0$ in the both of CoBIT and theoretical spectra, although there is a quasi-stable low-lying excited level: $4f^{14}5s5p\ ^3P_0$ which is strictly forbidden to decay by emitting single photon. Based on calculated inflow and outflow rates of populations of excited states, we elucidate why the population trapping is not facilitated for this quasi-stable excited level of the Sm-like ions.

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UNDERSTANDING THE STABILITY OF CHARGED FULLERENES: UNRAVELING THE KEY FACTORS FROM A UNIFIED VIEW

Yang Wang[a,b], Sergio Díaz-Tendero[a,c], Manuel Alcamí[a,b], Fernando Martín[a,b,c]

[a]Departamento de Química, Módulo 13, Universidad Autónoma de Madrid, 28049 Madrid, Spain

[b]Instituto Madrileño de Estudios Avanzados en Nanociencia (IMDEA-Nanociencia), Cantoblanco, 28049 Madrid, Spain

[c]Condensed Matter Physics Center (IFIMAC), Universidad Autónoma de Madrid, 28049 Madrid, Spain

Multiply charged fullerenes have been the object of intensive investigations in recent years [1]. Both cationic and anionic forms of fullerenes exist abundantly in nature and have also been synthesized in laboratories. They have unique physical and chemical properties that endow them with promising applications in material science, biomedicine and astrophysics. An unusual behavior of charged fullerenes is that the isomer stability is often substantially different from that of their neutral counterparts. The well established stability rules for neutral fullerenes, such as isolated-pentagon rule (IPR), are no longer valid for many experimentally observed structures [1-3]. So what is then the key factors governing the stability of charged fullerenes?

This fundamental question has attracted much attention in fullerene chemistry. Some approximate rules, based on different physical arguments such as electrostatic repulsion and aromaticity, have been proposed for fullerene anions. These rules, however, often lead to conflicting predictions and require elaborate quantum chemistry calculations for all possible charge states and isomers, which limits their practical applications.

Here, we present a simple and universal model that allows us to fully understand the stability of both positively and negatively charged fullerenes. Based on the concepts of cage connectivity and frontier π orbitals, the model requires solely the knowledge of fullerene topology, with need for neither geometry optimizations nor iterative electronic structure calculations. Therefore, it permits a rapid determination of experimental structures and the energy ordering of isomers, among a very large number of possible forms. The predictive power of this approach has been systematically checked by considering all fullerene isomers with charges between +6 and -6, and cages from C_{28} to C_{104}. The model correctly predicts all experimental structures and explains why, for fullerene anions, the IPR is often violated, while, for fullerene cations, the opposite is observed.

Our new scheme has also been successfully extended to understand the stability of exohedral fullerene derivatives $C_{2n}X_{2m}$ (X = H, F, Cl, Br and CF_3), where millions or billions of isomers are possible.

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CRYOGENIC ELECROSTATIC STORAGE RINGS FOR LOW-ENERGY ION BEAMS

Andreas Wolf[a]

[a]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

Since many years electrostatic storage rings [1] are making it possible to store keV-energy beams of atomic as well as polyatomic molecular ions and clusters with typical beam lifetimes up to some seconds. Recently, strong progress was achieved in beam lifetimes by realizing the beam vacuum chamber and the electrostatic components at cryogenic temperature, typically 10 K. The facilities DESIREE at Stockholm University, RICE at RIKEN (Tokyo) and CSR at the Max Planck Institute for Nuclear Physics (Heidelberg) have now reported first results on the storage conditions [2,3,4] and also physics experiments [5,6].

Beam lifetimes measured so far were many minutes up to the order of an hour (reported average storage lifetimes of ~16 min to ~30 min for, respectively, 10 keV S^- and Te^- [5] and ~45 min for 60 keV Ag_2^- [4], see Figure). At DESIREE, the radiative decay rates of long-lived excited states in atomic ions could be measured, such as the 8.4 min radiative lifetime of the fine-structure excited state $2p^5\ P_{1/2}$ in S^- [5]. Furthermore, first studies at the CSR revealed the relaxation of the stored CH^+ ions with effective environmental radiative temperatures of ~20 K. With the stored CH^+ ions, rotational-state dependent near-threshold photodissociation resonances could be measured, separating the dominant $J = 0$ contribution from that of the $J = 1$ state [6]. The report will present the new cryogenic facilities and discuss their experimental opportunities.

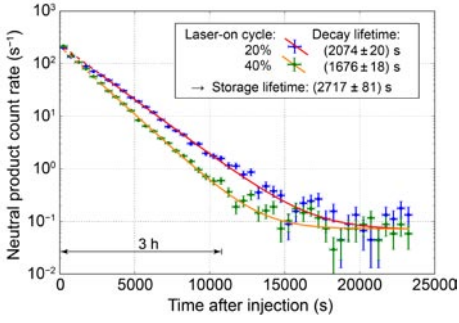

Figure: Beam storage lifetime measurements with 60 keV Ag_2^- ions in the CSR [4], probing the ion intensity by photodetachment at 633 nm. The small photodetachment rate used for the probing reduces the lifetime, as revealed by using different relative durations for the second-scale on/off cycle of the laser. Correcting for the losses by the probing yields the average storage lifetime, corresponding to 45.3 min.

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COOLING OF PAH CATIONS STUDIED WITH AN ELECTROSTATIC RING

J. Bernard[1], M. Ji[1,2], J. Matsumoto[3], C. Joblin[2], A. Cassimi[4], L. Chen[1], R. Brédy[1], S. Martin[1]

[1] Univ Lyon, Université Claude Bernard Lyon 1, CNRS, Institut Lumière Matière, F-69622, LYON, France

[2] Université de Toulouse, UPS-OMP, IRAP, Toulouse, France

[3] Department of chemistry, Tokyo Metropolitan University, Tokyo, Japan

[4] CIMAP, GANIL Université de Caen, Bd. H. Becquerel, Caen, France

The presence in the interstellar medium of polycyclic aromatic hydrocarbons (PAH) is now considered as the most probable explanation of some IR bands and DIBS (Diffuse Interstellar Bands). However, the formation and the stability of such complex molecular edifices in interstellar clouds (high dilution, exposition to UV, X-Rays, and all kinds of cosmic rays) is still a matter of debate. We present here a laboratory experiment demonstrating the fast radiative cooling of PAH cations, naphtalene$^+$ ($C_{10}H_8^+$), anthracene ($C_{14}H_{10}^+$) and Naphtalene dimers stored in a small electrostatic storage ring, the Mini-Ring [1] at a kinetic energy of 12 keV. Beams of naphtalene, anthracene and naphtalene dimer cations have been produced from our NanoGan ECR ion source (see mass spectrum in fig.1) and stored for 40 ms in the Mini-Ring. The internal energy distribution of the stored PAHs was probed by laser absorption using the 2nd or 3rd harmonics of a NdYAG laser and an OPO. Cooling rates in the hundred eV per second range were estimated from the measured time evolution of the internal energy distribution. The main contribution to this fast cooling rate is attributed to electronic fluorescence (Poincaré fluorescence). The contribution of infra-red emissions to the cooling rates was also estimated.

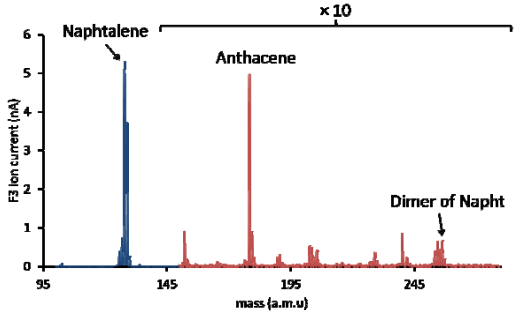

Figure 1: Mass spectrum of PAH molecular ions produced with our ECR ion source. Pressure of 2 10^{-5} mbar of naphtalene was injected (anthracene was an impurity due to previous experiments). Dimer of Naphtalene could be easily produced for injection into the Mini-Ring.

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HCI AND ASTROPHYSICAL ICES

Philippe Boduch[1], Hermann Rothard[1], Alicja Domaracka[1], Maria Elisabetta Palumbo[2], Giovanni Strazzulla[2], Enio F. da Silveira[3], and Emmanuel Dartois[4]

[1]Centre de Recherche sur les Ions, les Matériaux et la Photonique, CEA/CNRS UMR6252/ENSICAEN/UNICAEN, CIMAP-CIRIL-Ganil, BP 5133, 14070 Caen Cedex 05, France
[2]INAF–Osservatorio Astrofisico di Catania, Via S.Sofia 78, 95123 Catania, Italy
[3]Departamento de Física, Pontifícia Universidade Católica do Rio de Janeiro, Rua Marquês de São Vicente 225, 22451-900 Rio de Janeiro, RJ, Brazil
[4]Institut d'Astrophysique Spatiale, UMR8617, CNRS/Univ. Paris Sud, Université Paris Saclay, Univ. Paris Sud, F-91400 Orsay, France

Frozen gases that in astrophysics are collectively referred to as "ices" are ubiquitous in space. They are present in the dense phases of the interstellar medium (ISM, e.g. dense molecular clouds, proto-stellar cores) and on numerous icy bodies in the Solar System. They are mainly formed by simple molecules (like H_2O, CO, CO_2, NH_3 ...). Theses ices are exposed to different radiation fields (photons, electrons and ions). Heavy ions (C, O, S, Fe and Ni) are present in the solar/stellar wind, in cosmic rays and in the magnetosphere of giant planets. We present results on radiation effects of heavy ions on ices such as sputtering, amorphisation and compaction, dissociation of molecules, formation of new molecular species after radiolysis and by implantation of ions. The formation and the radio-resistance of organic molecules, related to the question of the initial conditions for the emergence of life, are briefly discussed. This review focusses on recent findings, with special emphasis on experiments with heavy multiply charged ion beams. These experiments aim in particular at simulating the effects of cosmic rays on icy grains in dense molecular clouds, and on the formation of molecules on icy bodies in the Solar System.

COULOMB CRYSTALLIZATION OF HIGHLY CHARGED IONS

Lisa Schmöger[a,b], O. O. Versolato[a,b], M. Schwarz[a,b], M. Kohnen[b], A. Windberger[a], B. Piest[a], S. Feuchtenbeiner[a], J. Pedregosa[c], T. Leopold[b], P. Micke[a,b], A. K. Hansen[d], T. M. Baumann[a], M. Drewsen[c], Thomas Pfeifer[a], J. Ullrich[b], P. O. Schmidt[b,e], J. R. Crespo López-Urrutia[a]

[a]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
[b]Physikalisch-Technische-Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
[c]Aix-Marseille Université, Ave Escadrille Normandie-Niémen, 13397 Marseille, France
[d]Aarhus University, Bygning 1520, Ny Munkegade, 8000 Aarhus C, Denmark
[e]Institut für Quantenoptik, Leibniz Universität, Welfengarten 1, 30167 Hannover, Germany

With the ability to simultaneously control both the excitation and the motional degrees of freedom of individual quantum objects, atomic physics has reached a degree of accuracy without peer among the experimental sciences. In principle, the binding energy of atomic electrons in their ground state is sensitive to all levels of Standard Model physics. Their wavefunction adapts to all small contributions arising from all known interactions. This universal pattern of sensitivity is expected to appear again if forces beyond the Standard Model were to exist.

In highly charged ions (HCIs), the wavefunction of the optically active electron has an enhanced sensitivity to electron-nucleus interactions and QED terms in general, and an extremely suppressed sensitivity to external field perturbations. Further, E1 forbidden optical transitions near level crossings in HCIs are extremely sensitive to possible drifts in the fine-structure constant α. These favorable properties have been widely recognized as an advantage for precision tests of fundamental physics and the development of HCI based clocks in many recent theoretical works. However, all known sources of HCIs produce them at high temperatures - typically in the MK regime - which severely limits the achievable spectral resolution of photonic studies. We have developed an experiment for retrapping, cooling and high-precision laser spectroscopy of HCIs [1]. It is based on continuously laser-cooled Be^+ Coulomb crystals in a linear cryogenic Paul trap [2] for stopping the motion of externally produced HCIs and sympathetically cooling them below 250 mK. This cooling induces the formation of stable mixed crystals – down to a single HCI cooled by a single co-trapped Be^+ ion [3]. The strongly suppressed thermal motion of the embedded HCIs offers novel possibilities for investigation of questions regarding the time variation of fundamental constants, parity non-conservation effects, and quantum electrodynamics. Our current work aims at high-precision spectroscopy of the $^2P_{1/2}$ - $^2P_{3/2}$ M1 transition at 441 nm in cold Ar^{13+} ions. Adding HCIs to the quantum toolbox is one important goal within the scope of next-generation experiments, which are currently being set up. One aims at applying quantum logic schemes to HCIs and developing an HCI optical clock, the other one at direct VUV frequency comb spectroscopy of electronic transitions in HCIs.

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ASYMMETRIES OF THE ELECTRON CUSP IN HEAVY-ION ATOM COLLISIONS

P.-M. Hillenbrand[a], S. Hagmann[a], Yu. A. Litvinov[a], and Th. Stöhlker[a,b,c]

[a]GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany
[b]Helmholtz-Institut Jena, 07743 Jena, Germany
[c]Institut für Optik und Quantenelektronik, F.-Schiller-Universität Jena, 07743 Jena, Germany

In collisions of heavy highly-charged projectile ions with atomic targets, the energy distribution of the emitted electrons is a characteristic observable for the underlying elementary charge-transfer processes. At the experimental storage ring ESR of the heavy-ion accelerator facility GSI, a dedicated magnetic electron spectrometer was installed downstream from the supersonic gas-jet target, which enables the measurement of high-energetic electrons emitted in ion-atom collisions, with electron velocities similar to the projectile velocity, emitted within a small cone in the forward direction. This provides the ability to extend the well known study of cusp electrons towards heavy-ion atom collisions at near-relativistic projectile energies. Through the electron-loss-to-continuum (ELC) cusp, double-differential cross sections of projectile ionization can be studied even for the heaviest few-electron projectiles [1]. But also a new channel opens up, the radiative electron capture to continuum [2], which can be directly compared to its non-radiative counterpart [3]. Using the electron spectrometer in combination with detectors for emitted x rays and charge-exchanged projectiles, the study of the collision system $U^{88+} + N_2$ @ 90 MeV/u revealed three processes, each characterized by a unique shape of the electron cusp [4].

Furthermore, the process of ELC was investigated for multi-electron projectiles in the collision systems

$$U^{28+}+H_2 \rightarrow U^{29+}+[H_2]^*+e^-,\ U^{28+}+N_2 \rightarrow U^{29+}+[N_2]^*+e^-,\ U^{28+}+Xe \rightarrow U^{29+}+Xe^*+e^-.$$

The experimental data revealed a significant electron cusp asymmetry, which increases towards heavier targets. This observation is inconsistent with presently available theories [5].

As a next step, an experimental study of ELC for U^{89+} ions colliding with different gaseous targets is envisaged, at a projectile energy just above the threshold for electron impact ionization. For these collision systems, relativistic CDW calculations predict a deviation of the electron energy distribution from first-oder perturbation theory due to the effect, that the electron emitted by the projectile is attracted by the target nucleus.

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CONVERGENT CLOSE-COUPLING APPROACH TO SCATTERING OF HIGHLY-CHARGED IONS

A. S. Kadyrov, I. B. Abdurakhmanov, J. J. Bailey, J. Faulkner, T. Fillingham, K. Massen-Hane, J. R. Williamson, and I. Bray

Department of Physics, Astronomy and Medical Radiation Sciences, Curtin University, GPO Box U1987, Perth, WA 6845, Australia

The two-centre convergent close-coupling (CCC) approach was originally developed for positron scattering on atomic hydrogen including positronium formation [1]. Later, it was extended to direct scattering and ionisation in ion-atom and ion-molecule collisions using the impact parameter representation (see [2] and references therein). Recently, we have generalised the CCC approach for heavy projectiles to include electron-transfer channels. We have developed two distinct versions of the two-centre CCC approach to ion-atom collisions. The quantum-mechanical convergent close-coupling (QM-CCC) approach [3] is based on the exact fully quantum-mechanical three-body Schrödinger equation for the total scattering wave function and leads to a set of coupled Lippmann-Schwinger integral equations for the transition amplitudes. The relative motion of the heavy particles is treated fully quantum-mechanically. The total scattering wave function is expanded using a two-centre pseudostate basis. This allows one to take into account all underlying processes, namely, direct scattering and ionisation, electron capture into bound and continuum states of the projectile. The off-shell integration in the coupled-channel Lippmann-Schwinger integral equations is taken analytically which greatly reduces computational effort and memory requirements. The semiclassical convergent close-coupling (SC-CCC) approach [4] is based on the semiclassical time-dependent Schrödinger equation for the electronic part of the scattering wave function and leads to a system of coupled differential equations for the transition probability amplitudes. Both methods have been applied to calculate cross sections and stopping powers in antiproton collisions with various atomic and simple molecular targets in the energy range from 1 keV to 1 MeV. The methods have also been applied to proton collisions including rearrangement channels. In particular, the SC-CCC approach has been applied to study the excitation and the electron-capture processes in proton-hydrogen collisions. The integral alignment parameter for polarisation of Lyman-α emission and the cross sections for excitation and electron capture into the lowest excited states have been calculated for a wide range of the proton impact energies. The QM-CCC approach has been used to investigate ionisation including electron capture into the continuum of the projectile. Due to a very general nature of the formulation, both quantum-mechanical and semiclassical implementations of the CCC methods are readily applicable for other scattering systems. We report on progress in applications of the CCC method to collisions of highly-charged ions with atomic hydrogen and hydrogen-like targets.

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CAPILLARIES AS SELF-ORGANIZED ELECTROSTATIC LENSES FOCUS: CHARGE RELAXATION AFTER ION BEAM IRRADIATION

E. Giglio[a], S. Guillous[a], G.U.L. Nagy[b], H. Zhang[d], A. Cassimi[a], R. D. DuBois[c], K. Tökési[b]

[a]Centre de Recherche sur les Ions, Matriaux et Photonique (CIMAP), F-14000, Caen, France

[b]Institute for Nuclear Research, Hungarian Academy of Sciences, 4026 Debrecen, Hungary

[c]Misssouri University of Science and Technology, Rolla, MO 65409 USA

[d]School of Nuclear Science and Technology, Lanzhou University, Lanzhou, China

While the guiding of ions through glass-capillaries due to charged patches is qualitatively understood [1], the complex nature of the electric conduction in such insulators makes quantitative predictions still a challenging task. Indeed, for a given ion beam, the guiding is determined by the charging rate combined with the discharge rate where the discharge dynamics of the charge patches at the surface depend on the electrical properties of insulators and on the position and nature of grounded electrodes. In order to get some insights into the discharge dynamics in those insulators, we did a combined experimental and theoretical study of the charge relaxation in glass capillaries. We studied two different cases: i) The discharge of a small single charge patch in a glass tube. ii) The discharge of a highly charged conical macro-capillary. In both cases, the electric field, induced by the deposited charges, is monitored by using the ion beam as probe. The Coulomb deflection of the probe beam is followed in time on a position sensitive detector, yielding the relaxation in time of the deposited charge. Using a home-made numerical code InCa4D [2], the same observables were simulated and compared to the experimental data. They highlighted the importance of the depolarization field due to the ionic conductivity in glasses, eventually validating the conductivity model used in our simulations. Also, it was found that much attention must be paid to secondary electrons generated by the beam, as they contribute to discharge the capillary, if poorly shielded. Taking advantage of the guiding properties of glass capillaries, we show via our realistic simulations that, under certain conditions, tapered capillaries can be used as self-organized electrostatic lenses to focus the beam.

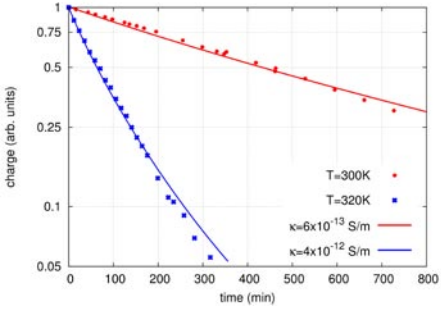

Figure 1: Discharge of a conical capillary for two different temperatures T=300K (red points) and T=320K (blue points). The solid lines stand for simulations with adjusted bulk conductivities $\kappa_1 = 6 \times 10^{-13}$ S/m and $\kappa_2 = 4 \times 10^{-12}$ S/m to fit the experimental data.

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BREAKDOWN CURVES OF CARBON-BASED MOLECULES FOR ASTROCHEMISTRY

M. Chabot[a] and K. Béroff[b]

[a]Institut de Physique Nucléaire d'Orsay, CNRS and Université Paris Sud F-91406 Orsay, France
[b]Institut des Sciences Moléculaires d'Orsay, CNRS and Université Paris Sud F-91405 Orsay, France

Carbon-based molecules are ubiquitous in astrophysical environments. The study of the composition and evolution of the molecular material is what is called astrochemistry. It involves the knowledge of a huge amount of data including fragmentation branching ratios (BR). The experimental group in Orsay (France) has developed a dedicated set-up (AGAT) for fragmentation recording of molecules and clusters of known charge and internal energy. Recently they showed how these data could be used to provide, within a statistical fragmentation context, BR for numerous physical and chemical processes of astrophysical interest [1]. The method relies on the construction of Breakdown curves (BDC), which are energy dependent BR. On the other hand, BDC have been calculated within the Microcanonical Metropolis Monte Carlo method (M3C) [2]. Figure 1 shows, for the C7 cluster, a comparison between the semi-empirical BDC and those obtained through M3C. The very good agreement validates so far the semi-empirical approach.

Whereas BDC of some hydrocarbon molecules were so constructed and used to predict BR for various processes [1] we aim at continuing those studies on CnHmq+ species with larger m and n (n≤5, m≤4 q≤2) and on nitrogenated species. BR of processes derived from the BDC will be included in the international astrochemical database KIDA (http://kida.obs.u-bordeaux1.fr) [3]. The impact of so-extracted BR in a particular astrophysical environment (Horse Head photo-dissociation region) will be presented and discussed.

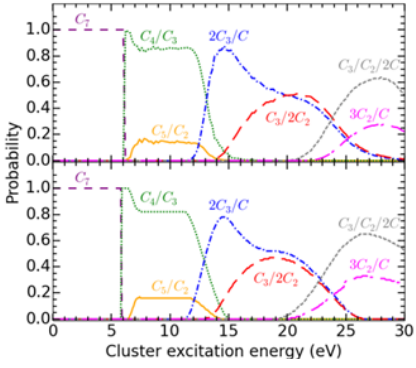

Figure 1: Breakdown curves for the C7 cluster. Upper panel: theoretical M3C calculations. Lower panel: semi-empirical model.

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CHARGE EQUILIBRATION AND ENERGY LOSS OF SLOW HIGHLY CHARGED IONS IN SINGLE LAYER GRAPHENE

E. Gruber[a], R.A. Wilhelm[a], V. Smejkal[a], R. Kozubek[b], J. Schwestka[a], A. Hierzenberger[b], M. Schleberger[b], S. Facsko[c], F. Aumayr[a]

[a]Institute of Applied Physics, TU Wien, Wiedner Hauptstr. 8-10/E134, 1040 Vienna, Austria
[b]Fakultät für Physik and Cenide, Universität Duisburg-Essen, 47048 Duisburg, Germany
[c]Helmholtz-Zentrum Dresden-Rossendorf, Inst. of Ion Beam Physics & Materials Research, 01328 Dresden, Germany

During the interaction of slow highly charged ions (HCIs) with solids their potential energy is deposited in a shallow surface region via multiple charge transfer and successive deexcitation processes [1]. After passing through only a few nanometers in a solid, HCIs rapidly reach their equilibrium charge state. Due to the short time scale (typically some fs) pre-equilibrium effects like a charge state dependent energy loss (stopping force) are experimentally hardly accessible. For a target film with a thickness in the sub-nm range the interaction time is no longer sufficient for a complete relaxation and charge equilibration of the projectiles [2,3].
The special combination of slow highly charged ions with charge states far away from equilibrium and an ultimately thin 2D target, as freestanding single layer graphene, is therefore ideally suited to study pre-equilibrium phenomena.
For this purpose freestanding single layer graphene sheets are irradiated with Ar^{q+} and Xe^{q+} ions of various charge states (q=4-40) and kinetic energies (4 keV-180 keV) at the Ion Beam Centre of the Helmholtz-Zentrum Dresden-Rossendorf and at TU Wien.
Studying the charge exchange and energy loss of transmitted ions utilizing an electrostatic analyzer enables to gain information on the equilibration dynamics and the stopping force. Extremely short charge-equilibration times are derived from the mean exit charge state, i.e. the number of captured and stabilized electrons as a function of the incident charge state and ion velocity. Additionally, the energy loss of highly charged projectiles is found to be strongly enhanced and to increase quadratically with the incident projectile charge state.

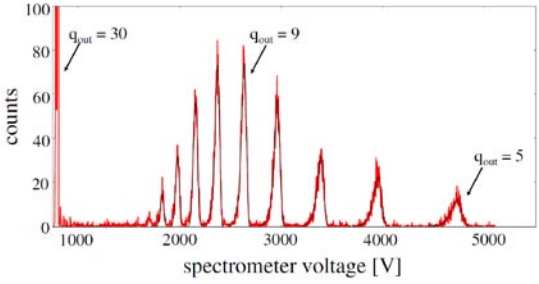

Figure 1: Exit charge state distribution of 135 keV Xe^{30+} transmitted through freestanding single layer graphene. The solid black lines are fits through every single peak.

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SELECTED TOPICS

IMPACT PARAMETER SENSITIVE STUDY OF INNER-SHELL ATOMIC PROCESSES IN THE EXPERIMENTAL STORAGE RING

A. Gumberidze[a], C. Kozhuharov[a], R. Zhang[a], S. Trotsenko[a,b], H. F. Beyer[a,b], K.-H. Blumenhagen[b,c], C. Brandau[a,d], A. Bräuning-Demian[a], W. Chen[a], O. Forstner[b,c], B. Gao[a], T. Gassner[a], R. Grisenti[a,e], S. Hagmann[a,e], P.-M. Hillenbrand[a], P. Indelicato[f], A. Kumar[g], M. Lestinsky[a], Yu. A. Litvinov[a], N. Petridis[a], D. Schury[a,d], U. Spillmann[a], C. Trageser[a,d], M. Trassinelli[h], X. Tu[a], Th. Stöhlker[a,b,c]

[a]GSI Darmstadt, Germany; [b]Helmholtz Institute Jena, Germany; [c]Friedrich-Schiller-Universität Jena, Germany; [d]Justus-Liebig-Universität Giessen, Germany; [e]Goethe-Universität-Frankfurt, Germany; [f]ENS, CNRS, UPMC, Paris, France; [g]NPD, Bhabha Atomic Research Centre, Mumbai, India; [h]INSP, CNRS and UMPC, Paris, France

In this contribution, we present an experiment devoted to impact parameter sensitive studies of inner shell atomic processes for low-energy (heavy-)ion-atom collisions [1-4].

The measurement was performed at the Experimental Storage Ring (ESR) at GSI Darmstadt with bare and He-like xenon ions (Xe^{54+}, Xe^{52+}) colliding with neutral xenon gas atoms, resulting in a symmetric collision system. This choice of the projectile charge states was made in order to compare the effect of a filled K-shell with the empty one. The beam energy (for both charge states) was 50 MeV/u. This value of the beam energy was chosen as a compromise between the adiabaticity of the collision and the reasonable beam lifetime/intensity in the ESR after deceleration. Although the energy is not very low, one can still expect significant non-perturbative effects due to the heavy target. In order to obtain information concerning the impact parameter and, in particular to pick out close collisions which are especially important for observing quasi-molecular effects, the scattered projectile ions which had undergone close collisions with the target atoms were detected by a particle detector (plastic scintillator) mounted in a specially constructed movable pocket at $\sim$3.5 m downstream from the target. In addition to the detector for the scattered projectiles, the x-rays emitted from the interaction zone were observed by an array of semiconductor and scintillator detectors mounted at different angles with respect to the ion beam direction. The physical processes leading to the x-ray emission are: excitation of the projectile/target electrons and electron capture from the neutral target into the highly-charged xenon ions.

By looking at the coincidences between the x-rays and the scattered projectiles, we were able to clearly demonstrate the possibility of picking out the characteristic x-rays stemming from the close collisions only. This offers us a new observable for the atomic collision experiments at the storage ring. The experimental results will be presented together with the state-of-the-art theoretical predictions [4].

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COUPLED-CHANNEL CALCULATION OF X-RAY EMISSION FOLLOWING Kr, Xe + Xe^{54+}, Xe^{52+} COLLISIONS @ 50-200 MeV/u

Y. S. Kozhedub[a], I. I. Tupitsyn[a], A. Gumberidze[b], C. Shao[c], D. Yu[c], and V. M. Shabaev[a]

[a]Department of Physics, St. Petersburg State University, Ulianovskaya 1, Petrodvorets, 198504 St. Petersburg, Russia

[b]GSI Helmholtzzentrum, Planckstrasse 1, 64291 Darmstadt, Germany

[c]Institute of Modern Physics, Chinese Academy of Science, Lanzhou 730000, P.R. China

Recently an essential progress was achieved at measuring of radiation spectra in quasi-symmetric highly-charged heavy ion-atom collisions at middle rage of collision energies. Thus an investigation of the Kr, Xe + Xe^{54+} collisions at 52-, 94-, 146, 197-MeV/u collision energies was carried out in IMP (Lanzhou, China) [1]. While the collisions Xe + Xe^{54+}, Xe^{52+} at 50 MeV/u were studied in GSI (Darmstadt, Germany) [2]. The present work is devoted to theoretical calculation of the radiation spectra. Method of calculations employs an independent particle model with effective single-electron Dirac-Kohn-Sham operator [3]. Solving of the single-electron equations is based on coupled-channel approach with atomic-like Dirac-Sturm-Fock orbitals, localized at the ions (atoms) [4]. Many-particle probabilities are calculated in terms of single-particle amplitudes employing the formalism of inclusive probabilities [5]. The analysis of the post-collisional processes resulting in the x-ray emissions is based on the fluorescence yields, the radiation, and Auger decay rates, and allows one to derive intensities of the x-ray emission and compare them with experimental data. The method of calculation takes into account the dynamics of all electrons in the system. The role of relativistic and many-particle effects is analyzed.

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ELECTRONIC TRANSITIONS IN HIGHLY CHARGED IONS AS FUTURE X-RAY WAVELENGTH STANDARDS

Sven Bernitt[a,b], Peter Micke[a,c], Hans-Christian Wille[d], Stanislav Tashenov[e], Sascha W. Epp[f], Joachim Ullrich[c], Thomas Pfeifer[a], Thomas Stöhlker[b], José R. Crespo López-Urrutia[a]

[a]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
[b]IOQ, Friedrich-Schiller-Universität, Max-Wien-Platz 1, 07743 Jena, Germany
[c]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
[d]Deutsches Elektronen-Synchrotron, Notkestraße 85, 22607 Hamburg, Germany
[e]Ruprecht-Karls-Universität, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany
[f]MPI für Struktur und Dynamik der Materie, Luruper Chaussee 149, 22761 Hamburg, Germany

With the newest generation of ultrabrilliant synchrotron light sources and free-electron lasers, the flux and brilliance of available X-ray photon beams has increased by several orders of magnitude. This has made many new applications feasible, ranging from material science and biology to fundamental atomic and nuclear physics [1,2]. However, many experiments depend on a precise knowledge of the wavelength of the photons delivered by the source, which is currently limited by the accuracy of available X-ray wavelength references. Often, users have to rely on absorption-edge measurements, which are subject to a number of systematic chemical and crystallographic effects limiting their reproducibility. Crystallographic lattice-spacing standards are subject to thermal expansion and thus limited to the 10^{-9} accuracy level. In contrast, wavelength standards based on electronic transitions in atoms or ions on the other hand are highly accurate and reproducible. We investigate the application of HCI as an atomic X-ray wavelength standard.

The transportable electron beam ion trap FLASH-EBIT [3] has been used in a number of experiments to provide targets of trapped HCI for VUV and X-ray radiation from the free-electron lasers FLASH and LCLS, as well as the synchrotron light sources BESSY II and PETRA III. By observing resonantly excited fluorescence we were able to measure transition energies [3,4,7], relative oscillator strengths [5] and natural line widths [4,6]. Our measurements have provided valuable atomic data for the interpretation of astrophysical X-ray spectra [5] and furthermore allowed to test atomic theory on the level of QED contributions [3,4,7]. Based on the methods explored with the FLASH-EBIT, we developed a novel electron beam ion trap based on permanent magnets. This PolarX-EBIT is equipped with instrumentation for X-ray laser spectroscopy and polarimetry with HCI, and will be used to provide a permanent X-ray wavelength reference for beamline P01 at PETRA III.

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GROUND STATE HYPERFINE SPLITTING IN LITHIUMLIKE AND HYDROGENLIKE BISMUTH

Johannes Ullmann[a,b] , Jonas Vollbrecht[d], Zoran Andelkovic[c], Carsten Brandau[c,l] Andreas Dax[h], Wolfgang Geithner[c], Christopher Geppert[b], Christian Gorges[b], Michael Hammen[e,g], Volker Hannen[d], Kristian König[b,c], Simon Kaufmann[b], Thomas Kühl[c], Yuri Litvinov[c], Matthias Lochmann[b], Bernhard Maass[b,c], Johann Meisner[f], Tobias Murböck[k], Rodolfo M. Sánchez[c], Stefan Schmidt[b,g], Matthias Schmidt[f], Markus Steck[c], Thomas Stöhlker[a,c], Richard C. Thompson[i], Christian Trageser[l], Christian Weinheimer[d], Danyal Winters[c], Wilfried Nörtershäuser[b]

[a]Helmholtz Institut Jena, Germany; [b]Institut für Kernphysik, Technische Universität Darmstadt, Germany; [c]GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany; [d]Institut für Kernphysik, Universität Münster, Germany; [e]Helmholtz Institut Mainz, Germany; [f]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany; [g]Institut für Kernchemie, Universität Mainz, Germany; [h]Paul Scherrer Institute, Villigen, Switzerland; [i]Department of Physics, Imperial College London, UK; [k]Institut für Angewandte Physik, Technische Universität Darmstadt, Germany; [l]Physikalisches Institut, Universität Giessen, Germany

While quantum electrodynamics (QED) is usually referred to as the most accurately tested theory, its validity for electrons in very strong fields is still not tested with high accuracy. The strongest magnetic fields available in the laboratory are experienced by electrons in the ground-state of highly charged heavy ions which can be probed by hyperfine spectroscopy. Even though the ground state M1 hyperfine transition in hydrogen-like bismuth was observed already in 1994 [1], the significance of the experiment as a test for QED was limited by the unknown magnetic moment distribution inside the nucleus. However, it was suggested that a so-called specific difference between the hyperfine splitting in hydrogen-like and lithium-like ions of the same isotope can be used to cancel nuclear structure effects and provide an accurate test of QED [2]. The transition in Li-like Bismuth was observed for the first time in 2011 at the Experimental Storage Ring ESR located at the GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt [3]. Yet the accuracy of the result was limited by the calibration of the electron cooler voltage, determining the ion velocity. Here, we report on improved laser spectroscopic measurements of the hyperfine splittings in hydrogen- and lithium-like bismuth ions ($^{209}Bi^{82+}$ and $^{209}Bi^{80+}$) at the ESR. The accuracy was improved by about an order of magnitude compared to the first observation in 2011 [3]. The most important new feature was an *in-situ* high voltage measurement system provided by German metrology institute Physikalisch-Technische Bundesanstalt. The voltage at the electron cooler platform could be determined with an accuracy at the 10-ppm level. As the dominant systematic effect, the space charge effect of the electron cooler current on the ion velocity was determined with two independent techniques that provided consistent results. We present the measured transition energies of both hydrogen- and lithium-like bismuth accompanied by a comprehensive uncertainty analysis and show the experimentally determined value for the specific difference in ^{209}Bi.

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HIGH ACCURACY MEASUREMENTS OF TRANSITION ENERGIES IN HIGHLY CHARGED IONS WITH A DOUBLE-CRYSTAL SPECTROMETER

J. Machado[a,b], P. Amaro[a], M. Guerra[a], M. Trassinelli[c], J.P. Santos[a], P Indelicato[b]

[a]Laboratório de Instrumentação, Engenharia Biomédica e Física da Radiação (LIBPhys-UNL), Departamento de Física, Faculdade de Ciências e Tecnologia, FCT, Universidade Nova de Lisboa, 2829- 516 Caparica, Portugal

[b]Laboratoire Kastler Brossel, Sorbonne University, Univ. Pierre et Marie Curie-Paris 06, École Normale Supérieure, Collège de France, CNRS, Case 74, 4 place Jussieu, F-75005 Paris, France

[c]Institut des NanoSciences de Paris, Sorbonne Universités, UPMC Univ. Paris 06, Case 840; 4, place Jussieu, F-75005 Paris

Highly charged ions (HCI) are relatively simple atomic systems compared with neutral atoms, in which one can control the number of bound electrons. Recently, the scientific and technological developments in the study of these exotic states of matter have enabled high-precision measurements of several parameters with unprecedented accuracy. One example is the absolute (reference-free) energy measurement of a heliumlike argon transition with an accuracy of 2.5 ppm[1] on the plasma of the electron cyclotron resonance ion source (ECRIS) SIMPA (Multicharged Ion Source of Paris)[2] at the Laboratoire Kastler Brossel (École Normale Supérieur, Université Pierre and Marie Curie (UPMC) and CNRS), using a double-crystal spectrometer (DCS)[3]. It has also been shown that in addition to the high-precision measurements of transition energies, analysis of DCS spectra can also provide natural line widths of the elements present in the ECRIS plasma[4].

Our goal is to extend the accurate transition energy measurements to other ions and species (Ar, Kr, Xe and S) aiming an accuracy less than 2 ppm. For that purpose, the DCS experimental apparatus is being updated and improved by implementing a better control of the temperature and verticality of the crystals and a new X-ray detector. With such accuracy, this method can be used to probe and test bound state quantum electrodynamics (BSQED), allowing validation of state-of-the-art theories, and provide new and more reliable X-ray standards in the few keV energy range.

The experimental setup, the current status of the experiment and the latest results will be presented, focused on data analysis.

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NONLINEAR INTERACTION OF ULTRA-INTENSE FEMTOSECOND FREE-ELECTRON LASER PULSES AT ÅNGSTROM WAVELENGTHS

J. Hoszowska[a], J. Szlachetko[b,c], J-Cl. Dousse[a], W. Błachucki[a], Y. Kayser[b], C. J. Milne[b], M. Nachtegaal[b], B.D. Patterson[b], R. Abela[b] and M. Pajek[c]

[a]Department of Physics, University of Fribourg, CH-1700 Fribourg, Switzerland
[b]Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland
[c]Institute of Physics, Jan Kochanowski University, 25-406 Kielce, Poland

The interaction of ultra-intense femtosecond hard x-ray free-electron laser (XFEL) pulses with matter may result in multi-photon absorption and nonlinear processes in the x-ray regime [1-6]. When the XFEL pumping rate is faster than the inner-shell decay rate a population inversion through rapid photoabsorption can be generated and thus x-ray lasing [7-9].

In this work we have investigated the nonlinear two-photon single and double K-shell ionization and the multi-color inner-shell x-ray lasing at Ångstrom wavelengths based on the inner-shell scheme for solid Fe. The experiment was performed at the CXI end-station of the Linac Coherent Light Source (LCLS) by means of the high energy resolution x-ray emission technique. The Fe K x-ray radiative transitions were measured with the bent crystal von Hamos x-ray spectrometer of PSI [10] installed at CXI and equipped with the CSPAD detector. The focused photon beam in the 7.0-7.6 keV range provided extreme peak power densities reaching $\sim 10^{17}$-10^{20} W/cm^2.

As a result of the population inversion of femtosecond duration by rapid K-shell photoionization, and the following atomic relaxation processes and sequential two-photon absorption within the pulse duration, x-ray lasing transitions of different wavelengths were observed. Multi-color hard x-ray lasing based on the inner-shell transition scheme was thus established. We will report on the x-ray flux dependence of the measured x-ray emission rates, saturable one-photon absorption, and cross-sections for two-photon single and double absorption processes.

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POLARIZATION TRANSFER IN ELASTIC PHOTON SCATTERING BY HEAVY IONS AND ATOMS

A. Surzhykov[a,b], A. V. Volotka[c], V. A. Yerokhin[d], Th. Stöhlker[c,e], and S. Fritzsche[c,e]

[a]Physikalisch–Technische Bundesanstalt, D–38116 Braunschweig, Germany

[b]Technische Universität Braunschweig, D–38106 Braunschweig, Germany

[c]Helmholtz–Institut Jena, D-07743 Jena, Germany

[d]Center for Advanced Studies, St. Petersburg State Polytechnical University, 195251 St. Petersburg, Russia

[e]Friedrich–Schiller–Universität Jena, D–07743 Jena, Germany

Recent advances in high–brilliance synchrotron sources and x–ray detectors are now enabling a new generation of studies of elastic photon scattering by heavy neutral atoms and highly–charged ions. For photon energies below 1 MeV, this $\gamma + A \to \gamma + A$ process is dominated by the x–ray scattering off bound atomic (or ionic) electrons. This so–called Rayleigh scattering is known as a versatile tool for investigating the structure of atoms, complex molecules, and even complex nano–objects. While in the past most of the Rayleigh experiments have been dealt with the total and angle–differential cross sections, much of today's interest is focused on the polarization of scattered photons [1]. To better understand the outcome of the polarization–resolved measurements, detailed theoretical analysis has been performed recently [2,3]. In particular, we have used the second–order perturbation theory and the density matrix approach in order to study how the polarization of scattered photons affected if the incident light is itself linearly polarized. Detailed calculations were performed for high–Z helium–, beryllium– and neon–like ions and neutral atoms and for photon energies up to 500 keV. Based on these calculations, we have found that the polarization of outgoing x–rays can be extremely sensitive to the polarization of incident light; the effect which becomes most pronounced for the large scattering angles. We argue, therefore, that the elastic Rayleigh scattering can provide a unique tool for the diagnostics of the polarization purity of synchrotron radiation.

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SINGLE PHOTON EXCITATION OF Kα IN HELIUMLIKE Kr^{34+}

S.W. Epp[a], R. Steinbrügge[b], S. Bernitt[b,c], J.R. Crespo López-Urrutia[b]

[a]Max-Planck-Institut für Struktur und Dynamik der Materie, Luruper Chaussee 149, 22761 Hamburg, Germany

[b]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

[c]Institut für Optik und Quantenelektronik, Friedrich-Schiller-Universität Jena, Max-Wien-Platz 1, 07743 Jena, Germany

The level structure of three-body-systems such as He-like ions is fundamental for our understanding of the electromagnetic interaction within atomic systems. We report on the measurement [1] of two fundamental transitions from the ground state $^1S_0$ to the excited states $^1P_1$ (*w* line) and $^3P_1$ (*y* line) in heliumlike Kr^{34+} by resonant single-photon excitation after combining an electron beam ion trap with a high brilliance synchrotron. We find transition energies of E(*w*) = 13114.47(14) eV and E(*y*) = 13026.15(14) eV, which are in excellent agreement with present theoretical calculations [2]. Our value for E(*w*) and the average of the hitherto reported experimental results $\overline{\mathrm{E}}_{\mathrm{Lit}}(w)$ = 13115.15(17) eV do not overlap within their two-sigma error boundaries. We can provide a value E(*w*)/E(*y*) = 1.006780(7) for the energy ratio of the two transitions with an accuracy of 8 parts-per-million. This ratio is obtained independently of any energy calibration since it does not require one.

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THE CRYRING@ESR PROJECT

F. Herfurth, M. Lestinsky for the CRYRING working group

Heavy, highly charged ions stored at low energy are ideal probes for various questions of modern physics that range from tests of QED especially at high fields to detailed investigations of nuclear reactions. CRYRING@ESR, the early installation of the low-energy storage ring LSR, a Swedish in kind contribution to the FAIR project in Darmstadt/Germany, provides the necessary environment for precise experiments with slow, highly charged ions. The CRYRING@ESR project will connect low energy storage ring physics with the heavy, highly charged ions available at GSI/FAIR.

The ring can store ions ranging from a few 100 keV/nucleon to a few MeV/nucleon. Heavy, highly charged ions up to bare or hydrogen like uranium are produced at the GSI accelerator facility at about 400 MeV/nucleon, decelerated and cooled in the experimental storage ring ESR to about 4 MeV/nucleon, and then transported into the CRYRING@ESR. There the ion beam can be decelerated further, cooled with a dedicated electron cooler, and stored for experiments, or extracted. An in ring gas target will be setup as well as a number of single particle detectors. All components have been transported to GSI in 2013. The infrastructure has been prepared and the major parts have been installed by now. The local injector produced successfully H_2^+ ions accelerated to 300 keV/nucleon for ring commissioning that is planned to start later this year.

PROSPECTS AND CHALLENGES OF LASER COOLING OF STORED BEAMS OF RELATIVISTIC HIGHLY CHARGED IONS

Michael Bussmann[a], Danyal Winters[b], Tobias Beck[c], Gerhard Birkl[c], Oliver Boine-Frankenheim[b,c], Christina Dimopoulou[b], Lewin Eidam[c], Volker Hannen[d], Daniel Kiefer[c], Thomas Kühl[b,e], Matthias Lochmann[b], Markus Löser[a,f], Xinwen Ma[g], Lijun Mao[g], Fritz Nolden[b], Wilfried Nörtershäuser[c], Benjamin Rein[c], Rodolfo Sanchez[b], Ulrich Schramm[a,f], Mathias Siebold[a], Peter Spiller[b], Markus Steck[b], Thomas Stöhlker[b,e,h], Sascha Tichelmann[c], Johannes Ullmann[b,c], Thomas Walther[c], Hanbing Wang[g], Weiqiang Wen[g], Daniel Winzen[d], Jiancheng Yang[g], Youjin Yuan[g]

[a]Helmholtz-Zentrum Dresden – Rossendorf, Germany
[b]GSI Helmholtzzentrum Darmstadt, Germany
[c]Technische Universität Darmstadt, Germany
[d]Westfälische Wilhelms-Universität Münster, Germany
[e]Helmholtz-Institut Jena, Germany
[f]Technische Universität Dresden, Germany
[g]Institute of Modern Physics, Lanzhou, China
[h]Friedrich-Schiller-Universität Jena, Germany

Laser cooling is a promising technique to attain ion beams with ultra-low longitudinal momentum spread at highly relativistic beam energies. It can even overcome intra-beam scattering, leading to highly brilliant ion beams that have the potential to undergo a phase transition to a crystalline state [1].

We discuss which lessons we have learned from recent experiments on laser cooling of relativistic C^{3+} ion beams [2,3] for the future application of laser cooling at high energy storage rings and synchrotrons [4].

Starting from an in-depth discussion on laser cooling of highly charged ions based on recent calculations for suitable cooling transitions we focus on the requirements for laser systems [5,6] and fluorescence detectors [7,8].

We conclude by showing how dedicated diagnostics can both open the window to laser spectroscopy of ultra-cold beams and provide a new tool to study their dynamics.

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PRODUCTION OF RYDBERG-STATE ONE-ELECTRON IONS

Joseph N. Tan[a], Joan M. Dreiling[a], Shannon F. Hoogerheide[a], Aung S. Naing[b]

[a]National Institute of Standards & Technology (NIST),
100 Bureau Drive, Mail Stop 8422, Gaithersburg, Maryland 20899, USA.

[b]University of Delaware, Department of Physics & Astronomy,
217 Sharp Laboratory, Newark, Delaware 19716, USA

We present experimental studies at NIST that are motivated by the potential use of highly-charged ions for precise measurements of fundamental constants. One focus is to isolate fully-stripped ions and allow them to capture the loosely-bound electrons in laser-excited Rb atoms to produce one-electron ions in high energy levels, which are well-suited for measuring the Rydberg constant [1]. These experiments provide not only new tests of basic models of charge exchange in the low energy regime [2], but also develop new techniques that are important for fundamental metrology by seeking an independent measurement of the Rydberg constant to help resolve the proton radius puzzle [3].

The experimental setup is illustrated in Figure 1. Highly charged ions are produced in the EBIT at NIST. A single charge state (such as fully-stripped neon, Ne^{10+}) is extracted into a compact Penning trap via a ~7 m beamline with an analyzing magnet. The Rb beam coming from a high-flux oven enters the Penning trap orthogonal to the ion beam through a small hole in the middle electrode. A counter-propagating laser beam for exciting Rb atoms enters the trap through the opposite hole. Electron capture is observed by ejecting the ions from the trap to a time-of-flight detector. Light emitted by the stored ions can also be collected by a photomultiplier via a small lens embedded in the middle electrode.

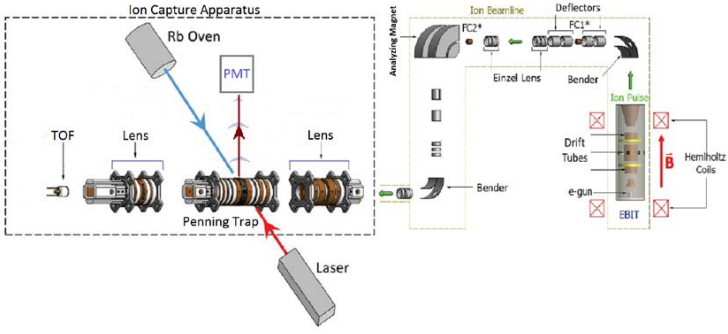

Figure 1: Experimental set-up illustrating the EBIT (far right), the ion extraction beamline, and the ion capture apparatus (left). An oven setup produces a Rb beam which is directed into the Penning trap, with a counter-propagating laser beam for exciting Rb atoms.

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EUV SPECTROSCOPY OF HIGH CHARGED SULFUR RELEVANT TO ASTROPHYSICAL PLASMAS

Safdar Ali, Hiroyuki Kato, Nobuyuki Nakamura

Institute for Laser Science, The University of Electro-Communications, Tokyo 182 8585, Japan

Spectroscopy is a fundamental tool to study and interpret emission spectra from the astrophysical plasmas. The EUV spectroscopy is in particular important to obtain physical conditions and parameters such as temperature, electron density, elemental abundence, chemical composition etc of solar and stellar atmospheres. Sulfur is an astrophysically abundant element with photospheric abundance of 2.14×10^{-5} that of hydrogen and contains a wealth of strong spectral lines in EUV wavelengths. Experimental observations for the EUV emission from highly ionized sulfur is therefore important for modeling and diagnosing hot astrophysical plasmas.

In the present work, we report laboratory observations for the emission of EUV radiation from highly charged sulfur ions in the wavelength range of 150-300 Å. The measurements were performed using a low energy electron beam ion trap called CoBIT at Tokyo EBIT laboratory [1]. For producing sulfur ions, SF_6 gas was injected into the center of the trap via a gas injection system. The device was tuned for several electron beam energies between 125 to 800 eV with electron beam current of 10 mA. The emitted radiation from the trapped ions at each energy was recorded with a flat-field grazing incidence spectrometer having groove numbers of 1200 groves/mm [2]. A typical spectrum acquired at an electron beam energy of 465 eV is shown in Fig.1. Tentative identifications are given for several lines corresponding to N-like S X. The wavelengths are compared with the calculations performed using Flexible Atomic Code (FAC) and with the available values from NIST and CHIANTI data base.

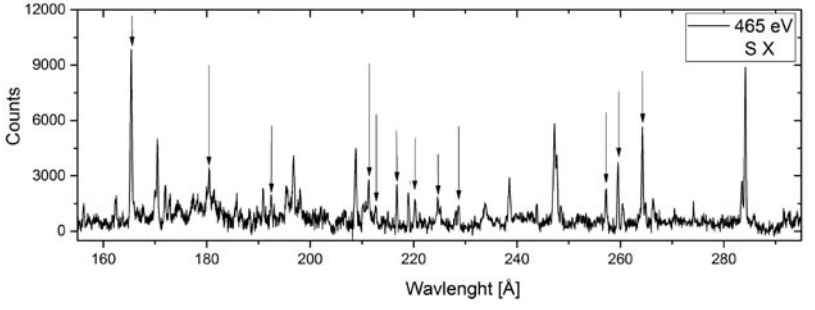

Figure 1: EUV emission spectrum of highly charged sulfur recorded at an electron beam energy of 465 eV. The lines indicated with arrows are identified preliminary from S X by varying the electron beam energy across the ionization thresholds of different charge states.

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CoBIT SPECTROSCOPY OF Mo AND Y IONS RELEVANT TO BEYOND EUV SOURCE DEVELOPMENT

Emma Sokell[a], Safdar Ali[b], John Sheil[a], Hiroyuki Kato[b], Nobuyuki Nakamura[b]

[a]School of Physics, University College Dublin, Belfield, Dublin 4, Ireland

[b]Institute for Laser Science, University of Electro-communications, 1-5-1 Chofugaoka, Chofu, Tokyo 182-8585, Japan

The relevance of the spectroscopy of highly charged ions for EUV (13.5 nm) and beyond EUV (6.x nm) light source development is well established [1]. In 2009, ASML prompted by the availability of La/B_4C mirrors with a reflectivity of ~40% in a 0.06 nm bandwidth near 6.7 nm, announced that sources would be needed at 6.x nm for future lithography [2]. This would necessitate focus on shorter wavelengths than 13.5 nm which has been extensively studied [1]. Experiments on laser produced plasmas (LPPs) of elements in the second transition row of the periodic table show a significant emission in the spectral range 2-8 nm. This is due to 3d-4p and 3d-4f emission [3]. The present study was conducted using a CoBIT [4] and focuses on two of these elements; Yttrium (Z=39) and Molybdenum (Z=42) in the 5-12 nm range. Spectroscopic studies using electron beam ion traps are complimentary to spectra obtained from LPPs, as the electron beam energy of the CoBIT can be set to optimize the abundance of a particular ion stage in the trap. This study focused on ion stages in the vicinity of Ni-like Y^{11+} and Mo^{14+}, with ionization energies of 374 eV and 544 eV, respectively [5]. For each of the elements studied, the CoBIT spectra are far simpler than those obtained from LPPs. The major difference between the two plasmas is the number density of electrons and this factor strongly influences the lines that appear in the BEUV spectra. In LPPs the number density of electrons is sufficiently high that metastable levels are likely to be collisionally depopulated before they can radiate. In contrast in CoBIT plasmas, such metastable levels live long enough to radiate and may give rise to optically forbidden lines, such as the $3d^{10}$-$3d^9$4s (J=2) line of MoXV [6]. The prominent appearance of these lines in the CoBIT spectra, indicate that the population of the $3d^9$4s state is enhanced within the electron beam ion trap.

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VISIBLE AND INFRARED LASER SPECTROSCOPY FOR HIGHLY-CHARGED HIGH-Z IONS

Yuri Ralchenko

National Institute of Standards and Technology, Gaithersburg MD 20899-8422, USA

Visible and infrared (IR) lasers are extensively used for research with atoms and low-charged ions. For highly-charged ions, the typical transition energies rapidly increase with ion charge thus preventing utilization of standard laser techniques with $\Delta E < 2$-3 eV. Here we analyze a possibility of laser excitation of a forbidden magnetic-dipole transition between the two lowest levels of the $3d^9 4s$ configuration in Ni-like ions [1]. The lower level with J=3 can only decay to the ground state $3d^{10}$ via highly-forbidden magnetic-octupole (M3) transition. Therefore this state accumulates significant population that results in observable line intensities in low-density plasmas (e.g., in electron beam ion traps) (see, e.g., [2]). The slightly higher level with J=2 can decay via a strong electric-quadrupole transition in an x-ray range. The energy difference between these two levels is calculated with the relativistic-model-potential Flexible Atomic Code (FAC) and compared with the available experimental data as well as results from the relativistic many-body perturbation theory [3] (see figure 1). The excitation wavelength for this $\Delta n=0$ transition only weakly depends on the ion charge and is within near-infrared to visible spectral range for nuclear charges between 50 and 92 which allows application of modern lasers. We will also discuss the results of detailed time-dependent collisional-radiative modeling of x-ray fluorescence spectra due to laser photoexcitation for Ni-like W.

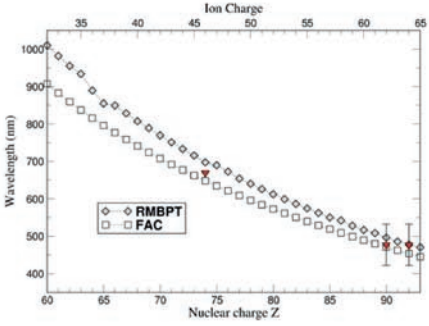

Figure 1: Calculated and measured wavelengths (in nm) for the J=3-J=2 lasing transitions in Ni-like ions.

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CHARGE TRANSFER INDUCED BY COLLISION OF CARBON IONS WITH THE HETEROCYCLIC ORGANIC MOLECULES

Marta Łabuda

Faculty of Applied Physics and Mathematics, Gdańsk University of Technology,
Department of Theoretical Physics and Quantum Information
Narutowicza 11/12, 80-233 Gdańsk, Poland

Over the past decades, extensive research has focused on understanding the effects of ionizing radiation on living matter and an enormous amount of work has been carried out in this field. It has been shown that interaction of ionizing radiation (i.e. β-rays, x-rays, γ-rays) with biological tissue can induce different types of damage to DNA. The most significant biological consequences are relied to single- and double-strand breaks [1,2] caused by the crossing of the radiation tracks with DNA, as it can be noticed for example in heavy ion therapy. Especially, the inclusion of heavy carbon ions is proven to be the best choice for selectively irradiating deep-seated tumors during the therapy. However, although considerable progress has been made, the available studies on charge transfer (CT) process in bio/molecular systems remain still rare in both the theoretical and the experimental approaches. Our previous theoretical study of the CT for a series of charge q=[2-4] of the C^{q+} + uracil system using an *ab initio* calculation of the molecular structure followed by a semi-classical dynamics in the keV energy range has shown that the fragmentation and CT process appear to be complementary [3].Therefore, in our recent calculations we have selected five- and six-membered heterocyclic molecules which also can serve as simple models and quasiprototypes of the DNA structural units (nucleic bases, deoxyribose) in the investigations of the action of ionizing radiation in biologically important material as well as in the synthesis of new compounds which are particularly useful in the medicinal chemistry.

In this contribution, we present results of recent investigations of CT mechanism in the collision of C^{2+} ions with heterocyclic molecules (tetrahydrofuran [4,5], isoxazole, furan). Firstly, the results of electronic structure properties of the heterocyclic molecules obtained by *ab initio* and density functional theory methods will be presented. Secondly, we will show the necessary calculations carried out at Complete Active Space Self Consistent Field level of theory in order to determine the lowest potential energy curves as well as couplings as a function of the internuclear distance between the incident C^{2+} and target molecule. Anisotropic effects and dynamics of the process in the collision energy range from eV to keV by means of semi-classical treatment will also be presented.

Acknowledgements: This work has been partially supported by the 7th Framework Programme of the European Union in the frame of Marie Curie Career Integration Grant. The calculations have been carried performed at the Academic Computer Centre (TASK) in Gdańsk.

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FRAGMENTATION OF MOLECULAR DIMER USING HCIS: PROBING THE GEOMETRY

X. L. Zhu[a], S. Yan[a], W. T. Feng[a], D. L. Guo[a], S. F. Zhang[a], Y. Gao[a,b], R. T. Zhang[a], S. Xu[a], H. B. Wang[a,b], Z. K. Huang[a,b], B. Hai[a,b], Q. S. Zhao[a], M. Zhang[a,b], D. B. Qian[a], D. M. Zhao[a], W. Q. Wen[a] and X. Ma[a,b]

[a]Institute of Modern Physics, Chinesese Academy of Sciences, Lanzhou 730000, China
[b]University of Chinese Academy of Sciences, Beijing 100049, China

Molecular dimers widely exist in planetary atmosphere, and play an important role in molecular and surface physics, astrophysics, and climate [1]. The knowledge of intermolecular interaction among different molecules is important for simulating its spectroscopic and bulk properties. Recently the $(N_2)_2$ dimer was suggested to be used in constraining planetary habitability and discriminating against false positives for life [2]. However, the corresponding equilibrium geometry conformation is controversial. The indirect measurement of infrared spectra shows the most probable conformation is T-shape configuration [3]. But different calculations suggest different equilibrium geometries, such as T-shaped, canted, H-shaped or X-shaped conformations [4-6].

In the present work, the Coulomb Explosion imaging method [7] was used to probe the geometry conformation of molecular dimer for the first time induced by highly charged Ne^{8+} ions at an impact energy of 50 keV/u, the fragment ions momenta of three-body and four-body fragmentations were measured. Our results indicate that $(N_2)_2^{3+}$ ion can decay from nonsequential dissociation or sequential dissociation. As shown in Figure 1, these two mechanisms can be directly distinguished in Newton diagrams. Furthermore, the most stable equilibrium conformation of $(N_2)_2$ dimer was determined as the spatial X-shaped structure.

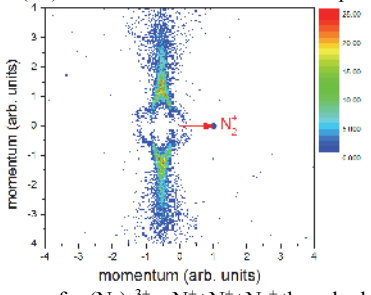

Figure 1 The Newton diagrams for $(N_2)_2^{3+} \rightarrow N^+ + N^+ + N_2^+$ three-body fragmentation channel.

This work was supported by the NSFC of China under Grants Nos. 10979007 and 11274317.

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HIGHER-ORDER PERTURBATIVE RELATIVISTIC CALCULATIONS FOR FEW-ELECTRON ATOMS AND IONS

Dmitry A. Glazov[a,b], Andrey V. Volotka[a,c], Aleksei V. Malyshev[a,b], Vladimir M. Shabaev[a], Ilya I. Tupitsyn[a], Guenter Plunien[d]

[a]Department of Physics, St. Petersburg State University, Universitetskaya nab. 7/9, 199034 St. Petersburg, Russia

[b]State Scientific Centre "Institute for Theoretical and Experimental Physics" of National Research Centre "Kurchatov Institute", B. Cheremushkinskaya st. 25, 117218 Moscow, Russia

[c]Helmholtz-Institut Jena, Fröbelstieg 3, D-07743 Jena, Germany

[d]Institut für Theoretische Physik, Technische Universität Dresden, Mommsenstraße 13, D-01062 Dresden, Germany

An effective computational method is developed for evaluation of the perturbation theory terms for few-electron atoms and ions on the basis of the Dirac-Coulomb-Breit Hamiltonian. One-electron finite basis set is constructed within the DKB approach [1]. Many-electron wave functions are represented by the Slater determinants. The recursive formulation of the perturbative series provides an efficient access to the higher-order contributions of the interelectronic interaction. The presented approach is applied to evaluation of the binding and transition energies, g-factors and hyperfine splittings in lithiumlike and boronlike systems. The results obtained are in agreement with the large-scale configuration interaction Dirac-Fock-Sturm method and other all-order calculations. For the g-factor of lithiumlike ions the accuracy of the total theoretical values [2] is improved, which strengthens the agreement with the recent experimental data for $^{28}Si^{11+}$ [3] and $^{40,48}Ca^{17+}$ [4].

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TWO- AND THREE-BODY FRAGMENTATION OF NITROUS OXIDE IN COLLISION WITH HIGLY CHARGED IONS

Arnab Khan, Lokesh C. Tribedi, **Deepankar Misra**

Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai-400005, India

The investigation of the multiple-ionization and subsequent dissociation of molecules by ion impact is one of the most challenging and complex problems in collision physics. In the last few decades a lot of ion impact work has been devoted to the study of fragmentation of diatomic molecules such as N_2, CO and triatomic molecules such as CO_2, CS_2, etc. On the other hand, ion-induced dissociation mechanism N_2O has received comparatively less attention. Further, the ionization and fragmentation dynamics of N_2O were mainly investigated in photon [1-2] and electron [3] impact experiments. Here we investigate two- and three-body dissociation of multiply charged nitrous oxide molecular ion (N_2O^{q+} where $q \leq 7$) upon the impacts of highly charged heavy ions. The present measurements were performed using beams of 1 a.u. Ar^{8+} and Xe^{15+} ions from the ECR based ion accelerator at TIFR, Mumbai. The electrons and fragment ions from the highly ionized parent molecular ions were detected in coincidence using a recoil ion momentum spectrometer. The experimental setup and an earlier result can be found here [4, 5].The kinetic energy release (KER) distributions are derived and compared with the pure Coulombic model as well as with the available data in the literature. It has been observed that N_2O^{q+} breaks up mainly in a concerted manner except $N_2O^{3+} \rightarrow N^+ + N^+ + O^+$ (1,1,1) and $N_2O^{4+} \rightarrow N^{2+} + N^+ + O^+$ (2,1,1) channels. For both these channels the presence of an intermediate rotating NO^{2+} has been identified. Further, we have also investigated the projectile charge-state dependence of the fragmentation dynamics of N_2O. As opposed to the earlier high velocity ion impacts, in the present study, it is seen that the KER spectra of fragment ions are strongly dependent on the projectile charge-states. In Fig. 1 we show the KER spectra for different two- and three-body decay channels. It can be seen that for two-body decay KER spectra do not depend on the charge-states of the projectile while for three-body decay channel clear charge-state dependence can be observed.

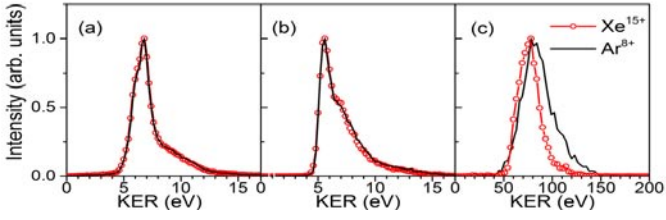

Figure 1: KER spectra for different two- and three-body decay channels: (a) $N^+ + NO^+$, (b) $O^+ + N_2^+$, and (c) $N^{2+} + O^{2+} + N^+$.

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STOPPING POWER DATABASE: FOLLOWING THE TRENDS IN STOPPING POWER OF IONS IN MATTER

C. C. Montanari[a], P. Dimitriou[b]

[a]Instituto de Astronomía y Física del Espacio, CONICET and Universidad de Buenos Aires, Buenos Aires, Argentina

[b] Division of Physical and Chemical Sciences, International Atomic Energy Agency, Vienna, Austria.

The aim of this work is to present an overview of the state of art of the stopping power of ions in matter, based on new developments in the stopping power database of the International Atomic Energy Agency (IAEA) [1]. This exhaustive collection of experimental data, graphs, programs and comparisons, is the legacy of Helmut Paul ([1, 2] and references therein) who made it accessible to the global scientific community, and has been extensively employed in theoretical and experimental research during the last 20 years. The field of stopping powers in matter is evolving [3, 4, 5, 6, 7] with new trends in materials of interest, including oxides, polymers, and biological targets. Our goal is to identify areas of interest and emerging data needs to meet the requirements of a continuously developing user community.

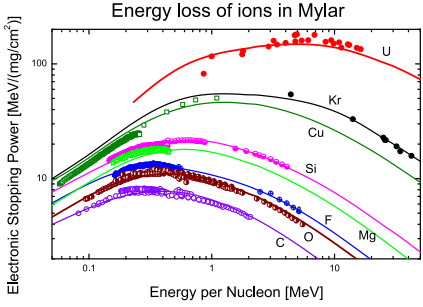

Figure 1: Stopping cross section of ions in Mylar and Kapton [1] compared with SRIM code [7].

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THE STUDY OF THE INTERACTION OF LOW ENERGY IONS WITH A PLASMA TARGET

R.Cheng[a], Y.Zhao[b], X. Zhou[a], J.Deng[a], Y.Wang[a], R.Gavrilin[c,d], S. Savin[c], D.H.H.Hoffmann[e], H.Peng[f], A.Golubev[c,d], I.Roudskoy[c,d], Y.Sun[a], Y.Lei[a], J.Ren[a], S.Liu[a], X Ma[a] and G.Xiao[a]

[a]Institute of Modern Physics, 509 Nanchang Road, Lanzhou 730000, China
[b]Xi'an Jiaotong University, 28 Xianning Xi Road, Xi'an 710049, China
[c]State Scientific Center Russian Federation - Institute for Theoretical and Experimental B. Cheremushkinskaya 25, Moscow 117259, Russia
[d]National Research Nuclear University MEPHI (Moscow Engineering and Physics Institute) Kashirskoe shosse, 31,115409 Russia
[e]Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt 64289, Germany
[f]Lanzhou University, 222 Tianshui Nan Road, Lanzhou 730000, China

The investigation of the interaction of ion beam with matter has always been a classical topic of atomic physics. There is a still growing need for a deeper understanding of the physical processes. Especially the energy deposition in the low energy range as well as interaction with degenerate matter is of importance for very intense heavy ion beams, which eventually deliver a high-power-density deposition of energy to drive an inertial fusion target.

The energy loss measurements for low energy protons and helium ions in a plasma target produced by an electrical discharge in hydrogen gas at Institute of Modern Physics were carried out [1-3]. Combined with independent measurements of the linear electron density of the plasma column using laser interferometry, the energy loss for the ions in the low energy regime with linear electron density of $10^{17}cm^{-2}$ is obtained. The obvious enhanced energy losses in plasma than that in cold gas for both of proton and helium ions are found.

For 100 keV protons, within the error limit of the results are in agreement with the Bethe, Standard Stopping Model (SSM), Li-Petrasso and Vlasov models (see Fig.1). The experimental energy loss of proton in plasma is enhanced by a factor of 2.8 relative to that in cold gas; in this energy regime the Bethe-Bloch Coulomb logarithm term of the stopping equation is larger by a factor of 4 for free electrons as compared to the situation where bound electrons prevail.

For 400 keV helium ions, the enhancement factor of energy loss is about 3.3, and the effective charge state of He ion in plasma seems higher than the value in cold gas.

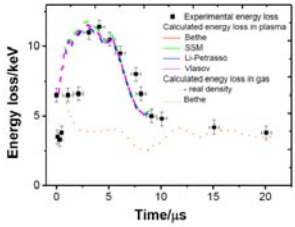

Figure 1: Energy loss of 100 keV protons in plasma as a function of time.

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MAGNETIC-FIELD INDUCED TRANSITIONS: A NOVEL METHOD TO DETERMINE MAGNETIC FIELDS IN LOW-DENSITY PLASMA

Wenxian Li[a,b], Jon Grumer[b], Tomas Brage[b], **Roger Hutton**[a] and Yaming Zou[a]

[a]Shanghai EBIT lab, Modern physics institute, Fudan University, Shanghai, China
[b]Division of Mathematical Physics, Department of Physics, Lund University, Sweden

Magnetic fields play an important role in many different astrophysical and laboratory plasma, e.g. solar protuberances and Tokamaks. They affect ions by introducing splitting of otherwise degenerated energy levels. An even more interesting effect is that the external field breaks the atomic symmetry and mixes states that have the same magnetic quantum number and parity. This will introduce new decay channels from excited states, which we will label as magnetic-field induced transitions (MITs). These transitions have attracted new attention recently, due to the development of accurate methods of calculations for their rates [1,2,3] and the possible application as a tool for measuring plasma magnetic fields.

The problem is that the internal magnetic fields in the ions are strong and this effect is only observable for comparable field strength. However, MITs can be enhanced by a close, accidental degeneracy of two quantum states. It is fortunate that such a close degeneracy occurs for Fe X, since this ion has a high abundance in astrophysical plasmas including the solar corona. Since the determination of the magnetic fields in the solar corona still poses one of the major remaining challenges in solar physics, the MIT in Fe X is proposed as a new method for a continuous space based measurement of the coronal magnetic field.

We will give an overview of the recent progress in this field in general and in particular present our results on Fe X. An important parameter in determining the size of the MIT effect is the degree of pseudo-degeneracy between the levels involved. We have made a measurement of this energy separation in Fe X using Electron Beam Ion Trap [4,5]. The measured value confirms that the splitting is small enough for MIT-intensity to be sensitive to magnetic fields in the active solar corona range. Finally we propose a method for using Fe X line ratio to determine the coronal magnetic field strength.

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STRONG HIGHER-ORDER RESONANT CONTRIBUTIONS TO Fe K_α X-RAY LINE POLARIZATION IN HOT PLASMAS

Chintan Shah[a,b], Pedro Amaro[a], René Steinbrügge[b], Sven Bernitt[b,c], Christian Beilmann[a,b], Stephan Fritzsche[c], Andrey Surzhykov[d], José R. Crespo López-Urrutia[b], and Stanislav Tashenov[a]

[a]Physikalisches Institut, Im Neunheimer feld 226, 69120 Heidelberg, Germany

[b]Max–Planck–Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

[c]Friedrich-Schiller-Universität Jena, Fürstengraben 1, 07743 Jena, Germany

[d]Helmholtz-Institut, Helmholtzweg 4, 07743 Jena, Germany

For a wide range of temperatures, resonantly captured electrons with energies below the excitation threshold are the strongest source of x-ray line excitation in hot plasmas containing highly charged Fe ions. The angular distribution and polarization of x rays emitted due to these processes were experimentally studied using an electron beam ion trap. The electron-ion collision energy was scanned over the *KLL* dielectronic, trielectronic and quadruelectronic recombination resonances of $Fe^{18+..24+}$ and $Kr^{28+..34+}$ with an excellent resolution of ~ 6 eV. The angular distribution of x rays was measured along and perpendicular to the electron beam propagation direction. Subsequently, polarization due to dielectronic recombination of $Kr^{28+..34+}$ was measured using Compton polarimetry as well [1].

The data reveal the alignment of the populated excited states and exhibit a high sensitivity of these parameters to the relativistic Breit interaction [1, 2]. We observed that most of the transitions lead to polarization, including hitherto neglected trielectronic and quadruelectronic resonances. Furthermore, these channels dominate the polarization of the prominent K_α x rays emitted by hot anisotropic plasmas in a broad temperature range, see Fig. 1. The present results comprehensively benchmark relativisitic atomic calculations carried out with the FAC [3] and RATIP [4] codes. We conclude that accurate polarization diagnostics of hot anisotropic plasmas, e. g., of solar flares and active galactic nuclei, and laboratory fusion plasmas of tokamaks can only be obtained under the premise of careful inclusion of relativistic effect and higher-order resonances which were most often neglected in previous works.

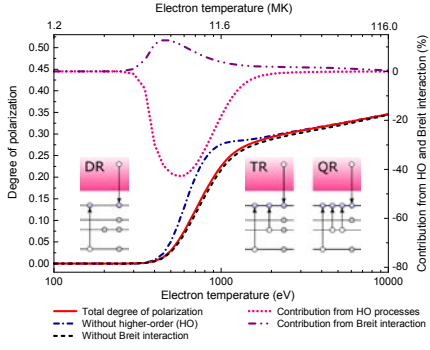

Figure 1: Maximum polarization of iron K_α x rays due to resonant recombination as a function of the plasma temperature.

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HCI COLLISIONS TO SUPPRESS THE THERMAL HYSTERESIS IN MAGNETOCALORIC THIN FILMS

M.Trassinelli[a], S. Cervera[a], L. Bernard Carlsson[a], M. Eddrief[a], V. Etgens[a], V. Gafton[a,b], V. Garcia[c], E. Lamour[a], Anna Lévy[a], S. Macé[a], M. Marangolo[a], L. Phillips[c], C. Prigent[a], J.-P. Rozet[a], S. Steydli[a] and D. Vernhet[a]

[a]Institut des NanoSciences de Paris, CNRS, UPMC Univ Paris 06, Paris, France

[b]Alexandru Ioan Cuza University, Faculty of Physics, Iasi, Romania

[c] Unité Mixte de Physique CNRS/Thales, Université Paris-Sud, 91405 Orsay, France

Magnetic materials with giant magnetocaloric effect are promising for application in magnetic refrigeration. But they all exhibit a first-order phase transition and suffer from a large thermal hysteresis which reduces significantly the efficiency of the refrigeration cycle. Several studies aimed at getting rid of the thermal hysteresis but it was to the detriment of the other magnetic properties, inducing for instance a collapse of the refrigerant power [1]. Recently, our group demonstrated that the thermal hysteresis of the MnAs thin film can be entirely suppressed by impact of Ne^{9+} at 90 keV whereas other structural and magnetic properties are barely affected [2]. In addition, we show this modification to be stable in time, but mechanisms at the origin of the thermal hysteresis suppression were not completely understood.

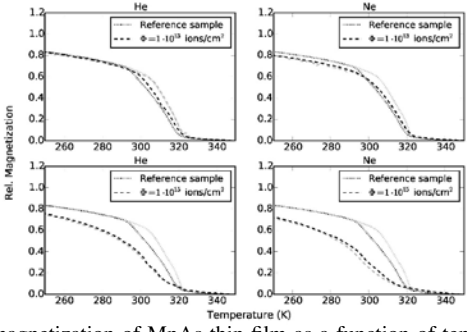

Figure 1: Relative magnetization of MnAs thin film as a function of temperature for the reference (dotted lines) and for the irradiated samples (dashed lines) with He and Ne ions at two fluences. Data obtained by a temperature increase (grey) and decrease (black).

Trying to disentangle ion implantation effect from and ion collision-induced defects, we investigated the role of different parameters like the projectile mass and energy, and the ion fluence, but also studying the bombardment effect on different magnetocaloric thin film as projectiles. As displayed in figure 1, comparing helium and neon ion impact at different fluences but with the same penetration depth, the ion mass is playing the major role. This indicates that the binary collision kinematics, at the origin of induced-defects, seems to be the key parameter responsible for the thermal hysteresis suppression. Further investigations are in progress and will be presented at the conference.

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STABLE TRANSMISSION OF HIGHLY CHARGED IONS GUIDED THROUGH NANOCAPILLARIES IN PET

N. Stolterfoht[a] . Z. Juhász[b], P. Herczku[b], S. T. S. Kovács[b], R. Rácz[b], S. Biri[b], and B. Sulik[b]

[a]Helmholtz-Zentrum Berlin für Materialien und Energie, 14109 Berlin, Germany
[b]Institute for Nuclear Research, Hungarian Academy of Sciences, 4026 Debrecen, Hungary

During the past decade the guidance of keV ions through insulating nanocapillaries [1] has widely been studied (see [2] and references therein). Ions deposited at the capillary wall produce a repulsive electric field that is capable to deflect the following ions at relatively large distances from the capillary wall. Thus, the ions are guided along the capillary axis maintaining their incident charge state. Ion guiding is based on a self-organizing process, which governs the charge deposition and ion transmission through the capillaries.

In recent years, a decrease of the ion transmission through nanocapillaries after having reached a maximum has received particular attention. This blocking of the ion guiding was first observed using capillaries in polycarbonate (PC) [3,4] whereas the transmission through capillaries in polyethylene terephthalate (PET) was found to be stable [1,3]. As the capillaries in PC had an areal density which was an order of magnitude higher than that of the capillaries in PET [3], the question arose whether the blocking was produced by density effects of by material properties. Therefore further measurements were performed with PET capillaries [5], which indicated that blocking effects are also significant for areal densities of 3 - 6×10^7 cm^{-2}. Thus, it was concluded from the experiments and also from model calculations that blocking of ion guiding sensitively depends on the areal density of the capillaries.

In this work we searched for blocking effects using PET capillaries with a relatively high areal density. The study was motivated by the fact that before the recent work [4] blocking effects have never been observed for PET capillaries. However, the previous measurements were generally conducted for a limited charge insertion into the capillaries. Furthermore, the PET capillaries, which showed blocking [5] and no blocking [1,3] were prepared at a different laboratories, i.e., GSI in Darmstadt and Flerov Institute in Dubna, respectively.

In the present measurements, we used PET capillaries from Dubna with an areal density of 10^8 cm^{-2}, which was higher than that used previously [5]. The experiments revealed no blocking, i.e., the transmission was stable for charge insertion as large as 140 fC per capillary, which again was higher than that used previously. The results indicate that blocking depends not only on the areal density but also on surface properties. We suggest that the differences in blocking are attributed to varying conductivities produced by different surface treatments.

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NEUTRALIZATION OF HIGHLY CHARGED IONS IN TRANMISSION THROUGH NANO-CAPILLARIES

HQ. Zhang[a, b], N. Akram[b], and **R. Schuch**[a]

[a]Physics Department, Stockholm University, Stockholm, Sweden

[b]The School of Nuclear Science and Technology, Lanzhou University, Lanzhou, 730000, Gansu, China

The transmission of slow Highly Charged Ions (HCI) transmitted through various insulating nano-capillaries has been studied over one decade since the so-called guiding effect was found [1-5]. Recently, by using mica capillaries of rhombic or rectangular cross-sections, we find that the transmitted ion beam profile is tailored into rectangular or rhombic shape, respectively [4-5].

In this abstract, we report about the charge state distribution of 70-keV-Ne^{7+}-incident ions transmitted through rhombic capillaries in a muscovite mica membrane at various tilt angles (e.g. Fig. 1 for tilt angle -0.1 deg.). The transmitted Ne^{q+}- ions were analyzed by an electric field downstream of the capillary membrane. It can be seen that the primary charge state is dominant and other charge states are two orders smaller or more. Also the amount of the lower charge states of 0 and +1 are larger than that of other intermediate charge states. The charge state distribution at the tilt angle close to zero is very different from that at a tilt angle near or larger than the geometrical opening angle of -0.6 deg. [5]. There the amount of neutrals is comparable or larger than of the primary charge state. Also the angular distributions show large differences. The charge separation of the transmitted projectiles and their very different behaviors gives us further insight for different mechanisms of guiding and scattering in nano-capillaries.

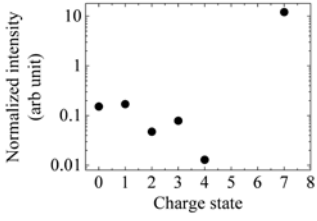

Figure 1: Charge state distribution of 70-keV Ne^{7+} ions transmitted through mica nano-capillaries at a tilt angle of -0.1 deg.

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LOCAL REPORT

EXPERIMENTS WITH HCI AT EBIS FACILITY

D. Banaś[a], J. Braziewicz[a], J. Czub[a], Ł. Jabłoński[a], P. Jagodziński[b], A. Kubala-Kukuś[a], D. Sobota[a], I. Stabrawa[a], M. Pajek[a]

[a]Institute of Physics, Jan Kochanowski University, Świętokrzyska 15, 25-406 Kielce, Poland
[b]Department of Mathematics and Physics, Kielce University of Technology, al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland

The electron beam ion sources (EBIS) offer unique experimental conditions for the studies of interaction of highly charged ions (HCI) with a matter. The experiments can be performed with HCI trapped in the EBIS and produced in sequential collisions with electrons a strong magnetic field, or HCI extracted from the EBIS and, usually after a charge-state separation, used in collisional experiments with solid surfaces. The studies of atomic processes occurring in the interactions of HCI with electrons in the EBIS are important for testing the atomic structure calculations, in particular, the relativistic multi-configuration Dirac–Fock (MCDF) approach, including the Breit and QED corrections. In turn, the interaction of slow (eV-keV) HCI extracted from the source with solids is dominated by a neutralization of HCI at surfaces resulting in a transient formation of the so-called hollow atoms [1]. Moreover, irradiation of solid surfaces with slow HCI lead to the surface modifications by imposing a substantial amount of potential Coulombic energy confined spatially in the atomic scale [2]. These processes are of great fundamental and technological interest.

Here we will report on results of first experiments with HCI performed at the EBIS facility [3] (Dreebit GmbH Dresden), which is installed at the Institute of Physics of Jan Kochanowski University in Kielce. The facility ion source (EBIS-A), equipped with 20 keV electron gun, can deliver the beams of bare and few-electron ions of various elements being in the gas phase. After extraction (up to 25 keV/q) in a pulsed or leaky mode the beams of HCI ions are charge-state analyzed in a double–focusing dipole magnet and a beam of selected charge-state can be directed to the multi-port UHV experimental chamber equipped with a motorized 5-axis, variable temperature (100-1000 K) sample manipulator. For observations of X-rays emitted directly from the trap or from the sample a silicon drift detector (SDD) (XFlash, Bruker) as well as 6-crystal diffraction spectrometer operating in Johann or Johansson geometry with Rowland radius R=21 cm (INCAWave, Oxford Instruments) can be used for low- and high-resolution measurements, respectively.

The first experiments aimed to observe of X-rays emission from highly charged xenon ions trapped with different electron beam energies in the EBIS, X-rays emitted in interaction of ~3 keV×q Xe^{q+} ions (q=26-40) with beryllium foil and modification of gold and titanium nanolayers by highly charged Xe^{q+} ions with q=33-36.

Acknowledgements

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POSTER SESSION A

QED THEORY OF THE QUADRATIC ZEEMAN EFFECT IN HIGHLY CHARGED IONS

Valentin A. Agababaev[a,b,c], Dmitry A. Glazov[a,b,c], Andrey V. Volotka[a,d], Vladimir M. Shabaev[a], Guenter Plunien[c]

[a]Department of Physics, St. Petersburg State University, Universitetskaya nab. 7/9, 199034 St. Petersburg, Russia

[b]State Scientific Centre "Institute for Theoretical and Experimental Physics" of National Research Centre "Kurchatov Institute", B. Cheremushkinskaya st. 25, 117218 Moscow, Russia

[c]Institut für Theoretische Physik, Technische Universität Dresden, Mommsenstraße 13, D-01062 Dresden, Germany

[d]Helmholtz-Institut Jena, Fröbelstieg 3, D-07743 Jena, Germany

The g factor of light hydrogen-like and lithium-like ions proved to be a sensitive tool for testing bound-state QED and for determination of fundamental constants [1,2,3]. Moreover, the QED effects beyond the Furry picture are accessible in these investigations [4]. Experiments with heavy boron-like ions can provide independent determination of the fine structure constant [5]. The ARTEMIS experiment presently being performed at GSI aims at measurement of the Zeeman splitting in boron-like argon [6]. Apart from the linear Zeeman effect (g factors) of the ground and first excited states, it will be sensitive to the non-linear effects in magnetic field. To date the g factor has been evaluated to high accuracy for hydrogen-, lithium- and boron-like ions, including the QED, interelectronic-interaction and nuclear effects. In contrast, theoretical investigations of the quadratic Zeeman effect are mainly restricted to the leading order (see, e.g. [7]). We present *ab initio* QED calculation of the second-order Zeeman effect for $2p_{1/2}$ and $2p_{3/2}$ states of boron-like ions including the first-order corrections: one-photon exchange, self-energy and vacuum polarization. As a result, the most accurate up-to-date theoretical values for the quadratic Zeeman effect are presented. In particular, the theoretical background for the ARTEMIS experiment is significantly improved.

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STRUCTURED RELATIVISTIC ELECTRON AND NEUTRON VORTEX BEAMS IN INTENSE LASER FIELDS

Armen G. Hayrapetyan[a], Jörg B. Götte[b], Jan-Michael Rost[a]

[a]Max-Planck-Institut für Physik komplexer Systeme, Nöthnitzer Str. 38, 01187 Dresden, Germany

[b]School of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, UK

Recent advances in technology and instrumentation have made it possible to generate vortex beams of electrons and neutrons with phase singularities at their cores, where the beam intensity is zero and the phase is undefined. These new types of beams, apart from the spin angular momentum, carry a quantized orbital angular momentum (OAM) along their axes of propagation resulting in a twisted wavefronts, pretty much like quantum tornadoes. In this presentation, we will discuss how the spin and OAM degrees of freedom give rise to an intrinsic spin-orbit coupling (also called spin-to-orbit conversion) in structured relativistic quantum waves. The main focus will be on the interaction of such twisted, both charged and neutral, matter waves with intense laser pulses. In order to demonstrate the possibility of controlling of vortex beams both in the transverse direction and in the temporal domain, we develop an exact relativistic quantum theory by constructing two new sets of Bessel-type solutions to generalized Dirac equations, accounting for the interaction of electrons and neutrons with external electromagnetic fields. We show that the laser field gives rise to a Lorentz-induced shift of the vortex core of twisted electrons, the transverse profile of which maintains its overall shape throughout the propagation in a pulse. In contrast, while the vortex core of twisted neutrons remains unaffected, the spin- and OAM-dependent profile experiences an inhomogeneous distribution due to the interaction of neutron's anomalous magnetic moment with the magnetic field of the laser. Our new solutions may be employed in many fields of physics, from atomic and subatomic physics to topological condensed matter theory, and can be useful for evaluating matrix elements for various laser-assisted scattering processes, especially, at high intensities.

K-SHELL X-RAY TRANSITION ENERGIES FROM MULTI-ELECTRON IONS OF SILICON AND SULFUR

P. Beiersdorfer[a], G. V. Brown, N. Hell[b], J. A. Santana[c]

[a]Physics Divisions, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

[b]Dr. Karl Remeis-Sternwarte and Erlangen Centre for Astroparticle Physics, Universität Erlangen-Nürnberg, Sternwartstr. 7, 96049 Bamberg, Germany

[c]Department of Chemistry, University of Puerto Rico at Cayey, Cayey, PR 00737, USA

Prompted by the detection of K-shell absorption or emission features in the spectra of high mass X-ray binaries, such as Vela X-1 and Cygnus X-1, recent measurements using the Livermore electron beam ion trap have focused on the energies of the n=2 to n=1 K-shell transitions in the L-shell ions of Li-like through F-like silicon and sulfur [1]. In parallel, we have made calculations of these transitions using the Flexible Atomic Code and the multi-reference Møller-Plesset (MRMP) atomic physics code. The MRMP calculations have been shown to be of high accuracy even for complex multi-electron ions [2], and we have attempted to produce sets of theoretical atomic data with spectroscopic accuracy for all the L-shell ions of silicon and sulfur. We will present the results of our calculations and compare them to the recent electron beam ion trap measurements as well as previous calculations.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and supported by NASA's APRA program under work order NNX12AH84G.

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MODEL OPERATOR APPROACH TO THE RELATIVISTIC LAMB SHIFT CALCULATIONS IN MANY-ELECTRON ATOMS AND HIGHLY CHARGED MOLECULAR IONS

I. I. Tupitsyn[a], D. V. Mironova[a,b], V. M. Shabaev[a]

[a] Department of Physics, St. Petersburg State University, Universitetskaya nab. 7/9, St. Petersburg 199034, Russia

[b] ITMO University, Kronverkskii ave 49, 197101 St. Petersburg, Russia

The *ab initio* Lamb shift calculations can be performed only for few-electron atomic systems such as H-like, He-like and Li-Like ions and for many-electron atoms in local density approximation (LDA). For this reason the construction of simple one-electron approach to one-loop QED operator is an important task of the relativistic quantum theory of atoms and molecules.

In this work we used two modifications [1,2] of the model QED potential approach to calculations of the Lamb shift in many-electron atoms and one-electron quasi-molecules. The model potential is constructed as a sum of local and nonlocal (separable) potentials. The nonlocal part of the model potential was introduced to reproduce exactly the diagonal elements [2] and also off-diagonal elements [1] of the one-loop ab initio QED operator. The local potential can be chosen in the simple analytical form [1]. More complicated radiative potential [3] was used as a local part of model potential in the paper [2].

The one-particle model QED operator was introduced in the Dirac-Fock and CI+MBPT relativistic calculations of the heavy and super-heavy atoms and in the calculations of the diatomic quasi-molecules. The efficiency of the method is demonstrated by calculations of the Lamb shifts in heavy and super-heavy atoms and ions. The comparison of the data obtained in the different approaches to the one-loop QED operator is presented. Model QED potential is applied to calculate Lamb shift in the U^{91+}-U^{92+} dimer. The obtained results are compared with the data of *ab initio* calculations [4].

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ON NATURAL LINE WIDTH BASED ON THE INSTRUMENTAL FUNCTIONS IN THE DOUBLE FLAT CRYSTALS X-RAY SPECTROMETER

Y. Ito[a], T. Tochio[b], M. Yamashita[c], S. Fukushima[d], M. Polasik[e], K. Słabkowska[e], Ł. Syrocki[f], E. Szymańska[e], J. Rzadkiewicz[g], P. Indelicato[h], J. P. Marques[i], M. C. Martins[j], F. Parente[j], and J. P. Santos[j]

[a]ICR, Kyoto University, Gokasho, Uji, Kyoto 611-0011 Japan, [b]Faculty of Science, Kobe University, 1-1 Rokkodai, Kobe 657-8501 Japan, [c]HIT, 3-1-12 Yukihira, Suma-ku, Kobe 654-0037 Japan, [d]NIMS, 1-2-1 Sengen, Tsukuba, Ibaraki 305-0047 Japan, [e]Faculty of Chemistry, Nicolaus Copernikus Univ., Gagarina7, 87-100 Toruń, Poland, [f]Faculty of Chemistry, Nicolaus Copernikus Univ., in Toruń 87-100 Toruń, Poland, [g]National Centre for Nuclear Studies 01-497 Warsaw, Poland, [h]Laboratoire Kastler Brossel, Ecole Normale Superieure, CNRS, Sorbonne Université´s, UPMC Univ. Paris06, Case74 ;4, place Jussieu, 75252 Paris CEDEX05 France, [i]BioISI-Biosystems & Integrative Sciences Institute, Faculdade de Ciências da Universidade de Lisboa, Campo Grande, C8, 1749-016 Lisboa, Portugal, [j]Laboratório de Instrumentação, Engenharia Biomédica e Física da Radiação,(LIBPhys-UNL), Departmento de Fisica, Faculdade de Ciências a Technologia da Universidade Nova de Lisboa, Monte da Caparica, 2892-516 Caparica, Portugal

Single crystal X-ray spectrometers may be curved or plate type. In the latter type a very narrow slit is needed in order to obtain high resolution. If the narrow slit is replaced by a second crystal we have a double flat crystal spectrometer. This (+, +) setting is also referred to as a double-crystal X-ray spectrometer. As only the length and spacing of the entrance slit, and the crystal dispersion contribute to the resolution, the latter is very simple to obtain [1].

We used a double-crystal X-ray spectrometer [2] to study the effects of line asymmetry and shake processes in the FWHM in $K\alpha_{1,2}$ spectra of Ca to Ge, and confirmed the reproducibility of the phenomenon by changing the resolution conditions, using several crystals. The $K\alpha_{1,2}$ spectra of some 3d elements (Ca, Sc, Ti, V, Fe, Cu) were measured in order to obtain the natural line widths to compare with the values of the Semi-empirical natural widths [3], with previous reports that based on experimental values, and with recommended natural widths [4].

Crystals of Si(220) and Ge(220), and Ge(111) were used in the two-crystal X-ray spectrometer. The determination of the natural line widths was carried out by fitting each peak of $K\alpha_{1,2}$ spectra with two Lorentz functions. This method, useful to estimate the contribution to the shake process due primarily to 3d electrons, has been reported by Ito et al. [2]. As seen in the theoretical calculation of the X-ray spectrum, the contribution of the [1s4s] shake process is present in the vicinity of the diagram line. Therefore, even with an experimental threshold excitation that cuts the high-energy component, it is very difficult to extracting the effect from the original diagram line.

We also compared precisely the Fe $K\alpha_{1,2}$ spectra obtained in Fe, and in the SUS430 and SUS304 steels. It was found differences between these spectra, especially related to Coster-Kronig transitions. The details on this point are also shown in the presentation.

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MEASUREMENT OF L-SHELL TRANSITIONS IN M-SHELL IONS IN THE LABORATORY AND IDENTIFICATION IN STELLAR CORONAE

J. K. Lepson[a], P. Beiersdorfer[b], N. Hell[b] , G. V. Brown[b] , E. Träbert[b,c]

[a]Space Science Laboratory, University of California, Berkeley, 7 Gauss Way, Berkeley, California 94720, USA

[b]Physics Division, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94551, USA

[c]Astronomisches Institut, Ruhr-Universität Bochum, D-44780 Bochum, Germany

Highly charged ions of iron provide important diagnostic tools for astrophysical plasmas, especially via their K-shell and L-shell radiation. Although weaker, the L-shell transitions of M-shell iron ions, i.e., those charge states of iron that have a partially filled n=3 shell, have gained new prominence in astrophysics because they are observed in the absorption spectra from active galactic nuclei. The measurement of these lines in the laboratory has been difficult, and few such measurements exist. Recently, we have succeeded to obtain high-resolution spectra of the iron emission near 15 Å using the Lawrence Livermore EBIT-I electron beam ion trap that exhibit L-shell transitions from autoionizing levels in the M-shell Fe^{13+}, Fe^{14+}, and Fe^{15+} ions. These were identified with the help of modeling based on the Flexible Atomic Code, augmented with very accurate transition energies produced by calculations using the relativistic multi-reference Møller-Plesset (MR-MP) perturbation theory.

With the help of these experimental and theoretical reference data, we were able to identify several of these features in grating spectrometer observations performed with the *Chandra X-ray Observatory* of stellar atmospheres. In particular, we present evidence of L-shell emission lines from M-shell iron ions in the spectra of Capella and Procyon. The spectrum of Capella's corona clearly shows lines from Fe^{15+} ions. These lines appear particularly strong in the spectra of Procyon, which is the cooler of the two stars. In addition, there is evidence for emission from the lower charge states of iron. Our recent observations of Procyon with *Chandra*'s high energy transmission grating spectrometer suggests that many of these lines will be identifiable, provided observations are made with longer observation time than we had available so far.

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QUANTUM INTERFERENCE IN LASER SPECTROSCOPY OF HIGHLY CHARGED LITHIUMLIKE IONS

Pedro Amaro[a], Laleh Safari[b], Filippo Fratini[c], Ulisses Loureiro[a], Paul Indelicato[d], Thomas Stöhlker[e,f], José Paulo Santos[a]

[a]Laboratório de Instrumentação, Engenharia Biomédica e Física da Radiação (LIBPhys-UNL), Departamento de Física, Faculdade de Ciências e Tecnologia, FCT, Universidade Nova de Lisboa, 2829-516 Caparica, Portugal

[b]IST Austria, Am Campus 1, A-3400 Klosterneuburg, Austria

[c]Vienna Center for Quantum Science and Technology, Atominstitut, Vienna University of Technology, 1020 Vienna, Austria

[d]Laboratoire Kastler Brossel, École Normale Supérieure, CNRS, Université P. et M. Curie -- Paris 6, Case 74; 4, place Jussieu, 75252 Paris CEDEX 05, France

[e]GSI Helmholtzzentrum für Schwerionenforschung, D-64291 Darmstadt, Germany

[f]Helmholtz-Institut Jena, D-07743 Jena, Germany

A subtle quantum effect that occurs in the process of light scattering by atomic systems, which happens in resonant laser spectroscopy, is the coherent interference between the main resonant path and other non-resonant paths. This effect leads to energy shifts that depend on the relative position and linewidth of each resonance. This is an important, yet frequently overlooked, systematic in laser precision spectroscopy experiments that measure transition frequencies with uncertainties bellow 10^{-5} [1-3].

In view of the future prospects of laser spectroscopy in lithiumlike ions in the Facility for Antiproton and Ion Research, FAIR, in Darmstadt, Germany [4,5], we calculate the QI shifts for 2s-2p-2s transitions in lithiumlike ions with hyperfine structure for selected isotopes of interest, namely $^{209}Bi^{+80}$, $^{207}Pb^{81+}$. This is done by extending the treatment of the QI shifts recently developed for muonic atoms [3, 6] to highly charged ions. A fully relativistic and full-multipole framework is thus implement that is mandatory for such relativistic atomic systems.

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HIGH-RESOLUTION SPECTROSCOPY OF K-SHELL TRANSITIONS IN M-SHELL FE IONS

N. Hell[a,b], P. Beiersdorfer[a], G.V. Brown[a], M.A. Leutenegger[c,d], E.W. Magee[a], J.K. Vogel[a]

[a]Lawrence Livermore National Laboratory, 7000 East Ave, Livermore, CA 94550, USA

[b]Dr. Karl Remeis-Sternwarte and Erlangen Centre for Astroparticle Physics, Universität Erlangen-Nürnberg, Sternwartstr. 7, 96049 Bamberg, Germany

[c]CRESST, University of Maryland Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250, USA

[d]NASA Goddard Space Flight Center, Astrophysics Science Division, Greenbelt, MD 20771, USA

The Kα transitions of M-shell Fe ions fall into a small energy range, resulting in many spectral lines of various ions building a strongly blended line forest. Previous measurements did not succeed in resolving line features of these transitions beyond a few prominent lines originating from ions with a closed sub-shell. Here, we present new measurements at higher spectral resolution with an imaging focusing spherical crystal spectrometer, dubbed EBHiX, at the Livermore electron beam ion trap EBIT-I. Due to the high intrinsic resolution of the instrument, the achieved resolving power of better than 3000 is only limited by Doppler broadening. Even at this higher resolution, we were still not able to identify further lines, although preliminary FAC calculations suggest that resolving powers exceeding $E/\Delta E = 3000$ should be sufficient to distinguish between the main contributions of different ionization stages. However, the gaps between these features may be filled in by transitions due to configurations with electrons in the $3d$ subshell, which are currently excluded from the calculation because of computing time.

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LINEAR AND NONLINEAR CONTRIBUTIONS TO THE ZEEMAN SPLITTING IN HIGHLY CHARGED IONS

Anastasiya S. Varentsova[a,b], Dmitry A. Glazov[a,b]

[a]Department of Physics, St. Petersburg State University,
Universitetskaya nab. 7/9, 199034 St. Petersburg, Russia

[b]State Scientific Centre "Institute for Theoretical and Experimental Physics"
of National Research Centre "Kurchatov Institute",
B. Cheremushkinskaya st. 25, 117218 Moscow, Russia

Substantial interest in theoretical investigations of the g factor of highly charged ions is motivated by the high-precision experiments, both recently performed and anticipated in the near future. Today's highlights in this field are the most accurate determination of the electron mass [1], the most stringent test of the many-electron QED effects in the presence of magnetic field [2,3], and the isotope dependence of the g factor of lithium-like calcium [4]. Planned experiments with heavy ions will give an opportunity for independent determination of the fine-structure constant [5]. Measurement of the Zeeman splittings of $2p_{1/2}$ and $2p_{3/2}$ states in boron-like argon is presently performed at GSI. In this case, the effects of second and third order in magnetic field have to be taken into account [6,7]. We present an effective computational approach for evaluation of various contributions to the linear and nonlinear Zeeman effect. The electron wave functions in the combined nuclear electric and external magnetic fields are constructed within the perturbation theory on the basis of the DKB-splines [8]. The one-electron and two-electron matrix elements are evaluated with these functions. The corresponding contribution to the kth-order Zeeman effect is obtained through the kth derivative with respect to the magnetic field strength.

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ANALYSIS OF THE SN XII-XV FINE STRUCTURE BY OPTICAL AND EUV SPECTROSCOPY IN AN EBIT

F. Torretti[a,b], A. Windberger[a,c], A. Borschevsky[d], A. Ryabtsev[e,f], S. Dobrodey[c], H. Bekker[c], W. Ubachs[a,b], R. Hoekstra[a,g], J. R. Crespo López-Urrutia[c] and O. O. Versolato[a]

[a]Advanced Research Center for Nanolithography, Science Park 110, 1098 XG Amsterdam, The Netherlands

[b]Department of Physics and Astronomy, Vrije Universiteit, de Boelelaan 1081, 1081 HV Amsterdam, The Netherlands

[c]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

[d]The Van Swinderen Institute for Particle Physics and Gravity, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands

[e]Institute of Spectroscopy, Russian Academy of Sciences, Troitsk, Moscow, 108840 Russia

[f]EUV Labs, Ltd., Troitsk, Moscow, 108840 Russia

[g]Zernike Institute for Advanced Materials, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands

Highly charged ions of tin (Sn IX-XV) are of technological interest as these are used in laser-produced-plasma (LPP) sources for the generation of extreme ultraviolet (EUV) light for nano-lithographic applications. Here, we present the results from spectroscopic measurements of these ions, both in the EUV and optical regimes, obtained in a charge-state-resolved manner with the FLASH-EBIT (Electron Beam Ion Trap) at the Max Planck Institute for Nuclear Physics in Heidelberg. Transitions were identified by the use of *ab initio* Fock space coupled cluster calculations, thus confirming the predictive power of this tool. Our identifications were further corroborated using semi-empirical calculations within the Cowan code framework. With our experimental and theoretical work we have re-evaluated the fine structure of SnXII-XV, and comparison with previous, foundation-laying, studies suggest that some of their level identifications of the Sn HCIs atomic structure based on EUV spectral data need to be revisited.

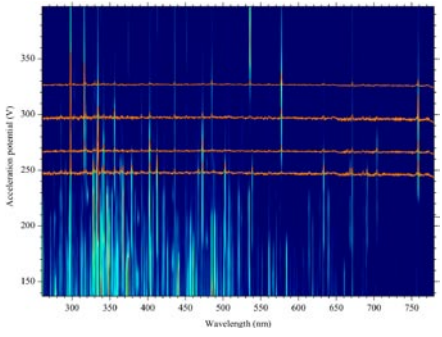

Figure 1: Composite spectral map obtained from EBIT measurements. The orange curves represent spectra of Sn XII-XV ions taken at a maximum of the fluorescence yield of a specific charge state.

HIGH ENERGY RESOLUTION MEASUREMENTS OF K-HYPERSATELLITE X-RAY SPECTRA OF SOLID Ca, V, Fe and Cu TARGETS BOMBARDED BY FAST C AND Ne IONS

J-Cl. Dousse[a], Y.-P. Maillard[a], J. Hoszowska[a], M. Kavčič[b], J. Rzadkiewicz[c] and K. Tökési[d]

[a]Department of Physics, University of Fribourg, CH-1700 Fribourg, Switzerland
[b]J. Stefan Institute, SI-1000 Ljubljana, Slovenia
[c]National Centre for Nuclear Research, 05-400 Otwock-Świerk, Poland
[d]Institute of Nuclear Research of the Academy of Sciences, H-4001 Debrecen, Hungary

In contrast to the double inner-shell ionizations induced by photon and electron impact which are rather weak, x-ray satellites and hypersatellites with markedly higher intensities are observed in x-ray spectra resulting from atomic collisions with heavy ions. Due to the strong Coulomb field of the projectile, several inner-shell electrons of the target atom can be indeed ionized simultaneously. As a consequence, x-ray spectra induced by heavy ion impact exhibit rich satellite and hypersatellite structures. High-resolution measurements of heavy-ion induced K-hypersatellites represent a sensitive tool for investigating the relativistic and quantum electrodynamics (QED) effects in atoms [1] as well as the dynamics of multiple ionization of atoms by heavy-ion impact [2].

We report on the K-shell double ionization of Ca, V, Fe and Cu induced by impact with swift fully stripped C and Ne ions. The measurements were performed at the Paul Scherrer Institute (PSI) in Villigen, Switzerland. The heavy ions from a 10-GHz ECR source were accelerated to final energies of 143 MeV and 180 MeV, respectively, by the variable energy Philips cyclotron of PSI. The x-ray spectra were measured by means of high resolution x-ray spectroscopy, using the von Hamos curved crystal spectrometer of Fribourg [3].

From the fits of the high resolution x-ray spectra, the centroid energies, linewidths and relative intensities of the transitions of interest were extracted and compared to theoretical predictions. In general, a good agreement with existing synchrotron radiation data is observed for the K-hypersatellite energies. The same holds for the natural hypersatellite linewidths, provided, however, that the additional unresolved M-shell satellite structures are considered in the fits. The double K-shell photoionization cross sections were derived from the hypersatellite-to-diagram intensity ratios and compared to results of calculations performed within the SCA and CTMC models. It was found that the experimental cross sections are reproduced rather well by the SCA model if relativistic Hartree-Fock wave functions are employed in the calculations, whereas the CTMC approach seems to overestimate the cross sections in the case of C and, on the contrary, to underestimate them in the case of Ne.

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HIGHER-ORDER RECOIL CORRECTIONS IN HELIUM AND HELIUM-LIKE IONS

Vojtěch Patkóš[a], V. A. Yerokhin[b], Krzysztof Pachucki[a]

[a]Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland
[b]Center for Advanced Studies, St. Petersburg State Polytechnical University, Polytekhnicheskaya 29, St. Petersburg 195251, Russia

In order to calculate nuclear charge radii from isotope shifts one has to calculate accurately the finite nuclear mass effects to atomic energy levels. This requires full Quantum electrodynamic theory as one cannot introduce finite nuclear mass at the level of Dirac equation. We present the calculation of nuclear recoil effects in Helium and Helium-like ions up to the order $m\,\alpha^6$ and present results for the ^{3}He$-^4$He charge radii difference.

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NUCLEAR RECOIL EFFECT ON THE g FACTOR OF FEW-ELECTRON IONS

A. A. Shchepetnov[a,b], D. A. Glazov[a,b], A. V. Volotka[a,c], V. M. Shabaev[a], I. I. Tupitsyn[a], G. Plunien[d]

[a] Department of Physics, St. Petersburg State University, Universitetskaya nab. 7/9, 199034 St. Petersburg, Russia

[b] State Scientific Centre "Institute for Theoretical and Experimental Physics" of National Research Centre "Kurchatov Institute", B. Cheremushkinskaya st. 25, 117218 Moscow, Russia

[c] Helmholtz-Institut Jena, Fröbelstieg 3, D-07743 Jena, Germany

[d] Institut für Theoretische Physik, Technische Universität Dresden, Mommsenstraße 13, D-01062 Dresden, Germany

Progress in experimental and theoretical investigations of the g factor of highly charged ions yielded the most accurate determination of the electron mass [1] and the most stringent test of the many-electron QED effects in the presence of magnetic field [2,3]. Recently measured g-factor difference for two isotopes of Li-like calcium is in perfect agreement with the theoretical prediction [4]. This difference is mostly determined by the nuclear recoil effect. In Ref. [4] the one-electron contribution to this effect has been calculated to the first order in the electron-to-nucleus mass ratio $\frac{m}{M}$ and to all orders in αZ, following the previous calculation for H-like ions [5]. The many-electron contribution has been obtained by extrapolation of the values of Ref. [6]. Here, we present the relativistic calculation of the many-electron contribution to the nuclear recoil effect to the first order in $\frac{m}{M}$ for Li-like and B-like ions. The leading-order term is calculated to all orders in αZ for B-like ions (it equals zero for Li-like ions). The interelectronic-interaction correction is evaluated by perturbation theory within the Breit approximation. The one-photon-exchange diagrams are calculated for various effective screening potentials. The result is complete through orders $\frac{m}{M}\frac{1}{Z}$, $\frac{m}{M}\frac{(\alpha Z)^2}{Z}$ and partially accounts for higher orders in αZ and $\frac{1}{Z}$. The total theoretical value for the nuclear recoil effect is improved for middle-Z Li-like ions. The most accurate up-to-date values of the nuclear recoil effect are presented for B-like ions in a wide range of Z, which improves and extends our previous non-relativistic calculation for B-like argon [7].

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QUANTUM CORRELATIONS BETWEEN THE PHOTONS EMITTED IN THE DIELECTRONIC RECOMBINATION OF HIGHLY CHARGED IONS

A. V. Maiorova[a,b], S. Tashenov, A. Surzhykov[c], V. M. Shabaev[b]

[a]Center for Advanced Studies, St. Petersburg Polytechnical University, Polytekhnicheskaya 29, St. Petersburg 195251, Russia

[b]St. Petersburg State University, Universitetskaya nab. 7/9, St. Petersburg 199034, Russia

[c]Fundamental Physics for Metrology Physikalisch-Technische Bundesanstalt Bundesallee 100, 38116 Braunschweig Germany

One of the prominent processes in collisions of electrons with highly charged ions is dielectronic recombination (DR). DR has attracted much attention during past decades, both in experiment and theory, because this process is a very effective tool for diagnostics of hot plasmas, for investigations of the Breit interaction [1], for probing a variety of nuclear properties [2]. Investigations of polarization of DR transitions allow to study the alignment properties of the states populated by the dielectronic capture. Moreover, the observation of the correlated x-rays gives opportunities to study quantum entanglement in the relativistic regime. These photon-photon polarization correlations can be employed, for example, for testing of the Bell inequality in the relativistic regime. Here we consider the Clauser-Horne-Shimony-Holt's (CHSH) inequality

$$|\Delta(\mathbf{a}, \mathbf{a}', \mathbf{b}, \mathbf{b}')| \leq 2, \tag{1}$$

which is one of a family of Bell inequalities.

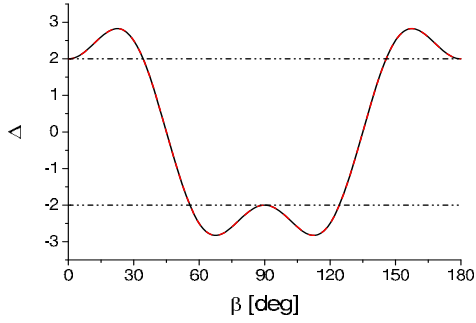

Figure 1: Test of CHSH inequality (1) in DR into the $(2p_{3/2}2p_{3/2})_0$ state of He-like uranium. β is angle between $\mathbf{a}$ and $\mathbf{b}$, $\mathbf{b}$ and $\mathbf{a}'$, and $\mathbf{a}'$ and $\mathbf{b}'$ [3].

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VISIBLE SPECTROSCOPY OF HIGHLY CHARGED HOLMIUM IONS OBSERVED WITH A COMPACT ELECTRON BEAM ION TRAP

Takayuki Nakajima[a], Kunihiro Okada[b], Michiharu Wada[c], Vladimir A. Dzuba[d], Marianna S. Safronova[e,f], Ulyana I. Safronova[g], Noriaki Ohmae[h,i,j], Hidetoshi Katori[h,i,j,k], and Nobuyuki Nakamura[a]

[a]Inst. for Laser Science, The Univ. of Electro-Communications, Tokyo 182-8585, Japan

[b]Dept. of Physics, Sophia University, Tokyo 102-8554, Japan

[c]Wako Nuclear Science Center, Inst. of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK), Saitama 351-0198, Japan

[d]The University of New South Wales, Sydney 2052, Australia

[e]University of Delaware, Newark, Delaware 19716, USA

[f]Joint Quantum Institute, NIST and the University of Maryland, Maryland 20899, US

[g]University of Nevada, Reno, Nevada 89557, USA

[h]Quantum Metrology Laboratory, RIKEN, Saitama 351-0198, Japan

[i]Innovative Space-Time project, ERATO, JST, Tokyo 113-8656, Japan

[j]Dept. of Applied Physics, The University of Tokyo, Tokyo 113-8656, Japan

[k]RIKEN Center for Advanced photonics, Saitama 351-0198, Japan

Recently, an optical clock utilizing transitions in highly charged ions has been proposed as a potential candidate for an accurate and stable clock that has an excellent sensitivity to the fine structure constant variation[1]. Dzuba *et al.* [2] have proposed to use Ho^{14+} and predicted several optical transitions which are useful for cooling and observation. However, the uncertainty in the predicted frequency is rather large as 10,000 cm^{-1} because Ho^{14+}, whose ground state configuration is $4f^6 5s$, has dense and complex energy levels arising from configuration interaction among a huge number of fine structure levels. It is thus important to determine the transition wavelength experimentally for designing and constructing the clock using Ho^{14+}.

In this paper, we present visible spectra of highly charged Ho ions observed with an electron beam ion trap (EBIT). We used a compact EBIT [3], called CoBIT, which is useful device to observe and identify previously-unreported transitions in highly charged ions. In the present study, several transitions of Ho^{14+} have been observed. The analysis of the spectra through the comparison with theoretical calculations is given.

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EXTREME ULTRAVIOLET SPECTROSCOPY OF HIGHLY CHARGED XE AND BA WITH A COMPACT ELECTRON BEAM ION TRAP

Safdar Ali, Nobuyuki Nakamura

Institute for Laser Science, The University of Electro-Communications, Tokyo 182 8585, Japan

Spectroscopy of highly charged ions with an electron beam ion traps (EBITs) play a vital role in various applications, ranging from basic physics to atomic and plasma physics. In a recent investigation, we have measured extreme ultraviolet (EUV) emission spectra from highly charged Xe and Ba ions using a low energy EBIT called CoBIT [1]. It is well known that Xe emit strong radiation in EUV wavelength at high temperatures and considered to be an important element to act as cooling agent for future tokamaks such as International Thermonuclear Experimental Reactor (ITER). The second element of present interest is Ba, which is only two unit different in atomic number from Xe is perhaps one of the easiest elements to study in EBITs. However, spectroscopic data is still missing for several charge states especially in the wavelength region below 15 nm and require more studies.

For Xe measurements, we injected Xe gas using a gas injection system while for Ba no external injection was employed since barium is present as dopant in the electron gun cathode and evaporates from the cathode as a result of heating. The ions were produced and trapped by the space charge of the electron beam and a well shape potential provided by the drift tubes. To produce different charge states and facilitate the identification, the electron beam energy was varied for several different values for both elements. The emitted radiation was recorded using a high resolution flat-field grazing incidence spectrometer with a groove number of 1200 groves/mm [2]. We identified several electric dipole transitions from highly ionized Xe and Ba in between 15-30 nm and 9-13 nm, respectively. The measured wavelengths are compared with the calculations performed using Flexible Atomic Code (FAC) and with the available data from literature.

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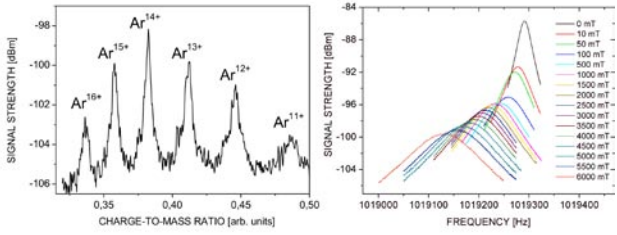
PENNING TRAP EXPERIMENTS FOR SPECTROSCOPY OF HIGHLY CHARGED IONS

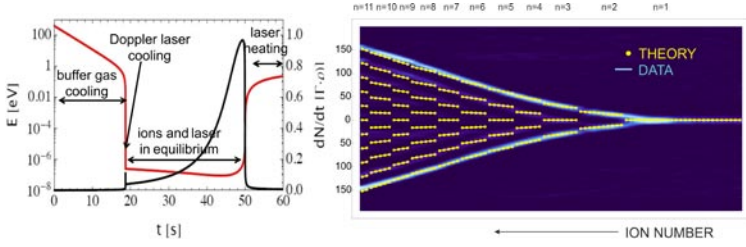
W. Quint[1], G. Birkl[2], A. Martin[2], T. Murböck[1,2], W. Nörtershäuser[2], M.S. Ebrahimi[1,3], S. Schmidt[1,2], N. Stallkamp[1,4], M. Vogel[1], M. Wiesel[1,2,3]

[1] GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany
[2] Technische Universität Darmstadt, 64289 Darmstadt, Germany
[3] Physikalisches Institut, Ruprecht Karls-Universität Heidelberg, 69120 Heidelberg, Germany
[4] Helmholtz-Institut Jena, 07743 Jena, Germany

We present the status of the two Penning trap experiments ARTEMIS and SpecTrap, located at the HITRAP facility at GSI, Germany, and show first measurements. The ARTEMIS experiment is designed for precision microwave spectroscopy of confined highly charged ions to the end of measuring the magnetic moments of bound electrons with high precision. This allows tests of calculations in the realm of QED in strong fields, and adresses the topic of higher-order Zeeman effects. So far, it has been operated with argon ions up to Ar^{16+}. Ion detection is achieved by superconducting resonators, the behaviour of which has been characterized in detail by measuring their properties in external fields between zero and 6 Tesla. Currently, spectroscopic measurements of the fine structure splitting in Ar^{13+} are being prepared.



The SpecTrap experiment is designed for optical precision spectroscopy of confined highly charged ions cooled by laser-cooled Mg^+ ions. We have performed Doppler laser cooling of Mg^+ ions and studied the formation of ion crystals by imaging with a CCD camera. The typical



cloud size of several thousands of ions leads to the formation of mesoscopic Coulomb crystals which display a particular shell structure in good agreement with theory. The applied combination of buffer gas cooling and laser cooling allows to cool the ions' motion from several hundreds of eV to below micro-eV within seconds. We compare the experimental results to theory and discuss the potential for sympathetic cooling of highly charged ions.

NUCLEAR EXCITATION IN THE TWO-PHOTON DECAY OF HIGHLY CHARGED IONS

A. V. Volotka[a,b], A. Surzhykov[c,d], S. Trotsenko[a,e], G. Plunien[f], Th. Stöhlker[a,e,g], S. Fritzsche[a,g]

[a] Helmholtz-Institut Jena, 07743 Jena, Germany
[b] Department of Physics, St. Petersburg State University, 198504 St. Petersburg, Russia
[c] Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany
[d] Technische Universität Braunschweig, 38106 Braunschweig, Germany
[e] GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany
[f] Institut für Theoretische Physik, Technische Universität Dresden, 01062 Dresden, Germany
[g] Theoretisch-Physikalisches Institut, Universität Jena, 07743 Jena, Germany

A new mechanism for nuclear excitation by atomic transition is suggested and explored theoretically by studying the two-photon decay of highly charged ions. This mechanism can be seen as a two-photon transition in the presence of an intermediate cascade state, which is given by the electron-nucleus state with the electrons in its ground level and the nucleus in an excited level. Similarly to the pure electronic two-photon decay, the presence of such a cascade leaves a clear footprint in the photon emission spectrum as sharp peaks in the energy regions when one of the photons has a frequency close to the nuclear excitation energy. Detailed calculations are performed for the E1E1 decay $1s2s\,2^1S_0 \rightarrow 1s^2\,1^1S_0$ in heliumlike $^{225}Ac^{87+}$ ion and for the resonant excitation of the known nuclear level at 40.09(5) keV above the nuclear ground state. The probability that such two-photon decay occurs via the nuclear excitation is found to be 3.5×10^{-9} and is, thus, similar to the corresponding values as obtained for the nuclear excitation by electron transition (NEET). The experimental observation of the proposed mechanism is discussed thoroughly as well as its possible applications for the search of low-lying isomeric states, energy storing, and controlled triggering.

DETERMINATION OF HYPERFINE SPLITTING IN HIGHLY CHARGED HELIUM-LIKE IONS VIA ANGLE-RESOLVED SPECTROSCOPIC ANALYSIS

Zhongwen Wu[a,b], Andrey V. Volotka[a,c], Andrey Surzhykov[d,e], Stephan Fritzsche[a,f]

[a]Helmholtz-Institut Jena, D-07743 Jena, Germany

[b]College of Physics and Electronic Engineering, Northwest Normal University, Lanzhou 730070, P.R. China

[c]Department of Physics, St. Petersburg State University, 198504 St. Petersburg, Russia

[d]Physikalisch-Technische Bundesanstalt, D-38116 Braunschweig, Germany

[e]Technische Universität Braunschweig, D-38106 Braunschweig, Germany

[f]Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität Jena, D-07743 Jena, Germany

Hyperfine splitting in highly charged high-Z ions provides an access to accurate tests of QED in strong electromagnetic field generated by a heavy nucleus. As an example, in recent years the ground-state hyperfine splittings in hydrogen- and lithium-like ions have been intensively studied both theoretically and experimentally for the purpose of the QED tests [1,2]. Helium-like ions represent another simple few-electron ionic system, which can also be served for the same purpose, for instance, the hyperfine structure of the $1s2p^3P_1$ level. However, in high-Z region the (natural) linewidth of individual hyperfine levels becomes comparable in magnitude to or even larger than its hyperfine splitting. Thus, it will hardly be measured experimentally by the conventional fluorescence spectroscopy due to their mutual overlapping. In this work, we propose an experimental scheme to measure the hyperfine splitting by analyzing angle-resolved properties such as angular distribution and polarization of the fluorescence photons emitted from these hyperfine levels. To this aim, we studied the angular distribution and linear polarization of the γ_2 fluorescence photons emitted in the process $1s2s\,^1S_0\,F_i = 5/2 + \gamma_1 \rightarrow 1s2p\,^3P_1, F = 3/2, 5/2, 7/2 \rightarrow 1s^2\,^1S_0\,F_f = 5/2 + \gamma_2$ of helium-like europium isotope ($I = 5/2, \mu_I = +3.4717\mu_N$), by using a theoretical method as presented in our previous work [3]. The initial $1s2s\,^1S_0\,F_i = 5/2$ level can be selectively produced in the collisions of lithium-like Eu^{60+} ion beam with gas target molecules [4]. The first-step decay occurs via stimulated emission mediated by a laser with γ_1 photons, and subsequently, the second-step spontaneous radiative decay brings the ion to its ground state with the emission of the γ_2 photons. It is found that the angular distribution and linear polarization of the emitted fluorescence γ_2 photons strongly depend upon the hyperfine structure values, if analyzed as a function of the γ_1 photon energy. Therefore, we argue that accurate measurements of angular distribution and linear polarization of the fluorescence photons allow us to determine the splitting of overlapping hyperfine levels, even if they can not be resolved by the conventional spectroscopy. The proposed measurement has also a significant meaning to the studies of parity-violation effects, since many of suggested scenarios require accurate knowledge of the hyperfine level structure in highly charged helium-like ions.

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SPECTROSCOPY OF EXCITED AND AUTOIONIZATION STATES IN SPECTRA OF MULTICHARGED IONS: He-LIKE IONS

V.V. Buyadzhi[a], A.V. Smirnov[a], O.A. Antoshkina[a], O. Yu. Khetselius[a], A.A. Svinarenko[a]

[a]Odessa State University-OSENU, P.O.Box 24a, Odessa-9, 65009, Ukraine

The paper is devoted to application of the a relativistic many-body PT [1] with the Dirac-Kohn-Sham (DKS) zeroth approximation combined with the generalized energy approach [1,2] to studying the single and double –excited and autoionization states in spectra of heavy atoms, and multicharged ions, in particular, spectra of He-like ions ($n_1l_1n_2l_2$; n_1,n_2=1-10; l_1,l_2=0-3), and searching unusual futures in behaviour of these states AR in an DC electric field. The wave function zeroth basis is found from the Dirac equation with potential, which includes the optimized DKS potential, the electric potential of a nucleus. All correlation corrections of the second order and dominated classes of the higher orders diagrams (electrons screening, particle-hole interaction, mass operator iterations) are taken into account within the Green's function method.

As an example, in table 1 we list the energies (Ry) of some (1s4s,4p) for the He-like krypton (KrXXXV): NIST data and theoretical (this work) data by the relativistic many-body PT with the Dirac-Kohn-Sham (DKS) zeroth approximation It carried out the detailed comparison of the obtained results with available experimental (compilation) by NIST and other theoretical data for energies of singly-excited states, namely, data obtained on the basis of the multiconfiguration relativistic Hartree-Fock, Dirac-Fock (Grasp 1,2) method with accounting for the Breit corrections, 1/Z PT and relativistic many-body PT with the Dirac-Kohn-Sham (DKS) zeroth approximation [3]. Difference between all available data is analyzed from the viewpoint of completeness of the accounting relativistic and correlation corrections. Besides, we list the preliminary estimates of the DC Stark shifts and broadening for the studied ions in the weak DC electric field, obtained with using the operator perturbation theory [1].

Table 1. The energies (Ry) of some (1s4s,4p) for the He-like krypton (KrXXXV): NIST data and theoretical data by the relativistic many-body PT with the DKS zeroth approximation (this work)

Conf/Term		NIST	This work
1s4s	$^3S_1$	1193.11010	1193.12032
1s4p	$^3P^\circ_0$	1193.48190	1193.49068
1s4s	$^1S_0$	1193.49370	1193.50008
1s4p	$^3P^\circ_1$	1193.50650	1193.51369

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"SHAKE-UP" AND NEET EFFECTS IN LASER ELECTRON-GAMMA-NUCLEAR SPECTROSCOPY OF ATOMIC MULTICHARGED IONS: ADVANCED DATA

A.V. Glushkov[a], O.Yu. Khetselius[a], V.V. Buyadzhi[a], Yu.V. Dubrovskaya[a], A.V. Ignatenko[a]

[a]Odessa State University-OSENU, P.O.Box 24a, Odessa-9, 65009, Ukraine

A new class of problems has been arisen and connected with modelling the cooperative laser-electron-nuclear phenomena such as the electron shell shake-up and NEET or NEEC (nuclear excitation by electron transition or capture) effects in heavy neutral atomic/nuclear systems [1,2]. Though the shake-up effects in the neutral atoms (molecules) are quite weak (because of the weak coupling of the electron and nuclear degrees of freedom), the possibilities of their realization significantly change in a case of the multicharged ions. We present consistent, relativistic approach to calculation of the probabilities of the different cooperative laser electron-gamma-nuclear processes in the multicharged ions (including the characteristics of the electron satellites in gamma-spectra of nuclei of the multicharged ions and the resonant NEET (NEEC) effects in heavy nuclei of multicharged ion). The theory is based on the relativistic energy approach (S-matrix formalism of Gell-Mann and Low) [3,4] and relativistic many-body perturbation theory [5]. Within the energy approach, decay and excitation probability (of the electron shell shake-up process or etc) is linked with the imaginary part of energy of the excited state for the "electron shell-nucleus-photon" system. For radiative decays it is manifested as effect of retarding in interaction and self-action and calculated within QED perturbation theory formalism. We firstly present new data about intensities of the electron satellites in gamma-spectra of nuclei in the neutral (low lying transitions) and multicharged O-and F-like ions for isotopes ${}^{57}_{26}Fe$, ${}^{133}_{55}Cs$, ${}^{171}_{70}Yb$, which demonstrate an existence of an new effect of the giant increasing (up 3 orders) electron satellites intensities (electron shell shake-up probabilities) under transition from the neutral atoms to the corresponding multicharged ions. We develop the similar relativistic energy approach to the NEET (NEEC) process in the heavy multicharged ions and present the advanced quantitative estimates of the corresponding NEET probabilities in the nuclei of ${}^{189}_{76}Os$, ${}^{193}_{77}Ir$, ${}^{235}_{92}U$, ${}^{268}_{109}Mt$, ${}^{197}_{79}Au$ of the O-and F-like multicharged ions. The received data demonstrate an effect of the significant changing the corresponding NEET probabilities under transition from the neutral atomic/nuclear systems to the corresponding multicharged ions.

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MULTIPLE IONZATION PRODUCED BY HCI-ATOM COLLISIONS NEAR THE BOHR VELOCITY

Xianming Zhou[a,b,c], Rui Cheng[a], Yuyu Wang[a], Yu Lei[a], Jieru Ren[a,c], Yongtao Zhao[a]

[a]Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[b]School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China
[c]University of Chinese Academy of Sciences, Beijing 100049, China

Investigating X-ray emission is an effective method to study the inner-shell process during the collision of highly charged ion with atom. Near the Bohr velocity, the projectile, having enough kinetic energy, interacts with the target atom at a close distance below the surface. Except for neutralization, the projectile is also ionized. At the balance of neutralization and ionization, the outer-shell could consist of multiple vacancies when the inner-shell X-ray emissions occur. This leads to energy shift of the associated X-ray and change of the relative intensity of the sub-shell X-ray [1, 2]. Here, we would like to present the multiple-ionization phoneme of the projectile in the collisions near the Bohr velocity.

The L-shell X-rays of xenon and idiom have been investigated for 6MeV Xe^{20+} and 3MeV I^{q+} ions impacting on solid targets. It is found that the X-ray energy of the projectile is larger than the atomic data, which is irrelative to the projectile charge state but increases with the increasing target atomic number. It is indicated that the outer-shells of the projectile consist of multiple vacancies under the balance of the ionization and neutralization. The extent of multiple ionization increases as a function of the target atomic number but is a constant with the increasing projectile charge state. The multiple-ionization not only leads to the energy shift, but also causes the change of the L-subshell X-ray relative intensity ratio. As a result, the ratio of I(Lα)/I(Lβ) is nearly an constant and smaller than the theoretical data for different charge state, and approximately decreases linearly with the target atomic number, as shown in figure 1.

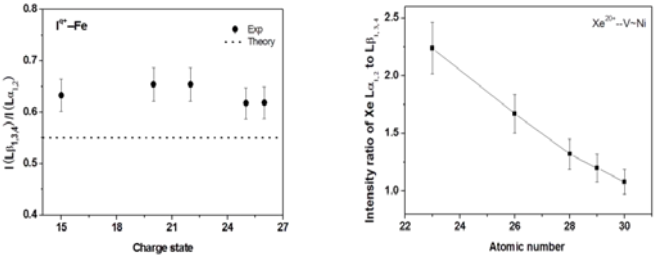

Figure 1: Relative intensity ratio of L-subshell X-ray as a function of projectile charge state and target atomic number

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E-mail: zhouxianming@impcas.ac.cn

ELECTRON EMISSION IN MULTICHARGED DRESSED IONS–ATOM COLLISIONS. NUMERICAL INITIAL CHANNEL PROJECTILE DISTORTION.

J M Monti*, M A Quinto*, J Fiol†, D Fregenal†, P D Fainstein†, R D Rivarola*, W Wolff‡, E Horsdal**, G Bernardi†, S Suárez†

* Instituto de Física Rosario (CONICET-UNR) and Facultad de Ciencias Exactas, Ingeniería y Agrimensura, Universidad Nacional de Rosario, Argentina
† Comisión Nacional de Energía Atómica and Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina
‡ Instituto de Física, Universidade Federal do Rio de Janeiro, Brazil
** Department of Physics and Astronomy, Aarhus University, Denmark

The electron emission mechanism on atomic collisions has been target of active research for many decades. It has implications on many areas as astrophysics, fusion reactors, and radiation damage among others. Many theoretical frames have been developed in order to investigate this reaction for low, intermediate-high, and high collision energy regimes. In the particular case of the intermediate-high impact energies and bare projectiles the distorted wave formalisms, such as the Continuum Distorted Wave (CDW) [1] and the Continuum Distorted Wave-Eikonal Initial State (CDW-EIS) [2] arose as reliable methods to calculate multiply differential and total cross section.

The CDW and CDW-EIS were extended to consider partially dressed projectiles [3,4] describing the non-Coulomb projectile potential with a parametric Green-Sellin-Zachor one [5] that can be separated in two terms: a pure Coulomb potential given by the net charge q of the projectile and a short range part determined by its electronic cloud. In such extensions, the initial channel distortion is considered as a hypergeometric function, for CDW, and an eikonal phase, for CDW-EIS, describing the interaction between the fully screened projectile and the target active electron. These functions give a correct asymptotic description of such interaction at large separations but they might differ from the exact function for smaller distances where the short-range part of the projectile potential is not negligible. This discrepancy is expected to be larger for smaller impact energies and projectiles with large number of electrons. In order to account for a good description of the projectile–active electron interaction over all the distance range we take into account a numeric distortion obtained by numerically solving the Shrödinger equation to obtain a continuum state of the dressed projectile.

Details of the calculation and preliminary results on electron emission in collisions between Al^{q+} impinging over He atoms will be shown during the conference.

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ELECTRON EMISSION IN COLLISIONS BETWEEN NEUTRAL HYDROGEN AND WATER MOLECULES.

J M Monti*, M A Quinto*,‡, P F Weck†, O A Fojón*, J Hanssen*, C Champion‡, R D Rivarola*,

* Instituto de Física Rosario (CONICET-UNR) and Facultad de Ciencias Exactas, Ingeniería y Agrimensura, Universidad Nacional de Rosario, Argentina
† Sandia National Laboratories, Albuquerque, USA
‡ Université de Bordeaux, Centre d'Etudes Nuclaires de Bordeaux Gradignan, France

The determination of heavy ion track-structure in biological matter is of main interest in radiobiology to determine the dose deposition of the ion beam on the biological media. In order to simulate the ion track Monte-Carlo track-structure codes, such as TILDA-V [1] (based on a code previously developed by Champion *et al.* [2]), are used. These codes are based on a complete set of multiply differential and total cross sections for describing all the inelastic processes that take place along the slowing-down of the ions in water and DNA. In this sense it is extremely important to count with a reliable set of cross sections in order to correctly describe the ion track. Throughout the track, the ion beam can capture electrons from the surrounding media and therefore it is also relevant to consider the corresponding cross sections for the different possible charge states of the ion beam.
In this work we focus our interest on proton beams and in particular on calculating the electron emission process in collisions between neutral hydrogen, resulting when a proton captures an electron, and water molecules. The theoretical calculations are performed by using a distorted wave formalism in which the initial channel projectile distortion is numerically determined by solving the Schrödinger equation, therefore obtaining a numerical continuum state of the neutral hydrogen projectile.
Details of the theoretical calculations and results will be shown during the conference.

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SHAKING PROCESS DURING HEAVY ION-ATOM COLLISIONS

Prashant Sharma, Tapan Nandi

Inter University Accelerator Centre, Aruna Asaf Ali Marg, New Delhi 110067, India.

In the framework of sudden approximation limit, due to an abrupt change in the central potential and/or the electronic environment, orbital electrons of the corresponding atomic system may get excited (shakeup) or ionized (shakeoff). Collectively, these processes are called shaking process [1]. Several works can be found in the literature discussing these sudden charge changing processes [2]. In earlier works e.g. [3], increased charge states of nuclear products have been observed. Similarly, in our lab, the formation of highly charged projectile/target-like fragment ions are observed during the heavy-ion nuclear reactions using x-ray spectroscopy technique. The detailed analysis revealed that such unusual ionization is due to the shakeoff process, which occurs because of fast nuclear recoil and sudden change of nuclear charge. In the present theoretical work, we have discussed the collective role of nuclear recoil and charge change in the shakeoff process during the heavy ion-atom collisions. Using non-relativistic hydrogen-like wavefunctions shakeoff probability for any atomic system can be defined as follows [4]

$$P_{shakeoff} = 1 - \sum_{n',l',m'} |< n,l,m,Z \mid exp(-i\overrightarrow{k}\overrightarrow{r}) \mid n',l',m',Z' >|^2 = P_{NCC} + P_{Recoil} \quad (1)$$

here, n, l, m and n', l', m' are the quantum numbers of the parent (nuclear charge, Z) and daughter nucleus (nuclear charge, Z'), respectively and $\overrightarrow{k}$ denote the wave vector of the daughter nucleus. P_{NCC} and P_{Recoil} are the shakeoff probability due to nuclear charge change and recoil, respectively. The shakeoff probabilities have been calculated in the range of $Z = 2 - 90$ using 10^5 non-relativistic hydrogenic wavefunctions . Interestingly, it is found that during the fast ion-atom collisions (MeV energy range) shakeoff due to recoil plays a significant role in the charge changing processes, whereas in the slow collisions (keV energy range) change in nuclear charge shows dominance over the counterpart, shown in Figure [1].

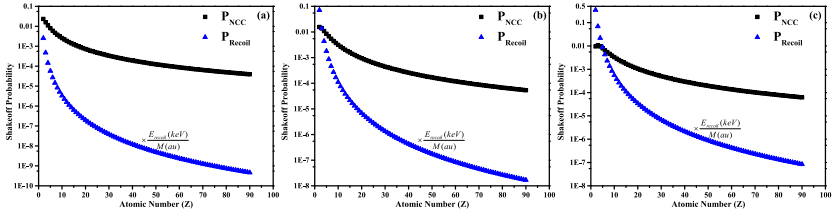

Figure 1: Shakeoff probability versus atomic number (Z) for a typical case of nuclear charge change $(\triangle Z = Z' - Z) = 1$ for different quantum numbers (n, l, m) (a) $(1, 0, 0)$, (b) $(2, 0, 0)$ and (c) $(3, 0, 0)$

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ELECTRON EMISSION IN 2 MeV C^{q+} IONS ON WATER COLLISIONS

A. Rossia[a], J. M. Monti[b, d], P. Pérez[d], C. Olivares[c], W. Wolff[e],
G. Bernardi[c], R. Rivarola[b, d], **S. Suárez**[a, c, d]

[a]Instituto Balseiro, Universidad Nacional de Cuyo. Av. Bustillo 9500
(8400) San Carlos de Bariloche, Argentina.
[b]Instituto de Física Rosario (IFIR-UNR), 27 de Febrero 210bis S2000EZP Rosario Argentina.
[c]Centro Atómico Bariloche Av. Bustillo 9500 (8400) San Carlos de Bariloche, Argentina.
[d]Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET)
[e]Instituto de Física, Universidade Federal de Río de Janeiro (IF-UFRJ)

Until recent works reported by Oshawa et al[1] and Bhattacharjee et al. [2], a few quantity of results were known in the literature on water ionization by heavy ions, despite of the claimed interest on heavy-ion cancer therapy, fundamental studies of charged particle interaction in biological matter or, simply, the need of experimental and theoretical data about the ionization of biological systems. Cited papers [1, 2], however, are mainly concerned with highly charged (q = 4, 6 for C^{q+} and q = 8 for O^{q+}) projectiles at high impinging energies 3 - 8 MeV/u. On the assumption that the energy deposition along the heavy-ion track is responsible to DNA damage and cell killing, and that this fact should occur near the Bragg peak, we consider useful to investigate and provide experimental and theoretical data of water ionization by different heavy ion charge states.

In the present communication we report on doubly differential cross sections (DDCS) for electron emission from water vapor induced by 2 MeV C^{q+} (q = 0, 1, 2, 3) for an extense electron energy range beyond the binary energy, and for several angles of emission by covering the complete angular range ($0^0 \leq \vartheta \leq 180^0$).

A comparison of our experimental data is furnished by CDW-EIS calculations for all projectile charge states investigated in this work.

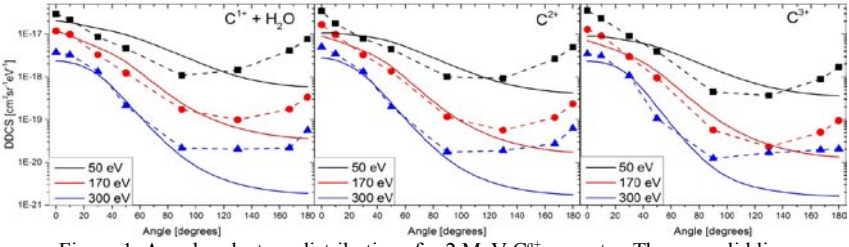

Figure 1: Angular electron distributions for 2 MeV C^{q+} on water. Theory: solid lines; Experimental results: symbols.

We indentified several electron structures in DDCS: i) The Charge Transfer into the Continuum (CTC) peak, ii) The binary peaks, particularly that at low electron energies. iii) Autoinozing Rydberg states from the projectile, and iv) The KLL Carbon peak from projectiles.

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ELECTRON-IMPACT IONIZATION OF W^{19+} IONS

A. Borovik, Jr.[a,b], B. Ebinger[a], D. Schury[b,c], S. Schippers[a] and A. Müller[b]

[a]I. Physikalisches Institut, Justus-Liebig Universität Gießen, Giessen, Germany

[b]Institut für Atom- und Molekülphysik, Justus-Liebig Universität Gießen, Giessen, Germany

[c]GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany

In tungsten-wall tokamaks, the unavoidable sputtering of tungsten into the plasma may result in significant energy losses up to preventing the plasma from ignition. At the same time, highly-charged tungsten ions can serve for diagnostics of the plasma [1]. Both aspects require detailed modeling of the tokamak plasma and, hence, there is a need for extensive sets of accurate data on atomic processes involving tungsten ions. We present a comprehensive experimental and theoretical study of electron-impact ionization of W^{19+} ions aimed at inferring accurate plasma rate coefficients [2]. The Giessen crossed-beams apparatus has been used to measure electron-impact ionization cross sections. Configuration-averaged distorted-wave calculations were performed to quantify the contributions of various ionization mechanisms, i.e., of direct ionization (DI) and excitation-autoionization (EA) processes involving different electron subshells. The figure shows the plasma rate coefficients for electron-impact single ionization of W^{19+} ions inferred from the experimental cross section and its theory-based extrapolation to higher energies for ions in the ground and first excited electron configurations. The rate coefficients are compared to previous theoretical data of Loch et al. [3]. The difference of around 30% is explained by the contributions of EA processes involving excitations of autoionizing states with principal quantum numbers $n > 8$, which were not included in the previous study.

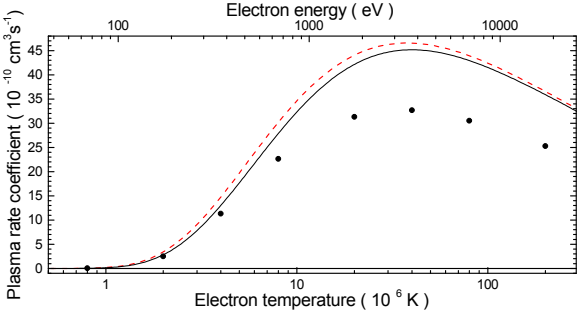

Figure 1: Inferred plasma rate coefficients for electron-impact ionization of W^{19+} ions in the ground- and first excited configuration (solid and dashed curves, respectively). Dots are the results of distorted-wave calculations by Loch et al. [3] neglecting high-n EA contributions.

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ELECTRON-IMPACT IONIZATION OF Xe^{24+} IONS: THEORY VERSUS EXPERIMENT

P. Liu[a], J. Zeng[a,b], **A. Borovik, Jr.**[c,d], S. Schippers[d], and A. Müller[c]

[a]Department of Physics, College of Science, National University of Defense Technology, Changsha Hunan, PR China

[b]IFSA Collaborative Innovation Center, Shanghai Jiao Tong University, Shanghai, PR China

[c]Institut für Atom- und Molekülphysik, Justus-Liebig Universität Gießen, Giessen, Germany

[d]I. Physikalisches Institut, Justus-Liebig Universität Gießen, Giessen, Germany

For many-electron systems, electron-impact ionization results from a complicated pattern of ionization mechanisms involving electrons from many atomic subshells. Previous studies on ionization of xenon ions revealed that the main mechanisms contributing to the single-ionization cross section are direct ionization (DI) and non-resonant excitation-autoionization (EA). For intermediate charge states, resonant processes such as resonant-excitation double autoionization (REDA) yield significant contributions, in addition [1,2]. Here, we report on experimental measurements and theoretical calculations of the cross section for electron-impact single-ionization of Xe^{24+} ions [3]. The measurements were performed using the crossed-beams method. For the cross-section calculations the fine-structure level-to-level distorted-wave approach was used as implemented in the Flexible Atomic Code (FAC). The calculations comprised DI, EA, as well as REDA processes and aimed at inclusion of all relevant partial cross-section contributions involving high-n and high-ℓ excited states. Figure 1 shows the comparison of the experimental and the theoretical results in the energy range where significant contributions by REDA occur.

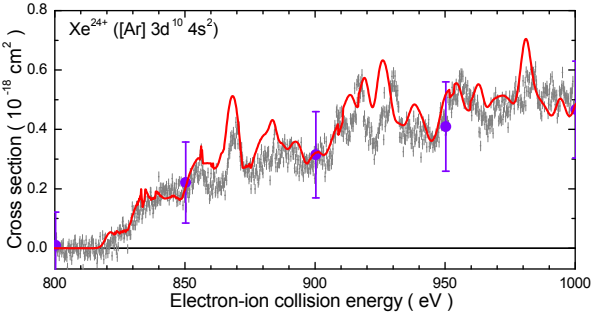

Figure 1: Cross section for electron-impact ionization of Xe^{24+} ions [3]. Symbols represent the experimental data. The solid (red) curve is the result of the theoretical calculation.

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IONIZATION AND ELECTRON CAPTURE CROSS SECTIONS FOR ELECTRON REMOVAL FROM H_2O BY Li^{3+} IMPACT

H. Luna, W. Wolff, and E.C. Montenegro, André C. Tavares, H.J. Lüdde, G. Schenk, M. Horbatsch, and T. Kirchner

Departamento de Física, Universidade Federal do Rio de Janeiro Caixa Postal 68528, Rio de Janeiro, 21945-970, RJ, Brazil
Departamento de Física, Pontifícia Universidade Católica do Rio de Janeiro, Caixa Postal 38071 , 22452-970, RJ, Brazil
Institut für Theoretische Physik, Goethe-Universität, D-60438 Frankfurt, Germany
Department of Physics and Astronomy, York University, Toronto, Ontario M3J 1P3, Canada

The report presents data on the ionization and fragmentation of water induced by Li^{3+} impact in the energy range of 0.75 to 5.8 MeV. Ionic fragments were measured by discriminating the collision events that produced either one, two or more ions and including the differentiation in the final projectile charge state, a stringent comparison with theory can be made. The experiment was carried out by selecting both the final charge state of the projectile and the ejected fragments in coincidence to obtain cross sections associated with ionization and electron capture channels. The ionic fragments and the emitted electrons produced under single collision conditions were collected by a time-of-flight spectrometer with single-hit (e.g. $OH^+ + H^0$) and double-hit events (e.g. $OH^+ + H^+$) properly discriminated [1].
For the one- and two-electron removal cases the calculations based on the basis generator method for orbital propagation agree well with the experiment for most of the collision channels studied. Auger-electron emission after vacancy production in the inner 2a1 orbital of H_2O is shown to have a substantial effect on the final charge-state distributions over the entire impact-energy interval. The results show an overall agreement between theory and experiment for the total single capture (fig. 1) and for pure single and double ionization, but the calculations overestimate higher degrees of ionization.

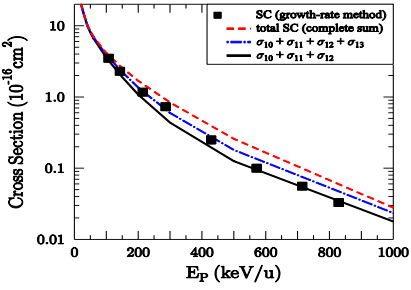

Figure 1: Total single capture cross section as a function of impact energy for Li^{3+} - H_2O collisions, Experimental data (solid squares) obtained via the growth-rate method. Theory: dashed line corresponds to the complete sum $\sum_l \sigma_{1l}$, dash-dotted line to the restricted sum $\sigma_{10} + \sigma_{11} + \sigma_{12} + \sigma_{13}$ and solid line to $\sigma_{10} + \sigma_{11} + \sigma_{12}$. The subscripts indicate the numbers of captured and ionized electrons.

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SINGLE AND DOUBLE ELECTRON PROCESSES OF HELIUM TARGETS INDUCED BY FULLY STRIPPED ION IMPACT

P.N. Terekhin [a,b], P.R. Montenegro [a] , M.A. Quinto [a], J.M. Monti [a], O.A. Fojón [a], R.D. Rivarola [a]

[a] Instituto de Física Rosario (CONICET-UNR), Bv 27 de Febrero, 2000 Rosario, Argentina
[b]NRC Kurchatov Institute, Kurchatov Sq. 1, 123182 Moscow, Russia

Collisions between fully stripped ions and He targets are the simplest systems for investigation of multiple electron transitions. The study of these collisional systems is crucial to fully understand the mechanisms underlying these basic reactions. Moreover, they are of interest in several fields such as heavy-ion therapy [1], thermonuclear fusion [2], hot plasmas [3], etc.

In this work, multiple electron processes (single and double ionization or capture, as well as transfer-ionization) of He targets impacted by H^+, He^{2+} and Li^{3+} projectiles are analyzed theoretically in detail at intermediate and high collision energies. Absolute cross sections for these processes are obtained by computation of transition probabilities as a function of the impact parameter in the framework of the Continuum Distorted Wave-Eikonal Initial State theory (CDW-EIS) [4]. A binomial analysis is employed to calculate exclusive probabilities using the independent electron (IEL) model, where electron correlation is neglected [5], as well as the independent event (IEV) model, in which the ionization is viewed as a two-step process [6]. It is worthy to note that only exclusive probabilities are able to describe properly the measured cross sections taking into account all possible processes.

The comparison with the available theoretical and experimental results shows that exclusive probabilities are needed for a reliable description of the experimental data. The total cross sections obtained within the IEV model and using exclusive probabilities are in better agreement with the experimental results than previous IEV calculations. The developed approach may be used to obtain the input database for modeling multiple electron processes of energetic charged particles passing through matter.

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DIELECTRONIC RECOMBINATION OF $^{36}Ar^{15+}$ AND $^{112}Sn^{34+}$ AT THE HIRFL-CSRm

Z. K. Huang[a,b], **X. Ma**[a], W. Q. Wen[a], H. B. Wang[a,b], X. Y. Chuai[a,b], L. J. Dou[a,b,d], X. L. Zhu[a], X. Xu[c], L. F. Zhu[c], W. Q. Xu[e], J. Li[a], X. M. Ma[a], T. L. Yan[a], L. J. Mao[a], J. C.Yang[a], Y. J. Yuan[a], G. Q. Xiao[a], J. W. Xia[a], L. Y. Xie[d], and C. Z. Dong[d]

[a]Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[b]University of Chinese Academy of Sciences, Beijing 100049, China.
[c]Department of Modern Physics, USTC, Hefei, 230026, Anhui, China.
[d]College of Physics and Electronic Engineering, NWNU, Lanzhou, 730070, China.
[e]Department of Mathematics and Physics, Bengbu University, Bengbu 233030, Anhui, China.

The total recombination rate coefficients of lithium-like $^{36}Ar^{15+}$ ions have been measured by employing the electron-ion merged-beams technique at the heavy ion storage ring CSRm at the Institute of Modern Physics, Lanzhou [1]. Fig. 1 (a) shows the DR spectrum for electron energy from 0 to 35 eV at center-of-mass frame. The energy resolution obtained was about 0.14 eV (FWHM) at the energy region around 1.2 eV. The electron temperature distribution for the transverse and longitudinal components were about 40 meV and 0.80 meV, respectively. The experimental peak positions and recombination rate coefficients are in good agreement with the theoretical calculation using the flexible atomic code (FAC). This experiment was used to calibrate the current DR experimental system at the CSRm.

Recently, DR experiments with different charge states of S-like, P-like, Si-like Tin ions were performed at the CSRm. Fig. 1 (b) shows the preliminary results of the measured recombined rate coefficients of $^{112}Sn^{34+}$ ions. We will present the details of the experimental setup and results on this conference. In addition, the upgrading of the electron cooler (300 kV) of the CSRe for DR experiments with HCIs and even radioactive ions is in progress, and the first DR experiment will be carried out in the second half of this year. We will present the preparation of the DR experiments at the CSRe and give an overview of the DR experiments plans on the upcoming new project High Intensity heavy ion beam Facility (HIAF) as well.

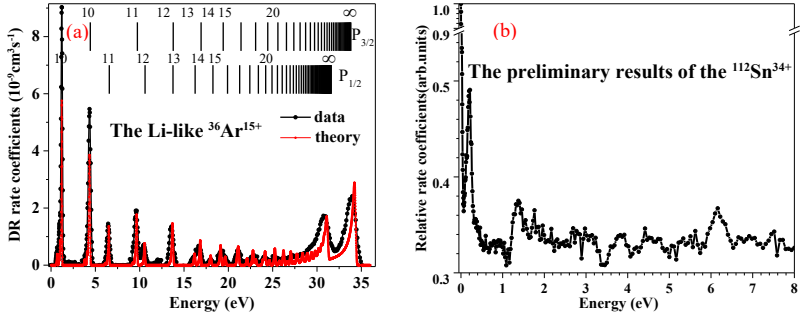

Figure 1: (a) The DR rate coefficients for $^{36}Ar^{15+}$ ions. The DR resonances involve $\Delta n = 0$ transition of the 2s core electron. The energies of Rydberg states with configurations $1s^2 2p_{1/2} nl$ and $1s^2 2p_{3/2} nl$ are indicated by vertical bars. (b) The total recombined rate coefficients of Si-like Sn^{34+} ions versus the relative energy at c.m. frame.

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MULTIPLE ELECTRON PROCESSES IN NEON AND WATER TARGETS COLLIDING WITH PROTONS BEAMS

P.N. Terekhin [a,b], P.R. Montenegro [a] , M.A. Quinto [a], J.M. Monti [a], C. Champion [c], O.A. Fojón [a], R.D. Rivarola [a]

[a] Instituto de Física Rosario (CONICET-UNR), Bv 27 de Febrero, 2000 Rosario, Argentina
[b]NRC Kurchatov Institute, Kurchatov Sq. 1, 123182 Moscow, Russia
[c]Université de Bordeaux, CNRS/IN2P3, Centre d'Etudes Nucléaires de Bordeaux Gradignan, Gradignan, France

Multiple electron processes in atomic and molecular collisions induced by ion impact are of fundamental interest in many areas such as tumor treatment [1], thermonuclear fusion [2], and plasma physics [3]. A particular charge state of the residual target may be produced by the combination of single electron reactions. Therefore, it is important to understand each of them to elucidate the basic governing mechanisms in multiple electron processes.

Proton impact on Ne and water targets are chosen in this work to investigate theoretically multiple electron processes at intermediate and high collision energies. The Continuum Distorted Wave-Eikonal Initial State approximation (CDW-EIS) [4] is used to calculate transition probabilities (capture and ionization) as a function of the impact parameter and absolute cross sections for the considered collisions. The Roothaan–Hartree–Fock (RHF) wavefunctions [5] were used to represent the atomic states of Ne. The initial wavefunctions of the active electrons bound to a particular water molecular orbital are described employing the complete neglect of the differential overlap (CNDO) approximation [6]. A trinomial distribution analysis has been employed to compute exclusive probabilities using the independent electron (IEL) model, where electron correlation is neglected [7].

From the comparison with the available theoretical and experimental results, we conclude that exclusive probabilities are required for a reliable description of the processes of interest. Finally, we note that the present approach could be used as a basis for obtaining multiple electron processes cross sections for targets such as macromolecules of DNA and RNA to model scenarios for the radiobiological consequences of the impact of charged energetic particles on those macromolecules.

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FERMI-SHUTTLE TYPE IONIZATION IN ATOMIC COLLISIONS

Károly Tőkési[1]

[1]Institute for Nuclear Research, Hungarian Academy of Sciences (ATOMKI), Debrecen, Hungary, EU

The aim of the present work is to find the possible source of generation of the high energy electrons in atomic collisions. At sufficiently low collision energies, it is known that the so-called Fermi-shuttle type ionization mechanism can produce high energy electrons [1]. Originally, Fermi proposed the mechanism as a possible source of energetic cosmic rays [2] where weak but giant magnetic fields, moving in outer space, can accelerate charged particles with extremely high energies in long sequences of reflection. In this case the number of collisions is approximately 10^8 and the particles gain approximated 10 eV energy at each collisions. Similarly, a light electron can be scattered forward and backward by heavy target atoms and an incoming projectile ion before being ejected. Taken into account the energy and momentum conservation, the velocity of the target electron is increased by approximately $2V$, in every 180° elastic scattering with the incoming projectile, while only the direction of the electronic motion is changed by scatterings on the target field. Due to the repeated collisions, the active electron can be accelerated to relatively high energies. After 1, 2, 3, 4, or 5 collisions the electron velocity increased approximated by 2V, 4V, 6V, 8V and 10V, where V is the velocity of the projectile. Therefore the corresponding energy gain is 4 E_V, 16 E_V, 36 E_V, 64E_V, 100 E_V, where E_V=0.5 $m_e V^2$. Hence, although naturally in atomic level the number scattering is much less compared with the case of giant magnetic field, but even after a few back and forth collisions the active electron can gain enormous energy.

In this work we present electron emission cross sections in collision between dressed Al^{q+} ions with He target at 100 keV/amu impact energy. The energy distributions of the ejected electrons as a function of the scattering angle were calculated using the classical trajectory Monte Carlo method [3]. We identified the signature of the Fermi-shuttle type ionization in the double differential cross sections thus indicating that the multiple scattering mechanism is important for describing the energetic electrons produced in low and medium energy ion-matter interactions. The theory delivers separate spectra for electrons emitted from the target and the projectile. By summing these two components in the rest frame of the target we may also make a comparison with available experimental data also.

Acknowledgement

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CALCULATIONS OF PAIR PRODUCTION IN SLOW HEAVY-ION COLLISIONS BEYOND THE MONOPOLE APPROXIMATION

I. A. Maltsev[a,b], V. M. Shabaev[a], I. I. Tupitsyn[a], Y. S. Kozhedub[a], G. Plunien[c], Th. Stöhlker[d,e,f]

[a]Department of Physics, St. Petersburg State University, Universitetskaya nab. 7/9, 199034 St. Petersburg, Russia

[b]State Scientific Centre "Institute for Theoretical and Experimental Physics" of National Research Centre "Kurchatov Institute", B. Cheremushkinskaya st. 25, 117218 Moscow, Russia

[c]Institut für Theoretische Physik, Technische Universität Dresden, Mommsenstraße 13, D-01062 Dresden, Germany

[d]Helmholtz-Institut Jena, Fröbelstieg 3, D-07743 Jena, Germany

[e]GSI Helmholtzzentrum für Schwerionenforschung, D-64291 Darmstadt, Germany

[f]Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität Jena, D-07743 Jena, Germany

A method for calculation of pair production in slow heavy-ion collisions beyond the monopole approximation is presented. The method is based on the numerical solving of the time-dependent Dirac equation with full two-center potential. The one-electron wave functions are expanded in the finite basis set constructed from B-splines defined on the two-dimensional spatial grid. Employing the developed approach the pair production probabilities are calculated for symmetric collisions of heavy bare nuclei at the energy near the Coulomb barrier for different values of the nuclear charge. The obtained results are compared with the corresponding values calculated in the monopole approximation [1, 2].

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RADIATIVE ASSOCIATION OF $^{36}Ar^+$ AND $^{38}Ar^+$ WITH HYDROGEN

Fatima Talhi[1] and **Moncef Bouledroua**[2]

[1]Physics Department, Badji Mokhtar University, Annaba, Algeria
[2]Département de Médecine and Laboratoire de Physique des Rayonnements, Badji Mokhtar University, Annaba, Algeria

In a recent paper [Barlow *et al.,* Science **342,** 1343 (2013)], the ArH^+ ionic system has been detected in the Crab Nebula. We accordingly propose to examine in this work the radiative association of the argon ions $^{36}Ar^+$ and $^{38}Ar^+$ with atomic hydrogen and calculate the related temperature-dependent rate coefficients. To do so, we have to construct the transition dipole moments and the potential-energy curves via which both Ar^+ and H species approach each other. The corresponding data points are borrowed from the most recent and reliable calculations of Stolyarov and Child [PCCP **7,** 2259 (2005)]. Once the curves are constructed, the rate coefficients are computed quantum mechanically and analyzed in the temperature range 1-10000 K.

MOLECULAR ION COLLISION CHEMISTRY IN CH_4 IONIZATION AND DISSOCIATION

A.T. Hasan[a], T. J. Gray[b]

[a]Department of Physics, American University of Sharjah, P.O. Box 26666Sharjah, UAE
[b]Department of Physics, Kansas State University, Manhattan, KS 66506, USA

Although the phenomena of atomic collisions have been the subject of extensive research, much more can be learned about these complex and variant processes. Further experimental and theoretical studies of ion-molecule collision will provide a better understanding of the atomic structure, collision phenomena, and molecular ion formation.
The use of the 90º hemispheric electrostatic high resolution analyzer [1] in conjunction with time of flight techniques allowed us to identify the various events associated with charged ion-molecular collision. In the present work, we have reported the relative intensities of the dissociative and non-dissociative ionization [2, 3] of CH_n^+ (n= 1-4) ions produced in a recoil ion source by a pulsed fast 19 MeV F^{4+} pump beam. High resolution translation energy spectrum for these ions was produced, at 0.5 mTorr pressure in the recoil ion source.
Figure 1 depicts several events involving methane collision which are graphed on a counts versus the time-of-flight. The mass to charge ratio which is proportional to the square of the time-of-flight is also shown.

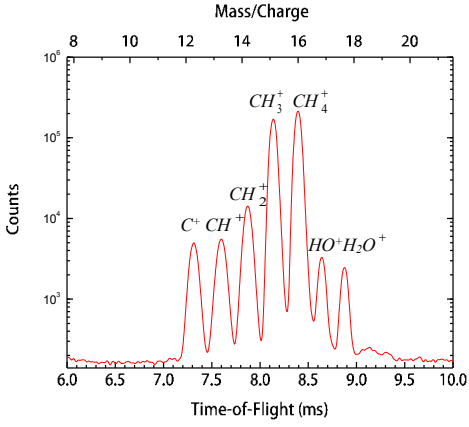

Fig. 1: The time-of-flight spectrum for F^{4+} + CH_4 recoil ions.

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RESONANT COHERENT EXCITATION OF THE "ELECTRON-COOLED" U^{89+} BEAM FROM ESR: TOWARDS A HIGH-PRECISION ABSOLUTE SPECTROSCOPY OF HIGH-*Z* HCIs

Yuji Nakano,[1] A. Bräuning-Demian,[2] A. Ananyeva,[2, 3] S. Menk,[1]
H. Bräuning,[2] C. Kleffner,[2] Th. Stöhlker,[2, 4, 5] and T. Azuma[1, 6]

[1] Atomic, Molecular and Optical Physics Laboratory, RIKEN, Saitama 351-0198, Japan

[2] GSI Helmholtzzentrum für Schwerionenforschung, D-64291 Darmstadt, Germany

[3] Johann Wolfgang Goethe Universität, Frankfurt, 60438 Frankfurt am Main, Germany

[4] Helmholtz-Institut Jena, D-07743 Jena, Germany

[5] Friedrich-Schiller University Jena, 07737 Jena, Germany

[6] Department of Physics, Tokyo Metropolitan University, Tokyo 192-0397, Japan

After the first demonstration of the resonant coherent excitation (RCE) of Li-like U^{89+} as a novel tool for high-precision spectroscopy [1], we performed an upgraded experiment by using the electron cooler. In 2014, the new experiment was performed with the "electron cooled" beam from the storage ring ESR at GSI, and showed a three-times enhancement in the energy resolution [2]. In addition, with the sharp resonance allows to determine the peak position in a 5 ppm precision. Figure 1 compares the RCE spectra measured with and without the electron cooler. The detailed analysis of the resonance profile suggested that the use or the electron cooler narrowed the resonance width to close to the Fourier transform limit. Report from the next beam time planned in May 2016 may be also included.

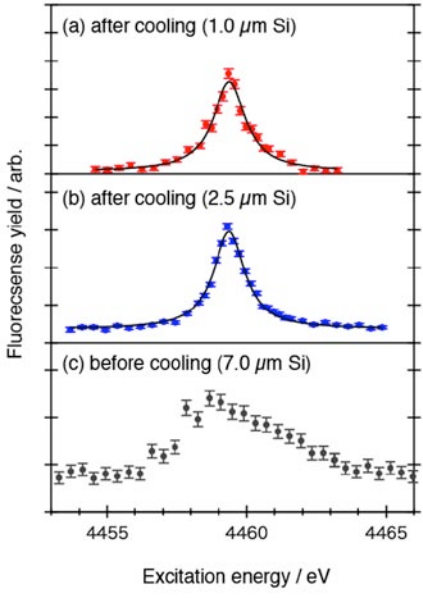

Figure 1: The RCE spectra of 190 MeV/u Li-like U^{89+} in Si crystals. (a) and (b) show the result from the upgraded experiment with the electron cooled beam. The spectrum (c) was measured with the direct beam from SIS without using the ESR.

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SPUTTERING OF H_2O AND D_2O ICES UNDER IMPACT OF LOW ENERGY (~keV/u) MULTIPLY CHARGED OXYGEN IONS

Aditya N. Agnihotri[a], Rafael Martinez[b], Hermann Rothard[a], Alicja Domaracka[a], Philippe Boduch[a]

[a] Centre de Recherche sur les Ions, les Matériaux et la Photonique CIMAP, GANIL, CEA/CNRS/ENSICAEN/UNICAEN, BP 5133, 14070 Caen Cedex 05, France
[b]Departamento de Física, Universidade Federal do Amapá, Brazil

Water ices are present on the surfaces of comets, on some satellites of the giant planets and on other bodies of astrophysical interest. Their abundance and structure may evolve with time under the influence of radiation (solar wind, cosmic rays, ions trapped in magnetospheres) or due to thermal processes. The effect of energetic ion impact on ices has therefore been an area of extensive research [1]. In the laboratory, ion beams can be used to simulate irradiation by cosmic ray or solar wind analogues.

We have performed Time-of-Flight Secondary Ion Mass Spectrometry (TOF-SIMS) [2-4] of ices of normal and heavy water under irradiation by a pulsed beam of low energy oxygen ions. The experiments were performed at the ARIBE facility at GANIL, Caen, France. The energy of the projectile ions ranges from 30 to 90 keV. The ices were deposited and irradiated at temperatures varying over a large range (from 10 K to 150 K). The measurements were also performed for several ice thicknesses.

As a result of ion-bombardment of the ice, secondary ions including water ions and fragments as well as protonated molecules (H_3O^+) and clusters ($(H_2O)_nH^+$) are emitted. The yields of water clusters per incoming projectile were determined as a function of temperature, projectile-energy and ice thickness. The size and yield of the water clusters shows a strong dependence on these parameters.

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VAN DER WAALS DIMERS VS COVALENT MOLECULES: DIFFERENCES AND SIMILARITIES

Alain Méry[a], Aditya Agnihotri[a], Xavier Fléchard[b], Benoit Gervais[a], Stéphane Guillous[a], Wael Iskandar[c], Jun Matsumoto[d], Jimmy Rangama[a], C.P. Safvan[e], Haruo Shiromaru[d], Amine Cassimi[a]

[a]CIMAP, CEA-CNRS-ENSICAEN-UNICAEN, Normandie Université, BP5133, F-14050 Caen Cedex 04, France

[b]LPC Caen, ENSICAEN, UNICAEN, CNRS/IN2P3, Normandie Université, 14050 Caen Cedex 04, France

[c]Lawrence Berkeley National Laboratory, Berkeley, CA-94720, USA

[d]Department of Chemistry, Tokyo Metropolitan University, 1-1 Minamiosawa, Hachiouji-shi, Tokyo 192-0397, Japan

[e]Inter University Accelerator Center, Aruna Asaf Ali Marg, New Delhi 110067, India

Covalent bonds and van der Waals bonds are known to have specific characteristics. Particularly, in weakly bound van der Waals dimers for which the internuclear distance is significantly longer than atomic sizes, electron mobility between the two atoms is expected to be very low [1]. At the opposite, in covalent diatomic molecules, valence electrons are shared between the two centers. A detailed study of covalently or van der Waals bounded diatomic edifices may allow to contrast the properties of these two kinds of bonds. In this purpose, collisions of slow 15 qkeV Ar^{9+} ions with N_2 molecules and Ar_2 dimers have been investigated using COLTRIMS technique.

Our previous results on ion collisions with rare gas dimers have showed that the large internuclear distance between the two atoms results in a low charge mobility along the dimer [2]. As a consequence, the charge repartition in the final fragmentation channels can be interpreted as a signature of the initial capture process. Thanks to this particular behavior and when considering asymmetric fragmentation channels $Ar_2^{3+} \rightarrow Ar^{+}+Ar^{2+}$ and $Ar_2^{4+} \rightarrow Ar^{+}+Ar^{3+}$, we were able to evidence that electrons are mainly captured from the closest atom to the projectile trajectory.

We used a similar approach to investigate ion collisions with covalently bound diatomic molecules (N_2). We will discuss the competition between symmetric and asymmetric fragmentation channels $N_2^{4+} \rightarrow N^{2+}+N^{2+}$ and $N_2^{4+} \rightarrow N^{1+}+N^{3+}$. As expected for covalent molecules, it appears that charge rearrangement following multiple electron capture takes place on a shorter time scale than fragmentation. Molecular orientation dependence will also be discussed for different fragmentation channels. As for Argon dimers, a preference for electron capture from projectile trajectories close to the median plane of the N_2 molecule is observed.

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ION COLLISIONS WITH $(N_2)_2$ MOLECULAR DIMERS: ROLE OF THE ENVIRONMENT ON THE MOLECULAR FRAGMENTATION DYNAMICS

Alain Méry[a], Aditya Agnihotri[a], Xavier Fléchard[b], Benoit Gervais[a], Stéphane Guillous[a], Wael Iskandar[c], Jun Matsumoto[d], Jimmy Rangama[a], C.P. Safvan[e], Haruo Shiromaru[d], Amine Cassimi[a]

[a]CIMAP, CEA-CNRS-ENSICAEN-UNICAEN, Normandie Université, BP5133, F-14050 Caen Cedex 04, France

[b]LPC Caen, ENSICAEN, UNICAEN, CNRS/IN2P3, Normandie Université, 14050 Caen Cedex 04, France

[c]Lawrence Berkeley National Laboratory, Berkeley, CA-94720, USA

[d]Department of Chemistry, Tokyo Metropolitan University, 1-1 Minamiosawa, Hachiouji-shi, Tokyo 192-0397, Japan

[e]Inter University Accelerator Center, Aruna Asaf Ali Marg, New Delhi 110067, India

Weakly bond systems are of increasing interest as they represent an intermediate step from gas phase to condensed matter. Many experimental and theoretical works have been done over the past decades to investigate properties of clusters ranging from atomic clusters to large molecular clusters. Nitrogen dimer $(N_2)_2$ constitutes a model system of polyatomic "molecule" containing both covalent (intramolecular) and van der Waals (intermolecular) bonds. We will show recent experimental results concerning both the geometrical conformation of the two molecules inside the dimer and the influence of the second spectator molecule on the dissociation dynamics of the other N_2 molecule.

Up to our knowledge, no experimental measurement of the $(N_2)_2$ dimer geometrical structure has been performed. However, quantum chemistry calculations have shown the existence of several isomeric states of the ground state of $(N_2)_2$ dimers [1]. These states correspond to different geometrical alignments of the constitutive molecules with respect to the dimer axis and have very close dissociation energies: between 15 meV ("S" shape) and 12 meV ("T" shape).

COLTRIMS technique allows to measure the 3D momentum vector of cationic fragments resulting from the dissociation of doubly $(N_2)_2^{2+}$ and triply $(N_2)_2^{3+}$ ionised dimers following collisions with 15 qkeV Ar^{9+} ions. A precise study of the 2-body $(N_2)_2^{2+} \rightarrow N_2^+ + N_2^+$ and 3-body $(N_2)_2^{3+} \rightarrow N_2^+ + N^+ + N^+$ fragmentation channels allows to get quantitative information on the geometrical structure of the dimer. For the 3-body case, classical Coulomb explosion simulations have been performed and convoluted to the experimental resolution of the apparatus. Comparison is made with experimental data to identify the $(N_2)_2$ conformation. Moreover, the $(N_2)_2^{3+} \rightarrow N_2^+ + N^+ + N^+$ fragmentation channel offers a clean experimental case where the presence of the recoiling neighbour N_2^+ molecular ion may affect the fragmentation of the other di-cation N_2^{2+} molecule. Results from this particular fragmentation channel of the dimer will be directly compared to the dissociation of the di-cation from the monomer $(N_2)^{2+} \rightarrow N^+ + N^+$.

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MODELING THE 1s2l2l′ AUGER PROJECTILE SPECTRUM IN C^{4+} (1s2s ^{3}S) COLLISIONS WITH He INCLUDING RADIATIVE CASCADE REPOPULATION AND AUGER DEPLETION

I. Madesis[a,b], A. Laoutaris[a,b], E.P. Benis[c], **T.J.M. Zouros**[a,b], T. Kirchner[d]
J.P. Santos[e], F. Parente[e] and M. C. Martins[e]

[a]Dept. of Physics, Univ. of Crete, P.O Box 2208, GR 71003 Heraklion, Greece.

[b]Tandem Accelerator Laboratory, INPP, NCSR Demokritos, GR 15310 Ag Paraskevi, Greece.

[c]Dept. of Physics, University of Ioannina, GR 45110 Ioannina, Greece.

[d]Dept. of Physics and Astronomy, York University, Toronto, Ontario M3J 1P3, Canada.

[e]LIBPhys-UNL, Dep. Física, FCT, Univ. NOVA de Lisboa, 2829-516 Caparica, Portugal.

We investigate the production of the 1s2s2p ^{4,2}P states populated by single electron capture in 12 MeV C^{4+} + He collisions. The ^{4}P/^{2}P ratio of Auger electron yields has been found not to obey the expected spin recoupling statistics, but instead is enhanced [1, 2]. Various explanations have been proposed [1-3], but none of them can fully account for the observed enhancement. Here, we combine our recent Monte Carlo approach for simulating the projectile Auger spectrum utilizing the SIMION package [3] including the important solid angle corrections to the long lived ^{4}P line together with calculations of single electron capture into (1s2s ^{3}S)*nl* states [4] which include repopulation by radiative cascades and Auger depletion to model the experimental spectra. Preliminary results are presented in figure 1.

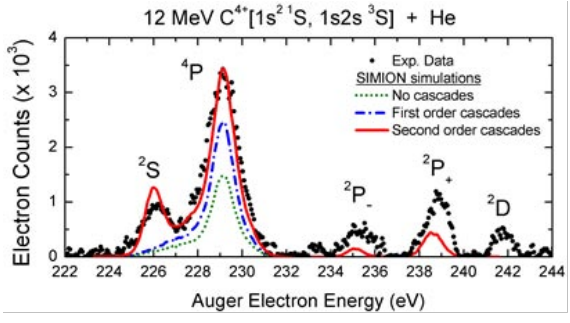

Figure 1: 1s2l2l′Auger projectile spectrum from 12 MeV C^{4+} + He collisions measured with our hemispherical analyzer. Lines: SIMION simulations including model contributions (normalized to the ^{4}P yield) are compared to the spectrum (black dots). The ^{4}P line is seen to be strongly enhanced by cascades, while the ^{2}P lines are not affected. The observed excess electron yield in the $^2P_{\pm}$ and ^{2}D states is due to Transfer-Excitation from the ground state not included in the capture calculations.

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EMISSION OF ANIONS FROM MOLECULAR SPECIES FOLLOWING CATION IMPACT

Z. Juhász[a], J.-Y. Chesnel[b], E. Lattouf[b], S. T. S. Kovács[a], E. Bene[a], P. Herczku[a], B. A. Huber[b], A. Méry[b], J.-C. Poully[b], J. Rangama[b], V. Vizcaino[b], J. A. Tanis[c] and B. Sulik[a]

[a]Institute for Nuclear Research, Hungarian Academy of Sciences, H-4001 Debrecen, Hungary
[b]Centre de Recherche sur les Ions, les Matériaux et la Photonique (CIMAP), 6 Bd Mar. Juin, F-14000 Caen, France
[c]Department of Physics, Western Michigan University, Kalamazoo, Michigan 49008 USA

It has been recently shown that besides positive ions negative ions are also ejected from gas-phase molecular species in a variety of collisions involving positive ions at a few keV impact energies [1-3]. These findings are relevant for studies of interstellar media and ionospheres, as well as for radiolysis and radiobiology since slow anions are efficient agents for charge transfer and chemical reactions.

We have observed that an H^- ion can be formed from an OH^+ ion when the H center is removed by collision on an Ar target atom [1-2]. The angular distribution of the so-created H^- ions has been found to be proportional to the one calculated for H scattering on the target atom. A similar result is found for the emitted H^+ ions. Also, the kinetic energy distribution of the H^+ fragments shows strong similarities with that of the ejected H^- ions. These findings indicate that the final charge state distribution of the emitted H centers does not depend on how closely the atomic centers approach each other during the collision. Rather, it seems to follow simple statistical laws. A statistical model will be presented.

Also, in 6.6-keV $^{16}O^+ + H_2O$ collisions, emission of both H^- and heavier (O^- and OH^-) anions has been observed, with a larger yield for H^- [3]. The experimental setup allowed separate identification of the anions formed in collisions with many-body dynamics from those created in hard, binary collisions. The spectra show that anion emission is concentrated at low emission energies. At emission angles below 90°, pronounced peaks are observed at higher energies. These peaks result from recoil anions formed in hard collisions occurring at small impact parameters. The spectral features are well reproduced by model calculations that include kinetic energy release due to electronic excitation and ionization processes. This indicates that these processes play a decisive role in H^- formation.

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EVALUATION OF $1s2l2l'$ $^4P/^2P$, $^2P_+/^2P_-$, $^2D/^2P$ RATIOS FROM COLLISIONS OF MIXED STATE ($1s^2\ ^1S, 1s2s\ ^3S$) He-LIKE ION BEAMS WITH H_2 AND He TARGETS

E. P. Benis[a], **I. Madesis**[b,c] and T. J. M. Zouros[b,c]

[a]Dept. of Physics, University of Ioannina, GR 45110 Ioannina, Greece.

[b]Dept. of Physics, Univ. of Crete, P.O Box 2208, GR 71003 Heraklion, Greece.

[c]Tandem Accelerator Laboratory, INPP, NCSR Demokritos, GR 15310 Ag Paraskevi, Greece.

New results are presented on the ratio R of $^4P/^2P$ populations of Li-like 1s2s2p quartet and doublet P states formed in energetic ion-atom collisions by single 2p electron transfer to the metastable 1s2s ^3S component of the He-like ion beam. Spin statistics predict a value of R=2 mostly in disagreement with reported measurements of R=3-10 [1-2]. A new technique is used in the evaluation of R which avoids the need for the normalization of the measured cross sections and allows for the determination of the separate contributions of ground- and metastable-state beam components to the measured spectra. Applying our technique to older zero-degree Auger projectile spectra from 4.5 MeV B^{3+} [3] and 25.3 MeV F^{7+} [4] mixed state ($1s^2\ ^1S$, 1s2s ^3S) ion collisions with H_2 targets, we report values of R=3.5±0.4 for boron and R=1.8±0.3 for fluorine. In addition, also reported for the first time are the ratios of $^2D/^2P$ and $^2P_+/^2P_-$ populations from either the metastable and/or ground state beam component, which provide a sensitive indicator of the importance of other active processes that can affect the overall intensities of the measured Auger spectra. They are evaluated in the same technique and compared to previously reported results for carbon collisions on helium [1].

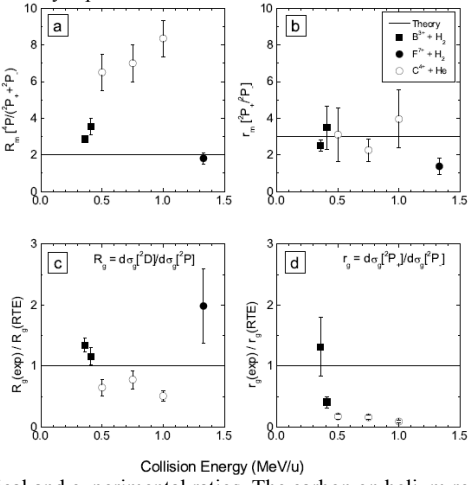

Figure 1: Theoretical and experimental ratios. The carbon on helium results are from [1].

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ELECTRON EMISSION IN IONIZATION OF BROMOURACIL IN COLLISIONS WITH FAST C^{6+} IONS

M.Roy Chowdhury[a,1], D. Misra[a] , C. Champion[b], L. C. Tribedi[a,2]

[a]Tata Institute of Fundamental Research, Mumbai 400005, India
[b]Universite Bordeaux 1, CENBG, Chemin du Solarium, 33175, Gradignan, France

The low energy secondary electrons, produced around the track of swift heavy ions interacting with biomolecular systems, are the primary sources for the damage of DNA/RNA molecules. The efficiency of damage thus depends on the intensity of the secondary electrons produced**.** In the context of tumor cells exposed to high energy ion beams, radio-sensitizers are well known reagents used to increase the killing efficiency of malignant cells. The effect of inserting a nanoparticle (Au, Pt, Gd) in the DNA and subsequently studying the ionization process induced by heavy ions is already under investigation [1,2]. Further, the radiosensitizing properties of halouracils is a subject of theoretical and experimental investigations. Several work have been carried out with halouracils, particularly in studying the fragment products [3]. However, a quantitative study of the enhancement of the electron intensity due to the presence of a nanoparticle in DNA base molecule is missing. In addition to our earlier investigations with uracil [4-6], here we present the double differential cross section (DDCS) of the secondary electrons in ionization of bromouracil by 42 MeV bare C ions. The same has been compared with existing data of uracil [4], to ensure the increase in cross section due to the substitution of H by a Br atom in uracil. The absolute DDCS measurement of halouracils is the first of its kind. The experiment have been performed with a vapourjet target of bromouracil. The DDCS measurements have been performed with a hemispherical electrostatic analyzer with a CEM to detect the electrons. The absolute DDCS spectra of bromouracil, for each angle have been compared with the corresponding existing data of uracil. The DDCS in case of bromouracil is substantially higher compared to that for the uracil in the low energy part of the spectrum. The total cross section has also been determined. The data have also been compared with the prediction of a theoretical model based on CB1 model. Details of the energy and angular distributions will also be presented.

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e-mail : [1]madhusree.roy@tifr.res.in
[2]lokesh@tifr.res.in

DOUBLE-ELECTRON CAPTURE BY HIGHLY CHARGED IONS ISOLATED AT VERY LOW ENERGIES: COMPARISON OF OBSERVATION AND THEORY

J.M. Dreiling[a], S.F. Hoogerheide[a], A.S. Naing[b], J.N. Tan[a], D.R. Schultz[c], and Yu. Ralchenko[a]

[a]National Institute of Standards and Technology (NIST), 100 Bureau Drive, Gaithersburg, Maryland 20899, USA

[b]University of Delaware, Department of Physics and Astronomy, 217 Sharp Laboratory, Newark, Delaware 19716, USA

[c]University of North Texas, Department of Physics, Denton, Texas 76203, USA

We report on a series of experiments which reveal both single- and double-electron capture by highly charged ions confined at energies less than 10 eV in a compact Penning trap, comparing the new results with available models and predictions. A better understanding of electron capture processes by highly charged ions in collisions with neutral atoms, also known as charge exchange, is important in many areas including the study of comets [1], controlled fusion energy [2], and ongoing experiments to form one-electron ions in Rydberg states [3]. However, few studies have been performed at the very low energies (velocities $\ll 0.01$ atomic units) of interest in recently proposed applications.

The electron beam ion trap (EBIT) at NIST is used to produce highly charged ions, which can be extracted from the EBIT as an ion bunch. A specific charge state in the ion bunch is separated and captured in a unitary Penning trap [4]. Here, the isolated ions are held for varying lengths of time at thermal energies less than 10 eV. During their dwell time in the trap, the ions interact with controlled amounts of injected background gases from which they can capture electrons. The ions are then ejected from the trap to a time-of-flight (TOF) detector to quantify the evolution of the population for each charge state.

A systematic study was performed using Ne^{10+} and Kr^{17+} ion projectiles. Measurements were completed for a variety of background gases injected into the Penning trap region over a range of pressures. By fitting the observed TOF peaks as a function of time to a set of linear differential equations, the rates of electron capture are determined. Interesting differences are found when we compare the observed single- and double-electron capture rates with available models including the classical over-barrier model [5]. Progress in providing a more detailed collisional-radiative treatment will also be presented.

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RESONANT EXCITATION OF FE^{14+} OBSERVED WITH A COMPACT ELECTRON BEAM ION TRAP

Takashi Tsuda[a], Erina Shimizu[a], Safdar Ali[a], Hiroyuki A. Sakaue[b], Daiji Kato[b,c], Izumi Murakami[b,c], Hirohisa Hara[d,e], Tetsuya Watanabe[d,e], and Nobuyuki Nakamura[a]

[a]Inst. for Laser Science, The Univ. of Electro-Communications, Tokyo 182-8585, Japan

[b]National Institute for Fusion Science, Gifu 509-5292, Japan

[c]Department of Fusion Science, SOKENDAI, Gifu 509-5292, Japan

[d]National Astronomical Observatory of Japan, Tokyo 181-8588, Japan

[e]Department of Astronomical Science, SOKENDAI, Tokyo 181-8588, Japan

Spectra of highly charged Fe ions in the extreme ultraviolet (EUV) range are important for the spectroscopic diagnostics of astrophysical hot plasmas such as solar corona [1]. In such diagnostics, plasma parameters, such as electron temperature and density, are determined through the comparison between the observed spectra and theoretical spectra calculated with a collisional radiative (CR) model. For accurate diagnostics, the model spectra should thus be examined by laboratory benchmark spectra obtained with a well-defined condition. We have been studying EUV spectra of highly charged Fe ions with an electron beam ion trap (EBIT), which can realize well-defined plasma consisting of a quasi-monoenergetic electron beam and trapped ions with a narrow charge state distribution. In the previous studies [2-3], the dependence on the electron density was the main subject of interest. On the other hand in the present paper, the dependence on the electron energy is studied.

Experiment was performed with a compact EBIT, called CoBIT [4]. Highly charged Fe ions were produced by injecting a ferrocene gas into CoBIT with an electron beam energy of 500 eV. After a "cooking" time of 1600 ms, the electron energy was swept between 400 and 500 eV for 10 ms (probing time), and kept at 500 eV for 10 ms (keeping time) for preserving the charge distribution. A preliminary result is shown in Fig. 1, where the intensity enhancement due to resonant excitation is confirmed. Comparison between the experimental results and theoretical resonant emission cross sections is given.

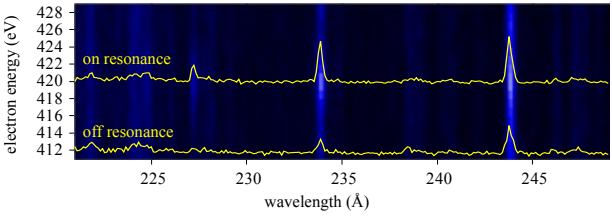

Figure 1: Electron energy dependence of Fe XV $3s3p - 3s3d$ lines observed with CoBIT: $^3P_1$–$^3D_2$ (227 Å), $^3P_2$–$^3D_3$ (234 Å), and $^1P_1$–$^1D_2$ (244 Å).

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CAPTURE OF ATOMIC ELECTRON INTO LOW-ENERGY CONTINUUM STATES OF HIGHLY CHARGED ION IN RELATIVISTIC COLLISIONS

Oleg Yu. Andreev[a], Alexander B. Voitkiv[b]

[a]Department of Physics, St. Petersburg State University,
7/9 Universitetskaya nab., St. Petersburg, 199034, Russia

[b]Institut für Theoretische Physik I, Heinrich-Heine-Universität Düsseldorf,
Universitätsstrasse 1, Düsseldorf, D-40225, Germany

In relativistic ion-atom collisions a variety of basic elementary processes may occurs. Among them one of the most interesting is capture of an atomic electron by the incident ion [1-2]. The capture has two main channels: radiative and non-radiative.

Radiative electron capture proceeds via emission of a photon. In collisions between a highly charged ion and a light atom this process is basically reduced to radiative recombination of a (quasi-) free atomic electron with the ion. In contrast, non-radiative capture cannot be reduced to a two-body problem since radiationless recombination of a free electron with an ion is not possible due to the energy-momentum constraints. As a result, this process is more difficult for a theoretical description. Very recently an experiment was performed at the GSI (Darmstadt, Germany) in which relativistic Be-like uranium projectile-ions were colliding with N2 targets [3-5]. The focus of this experiment was in the investigation of the formation of unbound electrons which move after the collision together with the ion being in the low-energy continuum states of the ion (so called cusp electrons). Such electrons may appear both due to the loss of an initially bound electron by the projectile-ion in the collision with the target (electron loss cusp ELC) and capture of an electron initially bound in the target by the projectile (electron capture cusp ECC).

At an impact energy of 90 MeV/u studied in the experiment there are two main mechanisms resulting in the formation of the ECC: radiative and non-radiative electron capture to the low-energy states in the field of the ion. The theoretical description of the radiative part of the ECC can be based on the analogy of this process to bremsstrahlung [3]. The fully relativistic calculation of the non-radiative channel of electron capture to the projectile continuum is, to our knowledge, still missing [5]. Moreover, at higher impact energies there appears one more mechanism for the formation of the ECC. According to it the electron capture cusp is formed via electron-positron pair production. One may expect that the importance of this channel increases with increasing the impact energy and that it will fully dominate the ECC at very high impact energies. We present a theoretical study of the ECC mechanisms of production of the cusp electrons in relativistic ion-atom collision

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ADVENT OF ION-ATOM COLLISION EXPERIMENTS AT LOW ENERGY ION BEAM FACILITY OF IUAC, NEW DELHI.

Punita Verma[a], Sarvesh Kumar[a,b], Deepak Kumar Swami[b], Gaurav Sharma[c].

[b]Department of Physics, Kalindi College, University of Delhi, New Delhi-110008, India
[b]Inter University Accelerator Centre, Aruna Asaf Ali Marg, New Delhi-110067, India
[c]Delhi Technological University, Bawana Road, New Delhi-110042, India

Investigation of ion-atom collision phenomena have been initiated at the recently developed experimental set up for this purpose at the 75° beam line of Low energy Ion beam Facility (LEIBF) at Inter University accelerator Centre (IUAC), New Delhi. The LEIBF facility with its 10GHz ECR-ion source provides a possibility of such experiments from few keV to few hundred keV's of beam energy and few hundred nA current. The atomic collisions at low energies find wide ranging applications in astrophysical plasmas, in planetary atmospheres and they play a major role in energy transfer as well as charge exchange processes.

Apart from regular cross section measurements several phenomena such as quasimolecular phenomena [1] can be investigated at these energies. Xe^{q+} ions ($8<q<13$) of 2 to 3 MeV were bombarded on solid state targets of Au and Zr having a thickness of 640 μg/cm^2 and 250 μg /cm^2 respectively (latter on a carbon backing of 40 μg/cm^2). Projectile as well as target X-rays were observed using Ketek's SDD and a Canberra LeGe x-ray detector. Fig.1 shows the energy calibrated spectra of the two collison systems investigated for an energy of 3 MeV and a charge state of 12+ of Xe. Effects of energy and charge state variation were investigated. Detailed inferences will be discussed.

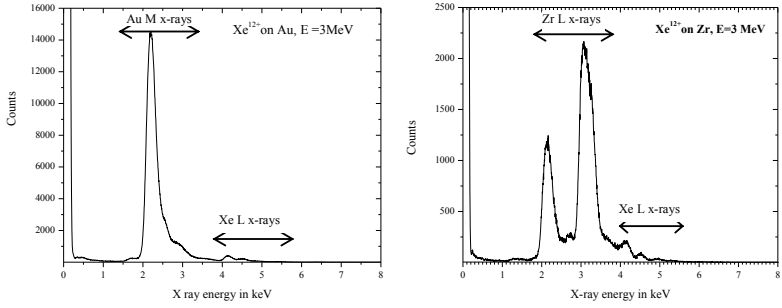

Figure 1: Spectra of 3 MeV Xe^{12+} on Au and Zr targets.

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INVESTIGATION OF FRAGMENTATION PATHWAYS IN HETEROCYCLIC NEUTRAL, SINGLY- AND DOUBLY-CHARGED FURAN MOLECULE

E. Erdmann[a], M. Łabuda[a], S. Díaz-Tendero[b], N.F. Aguirre[b], M. Alcamí[b]

[a]Gdańsk University of Technology, Narutowicza 11/12 80-233 Gdańsk, Poland
[b]Departamento de Química ,Universidad Autónoma de Madrid, 28049, Madrid, Spain

Theoretical studies of fragmentation processes induced by ion-molecule interactions are complex due to insufficient description of the fragmentation dynamics. Therefore, we have adopted three different state-of-the-art quantum chemistry methodologies in order to provide complementary information on the fragmentation process. Using those methods, we examined in detail fragmentation pathways of neutral as well as singly- and doubly- charged furan (C_4H_4O) molecule in the gas phase, a heterocyclic compound which can serve as an analogue of the deoxyribose sugar in the DNA.

Firstly, we applied Atom-Centered Density Matrix Propagation method [1] for the internal energy varying from 5 to 30 eV deposited to the system. An extensive statistical analysis of the results led to the conclusion that the overall dynamics of the fragmentation is dominated by unimolecular opening of the furan ring and hydrogen transfer. The most frequent channel involves production of acetylene by direct C-C bond cleavage. For the furan$^+$ the most abundant channels include production of formyl radical (CHO) and cyclopropenyl cation ($C_3H_3^+$) from C-C bond cleavages of the furan ring and C_3H_4O cation with H atom out of dehydrogenation process. Doubly-ionized furan fragmentation follows a completely different dissociation path. One channel can be clearly distinguished with very high occurrence probability (67% for the energy of 14 eV). This channel includes production of formyl cation (CHO^+) and cyclopropenyl cation ($C_3H_3^+$). Moreover, subsequent fragmentation and hydrogen loss appear frequently in the dynamics. Secondly, in order to gain complementary interpretation of the fragmentation mechanism, we performed calculations of minima and transition states on the potential energy surface of the most frequent channels appearing in the dynamical analysis. Finally, we used a statistical Microcanonical Metropolis Monte-Carlo (M_3C) method [2] which was applied to evaluate the main fragmentation channels as a function of the excitation energy. Our preliminary results compared with the experimental observations [3,4] show that M_3C method is a promising theoretical tool for reproducing the mass spectrum of the studied molecule.

Acknowledgements: Financial support by COST Action CM1204 and Erasmus Plus Programme (M.Ł) are gratefully acknowledged. The calculations have been performed at Centro de Computación Científica in Madrid and Academic Computer Centre in Gdańsk.

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RESONANCE PHENOMENA IN HEAVY He-Be-like MULTICHARGED IONS COLLISIONS

V.V. Buyadzhi[a], A.V. Glushkov[a], A.A.Kuznetsova[a], O.Yu. Khetselius[a], V.F. Mansarliysky[a]

[a]Odessa State University-OSENU, P.O.Box 24a, Odessa-9, 65009, Ukraine

An existence of a narrow e+ line in the positron spectra obtained from heavy nuclei (ions) collisions near the Coulomb barrier (see, e.g.,[1,2]). The consistent quantitative theory of these phenomena is of a great interest. In our paper a consistent unified operator perturbation theory formalism and QED approach [3-5] are used for studying the electron-positron pair production process in the heavy and superheavy multicharged ions collisions. The resonance phenomena in the nuclear system lead to structurization of the positron spectrum produced. The positron spectrum narrow peaks as a spectrum of the resonance states of compound super heavy nucleus are treated. To calculate the electron-positron pair production cross-section we used the modified versions of the relativistic energy approach, based on the S-matrix Gell-Mann and Low formalism [3,4]. The nuclear and electron subsystems are considered as two parts of the complicated system, interacting with each other through the model potential. The nuclear system dynamics is treated within the Dirac equation with an effective potential [5]. All the spontaneous decay or the new particle (particles) production processes are excluded in the 0^{th} order. We take into account for the corrections of the perturbation theory, which are corresponding to an effective attraction between the nuclear fragments because of the bounding action of electrons. The calculation (on the basis of the Superatom-ISAN PC complex [3,6]) results for cross-sections at different collision energies (non-resonant energies and resonant ones) for the colliding multicharged ions $^{232}Th^{86+}$-$^{232}Th^{88+}$and $^{238}U^{88+}$-$^{238}U^{90+}$ are listed. Calculation with the two-pocket nuclear potential is carried out. It led to principally the same physical picture as the calculation with the one-pocket one [6,7], besides an appearance of some new peaks. An additional electron potential has shifted the scattering states resonances in comparison with collision states ones on the values of order 0,8-1,1MeV. In result the additional irregularities in the positron spectra are produced due to this interaction.

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ASYMMETRY IN EMISSION OF C^+ AND O^+ FRAGMENTS IN DOUBLE ELECTRON CAPTURE BY HE^{2+} FROM CO

Y. Gao[a,b], **X. Ma**[a], S. F. Zhang[a], X. L. Zhu[a], S. C. Yan[a], D. L. Guo[a], W. T. Feng[a], R. T. Zhang[a], B. Hai[a], M. Zhang[a,b], H. B. Wang[a,b], Z. K. Huang[a,b], D. M. Zhao[a]

[a]Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[b]University of Chinese Academy of Sciences, Beijing 100049, China

Various processes occurring in collisions of ions with molecules have been attracting much attention [1]. Of particular interests in such collisions are interference effects caused by coherent scattering/interaction of the the ion on more than one atomic center [2-6]. The studies of ion-molecule collisions have been mainly restricted to homo-diatomic molecule (see [6] and references therein). In the present work, we study double electron capture in collisions between 135 keV/u He^{2+} ions and CO molecules which are accompanied by breakup of CO into C^+ and O^+ fragments. The Fig.1 shows the distribution of the orientation angle θ of CO molecular axis in kinetic energy release (KER) range of 8.5-9.1 eV.

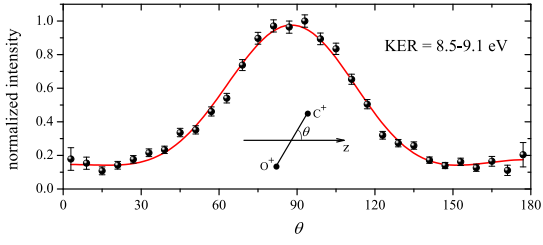

Figure 1: Orientation distributions of CO molecular axis, i.e., $\frac{d\sigma}{dcos\theta}$, when KER = 8.5-9.1 eV. The distribution is normalized to its maximum. The solid curve is our fitted result.

In the distribution, it is found that this process favors emission of C^+ into the forward direction (the direction of the projectile motion, i.e., z direction), whereas the O^+ is emitted mainly backwards. We propose an explanation that this asymmetric emission pattern is caused by interference between projectile waves scattering by different atomic centers of the CO molecule.

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INTERACTION OF HEAVY CHARGED IONS WITH HIGHLY ORIENTED PYROLYTIC GRAPHITE

E. E. Donets, E. D. Donets, A. Ramsdorf, **A. Boytsov**, V. Shutov,

Joint Institute for Nuclear Research, Joliot-Curie, 6, Dubna, Moscow region, Russia

Investigation of surface modification on highly oriented pyrolytic graphite was started in JINR. Samples of highly oriented pyrolytic graphite were bombarded by highly charge ions of Xe^{+41} and Tm^{+50} with kinetic energy (near 100 keV). Total amount of ions for Xe is 10^{10} particles and for Tm is 2.7^{10} particles on 1 cm^2. Pictures of surface were obtained by scanning tunneling microscope (STM) .

DISCHARGING PROPERTIES OF NANOCAPILLARIES PROBED BY ION TRANSMISSION

Z. Juhász[a], P. Herczku[a], S. T. S. Kovács[a], R. Rácz[a], S. Biri[a], B. Sulik[a] and N. Stolterfoht[b]

[a]Institute for Nuclear Research (Atomki), Hungarian Academy of Sciences, Bem ter 18/c, H-4026 Debrecen Hungary

[b] Helmholtz-Zentrum Berlin für Materialien und Energie, Glienickerstr. 100, D-14109 Berlin, Germany

Guiding of highly charged ions through nanocapillaries in different type of insulating materials has been intensively studied in the last decade [1-4]. The process is governed by the self-organizing electrostatic charging up of the inner walls. The incident ions collide with the surface of the capillary, deposit their charge and form a repulsive electrostatic field. A significant fraction of the subsequently incoming ions are guided through the capillary without colliding at the walls.

In most cases, the transmission of incident ions monotonously increases until a stable transmission is reached. Sometimes, the transmission become partially or completely blocked [5,6]. The development of regular or blocked transmission strongly depends on the (surface) conductivity of the insulating material. The estimated electric field strength in the capillaries is rather high and falls in the non-linear conductivity regime. The non-linear conductivity of insulators is described by the Frenkel-Poole equation [7].

We measured the transmission of 3-keV $^{22}Ne^{7+}$ ions through nanocapillaries in a PET foil. After charging up of the sample, we switched off the incident beam and the discharging dynamics of the capillaries were studied. During the discharging process the time development of accumulated charge inside the capillaries is determined only by the discharge current. From time to time, the transmission rate was tested by short pulses during a long period of several hours. The test pulses were repeated for a few times shortly one after the other in order to test their recharging effects on the transmission. The recharging was found to be negligible. The transmission rate monotonically decreased with time. In the beginning the transmission dropped quickly but later the decay slowed down significantly. In a linear-logarithmic scale the data deviates from a straight line, which demonstrates that the decay is not exponential as one could expect in the case of linear conductivity. The experimental data can well be described by a model calculation involving a Frenkel-Poole type conductivity.

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LOCAL TRANSFORMATION OF AMORPHOUS ALLOY SURFACE AND THIN FILM UNDER IMPACT OF SLOW HEAVY ION

Romuald Brzozowski[ab] and **Marek Moneta**[a]

[a] Katedra Fizyki Ciała Stałego, Zakład Fizyki Powierzchni
[b] Katedra Fizyki Jądrowej i Bezpieczeństwa Radiacyjnego
Uniwersytet Łódzki, Pomorska 149, 90-236 Łódź, Poland

Amorphous alloys, far from thermodynamic equilibrium, experience stress relaxation and partial crystallization if some initialization energy is delivered. These transformations under a single ion impact is limited by thresholds, either in the potential energy, ~10keV deposited by highly charged ion or in electronic energy loss, ~5keV/nm transferred by swift heavy ion. This energy is much faster deposited to the material through electronic excitations (10^{-15}s), than subsequently transferred to the lattice through electron-phonon coupling (10^{-13}s). The pulse of energy and shock wave can cause rearrangement of target atoms and relaxation of internal stress. The process is governed by mobility of electrons, which may be reduced in amorphous alloys, compared to metals, due to some clustering.
In this work thin foils of amorphous alloys VP800 ($Fe_{73}Si_{16}B_7Cu_1Nb_3$) and VV8025X ($Fe_4Co_{66}B_{14}Cu_1Nb_2Mo_1$) maintained at the onset point temperature for primary crystallization were irradiated with slow heavy ions at fluence ranging from 10^{10} to 10^{13} ion/cm^2. The preferential surface modification during ion implantation-sputtering were analyzed with SRIM and PIXE [1]. This change of surface composition influences on parallel running local structural modification of the surface due to delivery of crystallization energy to electron-ion system. With the use of conversion electron Mossbauer spectroscopy (CEMS) Fe and Fe(Si) clusters accompanied by Fe_3Si and even $Fe_{23}B_6$ nanocrystals were found in the films irradiated at lower fluence, whereas rather amorphous structure was found in surfaces more heavily implanted [2].

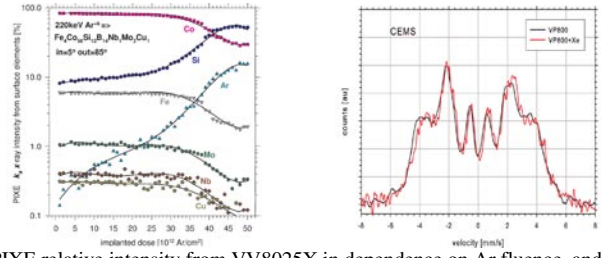

Figure a) PIXE relative intensity from VV8025X in dependence on Ar fluence and b) CEMS velocity distribution from pristine VP800 and from VP800 irradiated with 150 keV Xe ions.

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GRAPHENE DEFECTS INDUCED BY ION BEAM

Grzegorz Gawlik[a], Paweł Ciepielewski[a], Jacek Jagielski[a]

[a]Institute of Electronic Materials Technology, Wolczynska 133, 01-919 Warszawa, Poland
(12-point, centered)

Graphene is a unique one atom thick carbon layer with hexagonal atomic structure. The CVD graphene grown on Cu foil and then transferred onto a glass substrate was used in this work. The graphene layer was irradiated with helium ions having the energy of 100keV, atomic nitrogen N^+ and nitrogen particle N_2^+ ions with various energies (50 keV and 100keV), argon ions having 37 keV and 100 keV krypton ions at energy 100keV. and C_6^+ ions at energy 100keV. A method of graphene defects identification by using Raman spectroscopy proposed in [1] was applied to identify defect diameter and number of defects induced by ion taking into account proportions between so called lines D and G of Raman spectra.

It was found that defect formation efficiency increases with increasing of ion mass and with decreasing of ion energy. SRIM [2] simulation suggests that the efficiency of defect generation by a single atomic ion is proportional to the nuclear stopping power. For C_6^+ ions the defect efficiency was found very close to 1 defect per 1 ion what is essentially higher than for six carbon ions of 1/6 energy each. Application of graphene layer on the solid target surface and characterization by Raman spectroscopy made possible estimation of defect generation by ion in the first atomic layer of the solid. There is a unique opportunity to investigate of the interaction with more complex ions of chemically bonded particles before its decomposition in a solid target.

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MODIFICATION OF TITANIUM AND GOLD NANOLAYERS BY SLOW Xe^{q+} IONS

I. Stabrawa[a], D. Banaś[a,b], A. Kubala-Kukuś[a,b], Ł. Jabłoński[a], P. Jagodziński[c], D. Sobota[a], M. Pajek[a], J. Braziewicz[a,b], J. Czub[a], K. Skrzypiec[d], E. Mendyk[d], M. Teodorczyk[e]

[a]Institute of Physics, Jan Kochanowski University, Świętokrzyska 15, 25-406 Kielce, Poland
[b]Holycross Cancer Center, Artwińskiego 3, 25-734 Kielce, Poland
[c]Departament of Physics, University of Technology, Al. Tysiąclecia 7, 25-314 Kielce, Poland
[d]Departament of Chemistry, Maria Curie-Skłodowska University,
Plac M. Curie-Skłodowskiej 3, 20-031 Lublin, Poland
[e]Institute of Electronic Materials Technology, Wólczyńska 133, 01-919 Warszawa

Modifications of metallic nanolayers by an impact of slow highly charged ions (HCI) are of great importance for developing new technologies for fabrication of smaller functional electronics systems with nanometer dimensions. The interaction of slow highly charged ions with a surface is dominated by a large amount of potential Coulomb energy of a projectile being deposited at the area of a size atom. This leads to new features observed in irradiation of surfaces by HCI such as blisters, hillocks, craters or pits [1], which strongly depend both on the charge state and energy of HCIs and the structure of a surface [2].

In this work we present results of the studies of modification of gold and titanium nanolayers by highly charged Xe^{q+} ions delivered by the Kielce EBIS-A facility [3]. In the experiment highly charged Xe^{q+} ions with q=33-36 and energies 3 keV×q produced at the EBIS-A ion source, after extraction and charge-state separation in the double focusing magnet, were interacting with gold and titanium nanolayers deposited on quartz wafers. The nanolayers of a thickness 50 nm (gold) and 75 nm (titanium) were prepared by sputtering of studied metals on polished crystalline quartz SiO_2 (100).

Figure 1: Example of topographic contact mode AFM images of a gold (50nm) surfaces after irradiation with 100 keV Xe^{35+} ions.

After irradiations with fluence of HCI ions of about 10^{15} ions/cm^2 the studied samples were examined with atomic force microscopy (AFM) technique. Well defined hillocks were observed on, both, gold and titanium surfaces. The number of hillocks on a 500 nm × 500 nm AFM studied area turned out to be in good agreement with the applied fluence of the ions with estimated hillock formation probability close to one.

Acknowledgements
The equipment was purchased thanks to financial support of the European Regional Development programs (WNP-POIG.02.02.00-023/08 and POPW.01.01.00-26-013/09-04)

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SIMULATION STUDY FOR THE EFFECT OF TRACK POTENTIALS ON THE MOVEMENT OF SECONDARY ELECTRONS DUE TO HIGHLY CHARGED ION IRRADIATION

Kengo Moribayashi[a]

[a]National Institutes for Quantum and Radiological Science and Technology, 8-1-7, Umemidai, Kizugawa-city, 619-0215, Japan

For the study of swift highly charged ions, secondary electron produced from these ion impact ionization processes play a very important role. For example, energy transfer from secondary electrons to the target creates radial dose (D_r) distribution that are employed to estimate the cell survival rate in the treatment planning system for heavy particle cancer therapy. Here, the radial dose is the dose as a function of distances (r) from the incident ion path.

For ion-solid interaction, it is well known that positive track potential traps some secondary electrons near the incident ion path [1]. Here, the track potential is formed from the composite electric field of ions which lose bound electrons due to the incident ion impact. However, there were no good simulation models to study this track potential for insulator targets before our studies [2, 3] as far as we know. Figure1 shows N_{sf}/N_{sn} obtained from our simulations vs. ion impact ionization cross sections (σ_i), where N_{sf} (N_{sn}) is the number of secondary electrons, which reach the region far from the incident ion path, obtained from including (excluding) the track potential. In this figure, we also show values that fit experimental data [1]. Though we fit experiment data a little roughly and different target materials are employed between our simulations and the experiment [1], our results agrees well with the experimental ones. Figure 2 shows D_r obtained from including and excluding the track potentials due to the carbon ion irradiation [3]. Near the incident ion path that is very important region to estimate the cell survival, it is indicated that the track potential contributes significantly to D_r. Our simulation model may be useful for the treatment planning system for heavy particle cancer therapy.

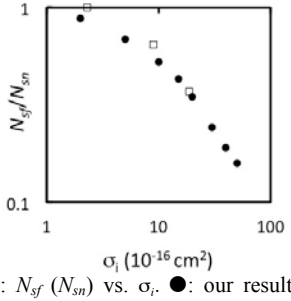

Figure 1: N_{sf} (N_{sn}) vs. σ_i. ●: our results, □: values that fit experimental data [1].

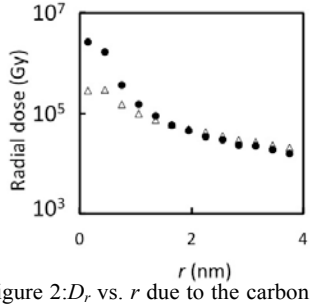

Figure 2:D_r vs. r due to the carbon ion irradiation with 5 MeV/u: the cases including (●) and excluding (△) track potentials.

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ENERGY LOSS OF H AND HE IONS IN ZINC OXIDE, THE CHARGE STATE EFFECT

C. C. Montanari[a], D. Mitnik[a] , J. C. Aguiar[b], R. C. Fadanelli[c], C. D. Nascimento[c], M. Behar[e], A. Turos[d], E. Guziewicz[e]

[a]Instituto de Astronomía y Física del Espacio, CONICET and Universidad de Buenos Aires, Buenos Aires, Argentina

[b]Autoridad Regulatoria Nuclear, Buenos Aires, Argentina

[c]Laboratorio de Implantação Iônica, Instituto de Física, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil

[d] Institute of Electronic Materials Technology, Warsaw, Poland; National Centre for Nuclear Research, Otwock, Poland

[e] Institute of Physics, Polish Academy of Sciences, Warsaw, Poland

We present a theoretical and experimental research on the the energy loss (stopping power and straggling) of H and He ions in zinc oxide [1]. The measurements were carried out at the facility of the Instituto de Física da Universidade Federal do Rio Grande do Sul, in Brazil, using the Rutherford Backscattering technique for (300-2000) keV H ions and (300-5000) keV He ions. The theoretical research was encouraged considering the molecular description of ZnO as crystal solid using the density functional theory. The energy loss calculations for H and He ions with different charge states were performed with the shelwise local plasma approximation (SLPA). The equilibrium charge state of He inside ZnO is analyzed based on the present stopping measurements, and a semiempirical charge state distribution is proposed.

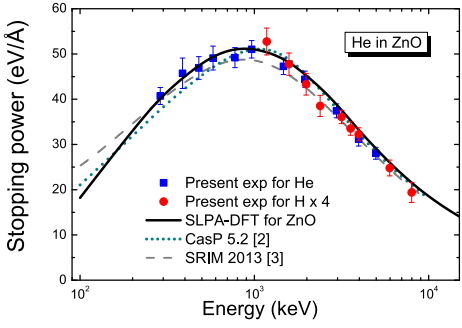

Figure 1: Stopping power of ZnO for He. Present calculations are based on the SLPA, using DFT for the molecular wave functions, and an empirical fitting for the mean charge state of He inside ZnO.

Our experimental and theoretical values show good agreement for both the stopping and the straggling, with the latter being highly sensitive to the homogeneity of the foil. We also compare the present stopping data with CasP5.2 [2] and with SRIM2013 [3] values.

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LASER-PRODUCED PLASMA EMISSION SPECTROSCOPY OF MEDIUM TO HIGH-Z ELEMENTS AND ABSORPTION SPECTROSCOPY IN THE EUV/ SOFT X-RAY SPECTRAL REGION

Elaine Long[a], Chihiro Suzuki[b], John Sheil[a], Elgiva White[a], Ragava Lokasani[a], Bowen Li[a], Robert Stefanuik[a], Paul Sheridan[a], Patrick Hayden[c], Emma Sokell[a], Padraig Dunne[a], Fergal O'Reilly[a] & Gerry O'Sullivan[a]

[a]UCD School of Physics, University College Dublin, Belfield, Dublin 4, Ireland
[b]National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan
[c]Dublin City University, Ireland

Much effort has gone into the development of laser-produced plasmas (LPPs) as sources of radiation in the extreme ultraviolet (EUV)/ soft X-ray spectral region with particular interest in the "water window" region (2.3 to 4.4 nm) and at 6.X nm [1,2]. Sources in the "water window" region of the spectrum enable high-contrast imaging of biological tissue due to the strong absorption by carbon and the low absorption by oxygen [1] in the region. The development of 6.X-nm BEUV (beyond extreme ultraviolet) lithography [2] and metrology tools require a high-brightness source at 6.X nm and multilayer mirrors with a high throughput at this wavelength (e.g. LaN/B and LaN⁄B4C) [3].

In this study, LPPs were formed on a range of target elements (Z = 12 to 68). Time-integrated spectra were recorded for several elemental targets using Nd:YAG lasers with wavelengths of 1064 nm and pulse durations of 180 ps and 8 ns at a variety of laser power densities. Emission spectra were recorded and spectral analysis was carried out with the aid of Hartree-Fock with configuration interaction calculations using the Cowan suite of codes [4].

The dual laser plasma (DLP) technique was used to measure the photoabsorption spectrum of LPPs. The DLP technique involves using one plasma to generate an absorbing column of the ions of interest and probing this plasma with the quazi-continuum emitted by another plasma Parameters such as laser power density, target geometry and the time delay between pulses were varied in order to observe the affect on the photoabsorption. Cowan code calculations and time dependent local density approximation (TDLDA) calculations were used to analyse DLP absorption spectra.

The spectrometer used was a 0.25-m grazing-incidence spectrograph, which is equipped with two variable groove spacing gratings (1200 and 2400 grooves/mm), and a thermoelectrically cooled, back illuminated CCD camera with 2048 pixels in the spectral direction covering the 2 to 20-nm region.

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EFFECT OF COLD PLASMA ON THE CHARACTERISTICS OF DPPC LIPOSOMES

Heba M Fahmy[1], **Asmaa A Hassan**[1], Ghada F Abdelfatah[1], Salma Y Mohamed[1], Mohamed H Gaber[1]

[1:] Biophysics Department, Faculty of Science, Cairo University

Recent progress in atmospheric plasmas has led to the creation of cold non-thermal atmospheric plasma (CAP). CAP is an ionized gas that has tremendous applications in biomedical engineering and is used as a possible therapy in dentistry and oncology. The aim of plasma interaction with tissue is not to denature the tissue, but rather to operate below the threshold of thermal damage and to induce chemically specific response or modification. Liposomes are used as models for artificial cells. This report therefore investigates the effect of cold plasma on 2-dipalmitoyl-sn-glycero-3-phosphocholine (DPPC) liposomes prepared by thin film hydration method which are used as a model for lipid bilayer membrane. DPPC liposomes were exposed to cold plasma 2, 3 and 5 minutes, respectively. The effect of cold plasma on DPPC characterization parameters such as size, charge, FTIR absorption spectrum, UV spectrum and phase transition temperature were investigated. The present study revealed that CAP could alter the molecular structure for DPPC liposomes as depicted in the change in the FTIR absorption peaks at 3439 and 1687 cm^{-1}. In addition, CAP affected the phase transitions for the DPPC by shifting it to higher temperatures. Moreover, CAP led to the increase of DPPC liposome size. 2 min exposure to CAP resulted in rapid coagulation of liposomes as depicted from the low zeta potential value obtained. However, the UV absorption spectrum for DPPC liposomes was not altered by CAP exposure. Hence, this work highlighted that CAP may modify the physical and chemical characteristics of DPPC liposomes.

STUDIES OF GAS MIXING AND ANOMALOUS EFFECTS IN KRYPTON ECR PLASMA

Pravin Kumar, Kedar Mal and G Rodrigues

Inter University Accelerator Centre, JNU New Campus, New Delhi-110067, India

We report the charge state distributions of pure, 25% and 50% oxygen mixed krypton plasma to shed some light on the gas-mixing and anomalous effects [1, 2] in the Electron Cyclotron Resonance (ECR) plasmas. The krypton plasma was produced using a 10 GHz all- permanent-magnet ECR ion source. The intensities of highly abundant four isotopes viz. ^{82}Kr ~11.58%), ^{83}Kr (~11.49%), ^{84}Kr (~57%) and ^{86}Kr (17.3%) up to ~ +14 charge state have been measured by extracting the ions from the plasma and analysing them in mass and energy using a large acceptance analyzer-cum-switching dipole magnet. The influence of oxygen gas mixing on the isotopic krypton ion intensities is clearly evidenced beyond +9 charge state. In contraction to previous results with xenon ECR plasma [3], the charge state distribution of krypton shows isotopic anomalous effect. Surprisingly, the intensity ratio of the isotopes of quite closer natural abundance viz. ^{82}Kr, ^{86}Kr and ^{83}Kr, ^{86}Kr shows a clear signature of anomalous effect in the pure and the oxygen mixed plasma, whereas the effect is quite weak for the intensity ratio of ^{86}Kr to ^{84}Kr. The anomalous effect tends to disappear with the oxygen mixing in the plasma as shown in figure 1. The experimental results, mainly in correlation with the Landau wave damping and subsequent heating of ions in the ECR plasma, are discussed in the paper.

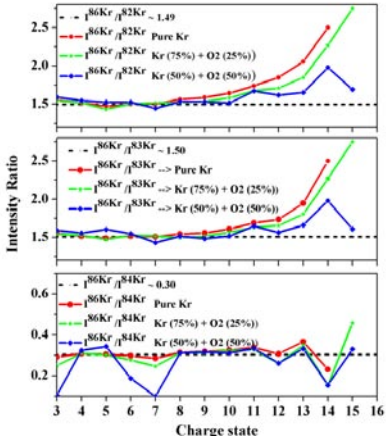

Figure 1: The influence of oxygen mixing on the isotopic anomaly in Kr ECR plasma. The black dotted line represents the expected intensity ratio as per natural abundance.

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ELECTRON-COLLISIONAL SPECTROSCOPY OF ATOMS AND MULTICHARGED IONS IN PLASMA IN DEBYE APPROXIMATION: ADVANCED ENERGY APPROACH

V.V. Buyadzhi[a], A.A. Kuznetsova[a], A.A. Svinarenko[a], T.A. Florko[a] , T.B. Tkach[a]

[a]Odessa State University-OSENU, P.O.Box 24a, Odessa-9, 65009, Ukraine

We have used generalized energy approach (EA) [1] combined with the relativistic many-body perturbation theory [2,3] to studying spectroscopic parameters (the collision cross-sections, collision strengths, oscillators strengths) of the multicharged ions in plasma with taking into account of a plasma effect in a Debye shielding approximation and inter-particle correlations within many-body perturbation theory. In fact the uniform quantum energy approach is firstly used in a theory of spectra and spectral lines shape for the multicharged ions in a plasma. By introducing the Yukawa-Debye type potential, the zeroth order electronic Hamiltonian for a N-electron multicharged ion in a plasma is given as : $H_0 = \sum_i [\alpha cp - \beta mc^2 - Z\exp(-\mu r_i)/r_i]$, where μ is connected with the plasma parameters such as the temperature T and the charge density n as follows: $\mu \sim \sqrt{e^2 n / k_B T}$. The energy shift due to the collision is arisen at first in the second PT order in the form of integral on the scattered electron energy ε_{sc} : $\mathrm{Im}\Delta E = \pi G(\varepsilon_{iv}, \varepsilon_{ie}, \varepsilon_{in}, \varepsilon_{sc})$, where G is the squared combination of the two-particle matrix elements, which contain the amplitudes $Q_\lambda^{\mathrm{Qul}}, Q_\lambda^{\mathrm{Br}}$ (the corresponding Coulomb part $exp(i|\omega|r_{12})/r_{12}$ and the Breit part $exp(i|\omega|r_{12})\alpha_1\alpha_2/r_{12}$ (α_i are the Dirac matrices) of the inter-particle interaction). We have carried out a studying the transition energies, oscillators strengths, collision cross-sections for a group of the low lying (plus Rydberg) transitions in spectra of the Be-like ions with a charge of a nucleus Z=26,36 and plasma parameters N_e= 10^{22}-10^{24}cm^{-3}, T=0.5-2keV. A part of the data has been firstly presented. To test the results of calculations we have compared the obtained data for some Be-like ions with other authors' calculations and available experimental data [2,4]. In table 1 we list the results of calculation of the energy shifts ΔE (cm^{-1}) for $2s^2$-$[2s_{1/2}2p_{1/2,3/3}]_1$ transitions for different plasma parameters. Comparison is performed with the multiconfiguration Dirac-Fock (DF) data by Li etal and Saha-Frische.

Table 1. Energy shifts ΔE (cm^{-1}) for $2s^2$-$[2s_{1/2}2p_{3/2}]_1$ transition in spectra of the Be-like Ni for different values of n_e (см$^{-3}$), T (in keV)

Z	n_e kT	10^{22} Li et al	10^{24} Li et al	10^{22} Our data	10^{24} Our data
Ni^{24+}	0.5	31.3	2639.6	33.8	2655.4
	1.0	23.4	2030.6	25.7	2046.1
	2.0	18.0	1597.1	20.1	1612.5

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EFFECT OF HOLLOW ANODE DIAMETER ON SOME CHARACTERISTICS AND PARAMETERS OF ARGON GLOW DISCHARGE PLASMA

Sh. Kh. Al-Hakary

Department of Physics, Faculty of Sciences, University of Zakho, Duhok, Iraq

An experimental investigation of hollow anode argon glow discharge plasma has been carried out at different argon gas pressure ranged from $2.2 \times 10^{-2} to\ 3mbar$ for constant discharge current. The glow discharge usually obtained by applying a high voltage between the electrodes sufficient to occurring breakdown of argon gas and sustaining the discharge. The experiments were conducted firstly to measure the breakdown voltage and Paschenc's law under the influence of hollow diameter. The hollow anodes inner diameters of values (10, 15, 20, 25, 30, 35, and 40) mm have been taken into consideration. Secondly, the study has been extended to measure some plasma parameters in the negative glow region of direct current argon glow discharge under the same conditions. Electric probes are used for measuring the temperature and density of electrons in the negative glow. Also a computer MATLAB program is used to obtain these parameters from the double probes (I_p-V_p) characteristics. It was found from the results that the measured Pashence's curve closes to the well-known theoretical Pashence's law. The voltage breakdown and its minimum breakdown voltage decrease due to increasing the diameter of cylindrical hollow. Increasing the hollow anode diameter, the Paschen's curve is widen and shifted to lower pressure. A dens and luminous intensity of plasma occurs in the negative glow region due to reduction area of hollow anode. Both electron temperature and density of electron are decreases due to increasing the diameter.

INVESTIGATIONS ON THE EFFECT OF DIFFERENT CARBON SPECIES ON THE GROWTH AND FIELD EMISSION PROPERTIES OF PLASMA GROWN GRAPHENE SHEET

Neha Gupta[a], Suresh C. Sharma[a], Ravi Gupta[a] , Rinku Sharma[a]

[a]Department of Applied Physics, Delhi Technological University, Shahbad Daulatpur, Bawana Road, Delhi 110042, India

The effect of different carbon species (i.e., hydrocarbon and fluorocarbon gases) on the plasma-assisted growth and field emission properties of the graphene sheet has been theoretically investigated. Two different plasmas constituting electrons, neutrals of CF_4/CH_4 and positively charged ions of CH_4^+/CF_4^+ are considered in the present investigation. Numerical calculations for the effect of CH_4 and CF_4 carbon species on the thickness of graphene sheet have been carried out for typically glow discharge parameters. It is found that CH_4 plasma favors the growth of thinner graphene sheets as compared to CF_4 plasma. The field emission of electrons from the graphene surface is also higher for the CH_4 plasma. Some of the results of the present investigation are in compliance with the experimental observations [1].

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THEORETICAL INVESTIGATION ON THE IMPACT OF VARIOUS PLASMAS ON THE GROWTH OF CATALYST NANOPARTICLE

Ravi Gupta[a], Surech C. Sharma[a], Neha Gupta[a], Rinku Sharma[a]

[a]Department of Applied Physics, Delhi Technological University (DTU), Shahbad Daulatpur, Bawana Road, Delhi-110042, India

The theoretical model is formulated to examine the impact of etching gases on the formation of catalyst nanoparticles from thin films. The model accounts the thermal and energy balance on the film surface placed over substrate, heat radiations, energy fluxes of various plasma species (i.e., electrons, positively charged ions, and neutrals). In our investigation, it is found that particles with lesser diameters are formed when hydrogen + nitrogen plasma is utilized than the pure hydrogen plasma. In addition, we found that number of catalyst particles per unit area increase when hydrogen + nitrogen plasma is used. The theoretical predictions are in concurrence with the experimental observations [1].

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ROLE OF MODULATED RELATIVISTIC ELECTRON BEAM ON THz RADIATION EMISSION IN A PERIODICALLY CORRUGATED PLASMA

Pratibha Malik[a], Suresh C. Sharma[a] and Rinku Sharma[a]

[a]Department of Applied Physics, Delhi Technological University (DTU),

Shahbad Daulatpur, Bawana Road, Delhi-110042, India

In this paper , we study the role of pre-modulated relativistic electron beam on tunable terahertz (THz) radiation emission in a corrugated plasma by using fluid equations model.Using this model, it is found that the wavelength of the THz radiation emission can be tuned by plasma corrugation period and beam velocity. Furthermore, the nonlinear interaction of electron beam with corrugated plasma leads to the amplification of growth rate and efficiency of the radiation wave. This amplification is being developed with the resonance between the modulated frequency of electron beam (REB) and the radiation frequency by means of Cerenkov interaction (i.e., when the frequency ω and wave number k of modulated beam are comparable to that of radiation wave (ω_o, k_{oz})). As a result, the frequency of the radiation wave increases with beam energy and modulation index Δ . Moreover, we also examined that the growth rate of the unstable THz radiation wave increases with beam density and modulation index Δ ,and scales as $\frac{1}{3}$ power of the beam density. It becomes larger as modulation index Δ approaches to unity.

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LOW FREQUENCY DUST ACOUSTIC WAVE INSTABILITIES IN PLASMA CONTAINING NEGATIVELY CHARGED DUST GRAINS

Jyotsna Sharma, Shatendra K. Sharma[1]

School of Basic & Applied Sciences KR Mangalam University Gurgaon, India
[1]University Science Instrumentation Centre, Jawaharlal Nehru University,
New Delhi -110067, India

Abstract
A low frequency electrostatic dust acoustic wave is driven to instability by an ion beam propagating through a plasma cylinder containing negatively charged dust grains via Cerenkov interaction. The unstable wave frequencies and growth rates are evaluated on the existing typical plasma parameters. It was found that the unstable wave frequencies and the growth rate both increases with the increase in relative density of negatively charged dust grains. Moreover, the growth rate of the unstable mode scales to the one-third power of the beam density.

Keywords—electrostatic dust acoustic wave, frequency, growth rates, unstable wave.

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ESTABLISHING NONLINEARITY THRESHOLDS WITH ULTRAINTENSE X-RAY PULSES

Jakub Szlachetko[a]

[a]Institute of Physics, Jan Kochanowski University, Świętokrzyska 15, 25-406 Kielce, Poland

X-rays have long been used to explore the electronic and structural properties of all forms of matter, using sources as varied as X-ray tubes to accelerator-based storage rings. X-ray methods have evolved over decades to become specialized tools for a broad range of investigations, with techniques ranging from X-ray scattering through X-ray spectroscopy to X-ray tomography. In general these methods all rely on X-ray measurements that depend linearly on the number of incident X-ray photons. With the advent of X-ray free electron lasers (XFELs), the ability to reach extremely high photon numbers in ultrashort pulse durations has resulted in a paradigm shift in our ability to observe nonlinear X-ray signals. This enormous increase in peak power (pulse energy/pulse duration) has been a double-edged sword, with new and exciting techniques being developed but at the same time well-established techniques proving unreliable [1-4]. This requires a fundamental change in our approach to X-ray science at FELs, since this nonlinear regime is a largely unexplored area, making it hard to predict not only when to expect nonlinear contributions to a measurement, but also to understand the very nature of this response [4, 5]. This has resulted in a number of contrasting scientific reports from XFELs where one set of measurements demonstrates the profoundly nonlinear response of atoms to the intense X-ray pulses [6], while another set of measurements claims to have measured "fully intact" molecular systems [7].

We report an X-ray spectroscopic study that reveals important details on the thresholds for nonlinear X-ray interactions. By varying both the incident X-ray intensity and photon energy, we establish the regimes at which the simplest nonlinear process, two-photon X-ray absorption (TPA), can be observed. From these measurements we can extract the probability of this process as a function of photon energy as well as the sub-femtosecond lifetimes of the intermediate electronic states, allowing us to develop an analytical equation that predicts the efficiency of the TPA process on the basis of straightforward linear X-ray measurements. This result is the first step towards allowing scientists to perform XFEL measurements with some degree of certainty as to whether they are in the linear or nonlinear X-ray regime.

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TUNABILITY OF THE HIGH POWER RADIATION GENERATED USING STRONG FIELD FREE ELECTRON LASERS

Jyotsna Panwar[a], Surech C. Sharma[a], Rinku Sharma[a]

[a]Department of Applied Physics, Delhi Technological University (DTU), Shahbad Daulatpur, Bawana Road, Delhi-110042, India

An analytical formalism for the generation of high power terahertz radiation has been developed. A prebunched relativistic electron beam (REB) is an effective source for the emission of radiation at wavelengths longer than the bunch length [1]. The REB acquires a transverse velocity on interaction with the strong field wiggler. This velocity component couples with the perturbed and modulated beam densities of the electron beam to give rise to the non-linear current density which leads to the emission of the radiation. The output THz radiation can be tuned by varying the parameters of the wiggler and the energy of the electron beam. The efficiency of the terahertz radiation increases with the modulation index. The results of the present study may be particularized for the practical applications of THz radiations.

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A TECHNIQUE TO RESOLVE LOW INTENSE PEAKS LOST IN THEIR INTENSE NEIGHBOURHOOD

Gaurav Sharma[a], and N. K. Puri[a]

[a]Dept. of Applied Physics, Delhi Technological University, New Delhi-110042, India

An X-ray absorption spectroscopy technique is discussed for resolving the low intense peaks obscured in the intense neighborhood of closely spaced peaks (as shown in Fig.1) and eliminating the pile-up effect completely & simultaneously. The technique is solely dependent on the Beer-Lambert's law of absorption of X-ray intensities. Dependence of absorption coefficient on E^{-3} [1], where E is the energy of incident photons can provide a good tool to handle the intensities of the different energies differently. Therefore the ratio of the peaks can be moderated by selecting the appropriate absorber and its thickness if the intense peak has lower energy than its unresolved component. A theoretical comparison reveals better efficiency over the available pile-up rejection techniques [2] for detection of higher energy end X-ray transitions. The technique does not change the fundamental characteristics of the peaks and therefore can be employed to measure the lifetime of the corresponding states and absolute cross sections. By comparing the life-time of a state calculated with this technique is found to be same as without attenuating intensity using any absorber as shown in Table 1.This method can be used to detect the low cross section processes like two electron one photon [3] etc. lying in the pile up region.

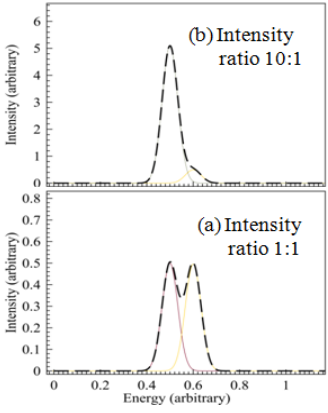

Table 1: fitting parameters for the Intensity curves, without and with Al absorber, fitted to the single exponential. Comparison of two curves shows the same decay-time of both the curves

Equation; $y = A*\exp(-x/t1) + y_0$		Value	Standard Error
Without absorber	y_0	-0.86848	3.90E-11
	A	97599.84	3.05E-11
	T	1.33987	1.29E-15
With absorber	y_0	-0.52109	2.50E-11
	A	58559.9	1.96E-11
	T	1.33987	1.38E-15

Fig.1. A comparison of the resolution is shown. (a) and (b) shows the effect of neighbourhood peak intensities on the resolution of the detector.

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HIGH RESOLUTION SPECTROSCOPY IN HCI USING HIGH-ORDER HARMONIC GENERATION

Janko Nauta[a], **Andrii Borodin**[a], Peter Micke[a,b], Lisa Schmöger[a,b], Maria Schwarz[a,b], Julian Stark[a], José R. Crespo López-Urrutia[a], Thomas Pfeifer[a]

[a]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

[b]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

HCI with just a few tightly bound electrons offer many advantages over neutral and singly charged ions for probing fundamental physics. They have much larger contributions from QED effects and show in most cases a reduction of the complexity of the electronic structure in comparison with many-electron systems. Furthermore, they are intrinsically more sensitive to variation of the fine-structure constant α. Their low polarizability makes them practically insensitive to black body radiation and laser-induced shifts. For these reasons HCI have been recently proposed as candidates for novel frequency standards in several works (cf. [1]).

Recent progress in trapping HCI in a cryogenic linear quadrupole trap, and sympathetically cooling them down to the mK regime with Be^+ ions [2] paved the way for performing high resolution laser spectroscopy of HCI. In order to expand the future applications of this technique towards higher photon energies, we have started a new project. It aims at performing ultra-high resolution laser spectroscopy of cold HCI in the extreme ultraviolet (XUV) regime, where they possess many interesting transitions. Those were so far only accessible at low resolution either in emission studies as well as by using free-electron lasers or synchrotron radiation to excite them. To this end, we are developing an enhancement cavity (shown in Figure 1) to amplify femtosecond pulses from a phase-stabilized infrared frequency comb. High order harmonics will be generated at the location of the tight focus in the cavity, and can be used for direct frequency comb spectroscopy of HCI to determine absolute transition energies.

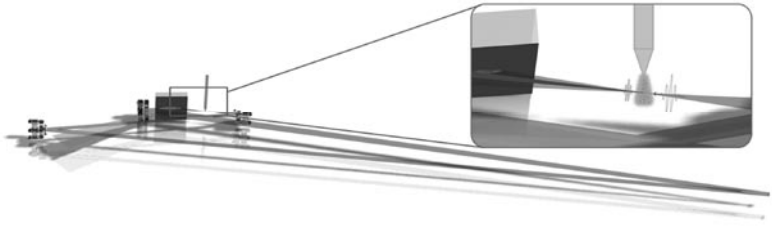

Figure 1: Overview of the enhancement cavity, which consists of four mirrors and a diffraction grating. The inset shows the region around the focus, where higher harmonics are generated.

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LASER COOLING OF RELATIVISTIC $^{12}C^{3+}$ ION BEAM WITH A PULSED LASER AT THE CSRe

H. B. Wang[a,b], **X. Ma**[a], W. Q. Wen[a], Z. K. Huang[a,b], D. C. Zhang[a], B. Hai[a,b], X. Y. Chuai[a,b], D. M. Zhao[a], X. L. Zhu[a], J. Yang[a], J. Li[a], X. N. Li[a], L. J. Mao[a], R. S. Mao[a], J. X. Wu[a], J. W. Xia[a], J. C. Yang[a], Y. J. Yuan[a], H. W. Zhao[a], L. Eidam[c], O. Boine-Frankenheim[c], D. Winters[c], B. Rein[d], Th. Walther[d], D. Kiefer[d], M. Loeser[e,f], U.Schramm[e,f], M. Siebold[e], and M. Bussmann[e]

[a]IMP, Lanzhou; [b]UCAS, Beijing; [c]GSI, Darmstadt; [d]TU Darmstadt; [e]HZDR, Dresden; [f]TU Dresden

A test experiment of laser cooling of relativistic $^{12}C^{3+}$ ion beams was performed at the storage ring CSRe in September 2014. A pulsed laser system with a repetition rate of 10 kHz and wavelength of 257 nm from HZDR Dresden was employed in this experiment. The optical transition of $2S_{1/2} \rightarrow 2P_{1/2}$ of $^{12}C^{3+}$ ions was Doppler shifted to be resonant with the counter-propagating laser beam at an energy of 122 MeV/u. Fig.1 (a) shows a schematic of the CSRe and the laser cooling experimental setup. In this beam time, the $^{12}C^{3+}$ ions and $^{16}O^{4+}$ ions were successfully stored in the CSRe. We recorded the Schottky noise signals of the ion beams by using a resonant Schottky pick-up (Fig.1 (b)). The ratio of $^{12}C^{3+}$ ions and $^{16}O^{4+}$ ions was determined to be 4:1 from Schottky spectra. The lifetime of the $^{12}C^{3+}$ ion beam, measured by both the DCCT and the Schottky pick-up, is longer than 20 seconds, which is sufficient for laser cooling experiment. A photomultiplier tube (PMT) and a new movable Channeltron photomultiplier (CPM) detector were installed and tested systematically. Both detectors are UV-sensitive from 110 to 230 nm. However, during this beam time, no evidence for the interaction of the pulsed laser with the stored and bunched $^{12}C^{3+}$ ion beams could be observed. In order to investigate the beam dynamics of longitudinally bunched ion beams [1], the bare $^{12}C^{6+}$ ions and $^{16}O^{8+}$ ions were produced by stripping the accelerated $^{12}C^{3+}$ ions and $^{16}O^{4+}$ ions with a carbon foil and stored in the CSRe. The results of these experimental investigations at the CSRe will be presented at this conference.

A new laser cooling experiment with a pulsed laser with 100 kHz repetition rate is being prepared at the CSRe, and will be carried out at the end of March 2016. In addition, we are preparing to use a CW laser with a wavelength of 220 nm to cool Li-like $^{16}O^{5+}$ ions for the first time at the CSRe.

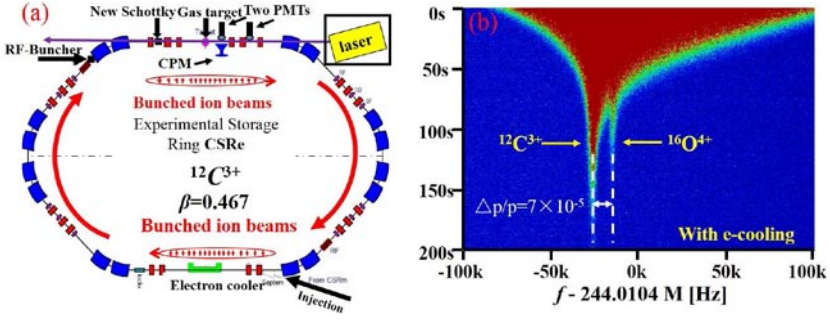

Figure 1: (a) Schematic of the CSRe and the experimental setup for laser cooling experiment, and (b) a Schottky spectrum of electron-cooled $^{12}C^{3+}$ and $^{16}O^{4+}$ ions.

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PROSPECTS AND CHALLENGES OF LASER COOLING OF STORED BEAMS OF RELATIVISTIC HIGHLY CHARGED IONS

Michael Bussmann[a], Danyal Winters[b], Tobias Beck[c], Gerhard Birkl[c], Oliver Boine-Frankenheim[b,c], Christina Dimopoulou[b], Lewin Eidam[c], Volker Hannen[d], Daniel Kiefer[c], Thomas Kühl[b,e], Matthias Lochmann[b], Markus Löser[a,f], Xinwen Ma[g], Lijun Mao[g], Fritz Nolden[b], Wilfried Nörtershäuser[c], Benjamin Rein[c], Rodolfo Sanchez[b], Ulrich Schramm[a,f], Mathias Siebold[a], Peter Spiller[b], Markus Steck[b], Thomas Stöhlker[b,e,h], Sascha Tichelmann[c], Johannes Ullmann[b,c], Thomas Walther[c], Hanbing Wang[g], Weiqiang Wen[g], Daniel Winzen[d], Jiancheng Yang[g], Youjin Yuan[g]

[a]Helmholtz-Zentrum Dresden – Rossendorf, Germany
[b]GSI Helmholtzzentrum Darmstadt, Germany
[c]Technische Universität Darmstadt, Germany
[d]Westfälische Wilhelms-Universität Münster, Germany
[e]Helmholtz-Institut Jena, Germany
[f]Technische Universität Dresden, Germany
[g]Institute of Modern Physics, Lanzhou, China
[h]Friedrich-Schiller-Universität Jena, Germany

Laser cooling is a promising technique to attain ion beams with ultra-low longitudinal momentum spread at highly relativistic beam energies. It can even overcome intra-beam scattering, leading to highly brilliant ion beams that have the potential to undergo a phase transition to a crystalline state [1].

We discuss which lessons we have learned from recent experiments on laser cooling of relativistic C^{3+} ion beams [2,3] for the future application of laser cooling at high energy storage rings and synchrotrons [4].

Starting from an in-depth discussion on laser cooling of highly charged ions based on recent calculations for suitable cooling transitions we focus on the requirements for laser systems [5,6] and fluorescence detectors [7,8].

We conclude by showing how dedicated diagnostics can both open the window to laser spectroscopy of ultra-cold beams and provide a new tool to study their dynamics.

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CONCEPTION OF AN IMPROVED SI(LI)-COMPTON POLARIMETER FOR THE SPARC COLLABORATION

M. Vockert[a,b], U. Spillmann[c], K.H. Blumenhagen[a,b], T. Krings[d], R. Märtin[b], G. Weber[b], and Th. Stöhlker[a,b,c], the SPARC collaboration

[a]Institute of Optics and Quantumelectronics, Friedrich Schiller Universität Jena, Germany;
[b]Helmholtz Institute Jena, Germany;
[c]GSI, Darmstadt, Germany;
[d]Semikon Detector GmbH, Jülich, Germany

The study of particle and photon polarization phenomena occurring in the interaction of fast ion and electron beams with matter is of particular relevance for the understanding of cosmic and laboratory plasmas where high temperatures, high atomic charge-states and high field strengths prevail. In addition, polarization-sensitive studies of radiative processes in highly-charged, heavy ions may provide detailed insights in both relativistic particle dynamics as well as QED effects and other atomic structure properties at extreme electromagnetic field strengths [1]. Moreover, x-ray polarimetry was proposed as a tool for diagnosis of spin-polarized ion beams [2]. Owing to the recent progress in x-ray detector technology, accurate measurements of the linear polarization for hard x-ray photons as well as the determination of the polarization orientation have become possible [3,4,5,6].

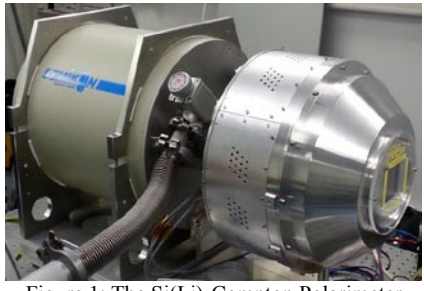

Figure 1: The Si(Li)-Compton Polarimeter

To strengthen the instrumentation portfolio in line with the scientific program of SPARC [7] a dedicated Si(Li)-Compton polarimeter was designed and build at Semikon Detector GmbH (see figure 1). First laboratory tests demonstrated a spectroscopic resolution of ~850 eV (p^+-side) and ~1300 eV (HV-side) at a γ-ray energy of 60 keV (Am-241). A more detailed conception of the features of each strip will be presented.

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A SUPERCONDUCTING RESONATOR-DRIVEN LINEAR RADIO-FREQUENCY TRAP FOR LONG-TIME STORAGE OF HIGHLY CHARGED IONS

Julian Stark[a], Lisa Schmöger[a,b], Andrii Borodin[a], Janko Nauta[a], Thomas Pfeifer[a], José R. Crespo López-Urrutia[a]

[a]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

[b]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

Electron beam ion traps (EBITs) are powerful tools for the production and spectroscopy of highly charged ions (HCIs). However, the high temperature of the trapped ions limits the achievable spectral resolution. By combining an EBIT with a cryogenic Paul trap [1,2] HCIs can be sympathetically cooled down to the mK range [3]. This should allow to resolve the natural linewidth of forbidden optical transitions in HCIs.

For high-precision laser spectroscopy in a Paul trap the ions need to be strongly localized. Since the trapping potential depends on the radio-frequency (RF) amplitude, phase and frequency, stable localization of ions requires a high voltage RF drive with low noise. Furthermore, instabilities in the RF drive cause excess micromotion and thus heating of the trapped ions [4]. Therefore, a superconducting RF resonator design with integrated Paul trap electrodes has been developed. A normal-conducting prototype is currently being commissioned. The high quality factor Q of this resonator enables high trapping voltages and drastically reduces the RF noise, as well as improves the overall stability of the trapping conditions. In the superconducting version a much higher Q value will render electrodynamical losses of trapped ions negligible and will greatly reduce Paul trap heating rates.

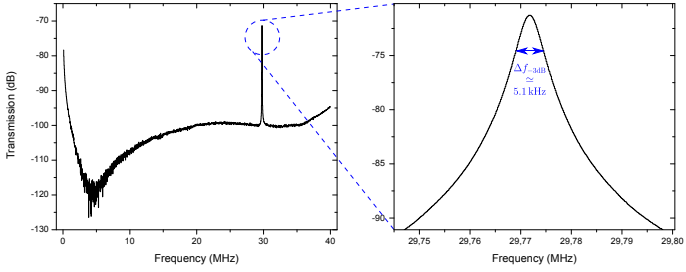

Figure 1: Transmission measurement of the high-puriy OFHC copper resonator prototype at 13 K temperature with loose capacitive coupling to the cavity. The isolated resonance at 29.771788(2) MHz yields a Q-value of 5822(6).

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CHANGE IN THE SENSITIVITY OF SOLID STATE NUCLEAR TRACK DETECTORS FOR IONS EMITTED FROM PLASMA

A. Malinowska, M. Jaskóła, A. Szydłowski

National Centre for Nuclear Research (NCBJ), Andrzeja Sołtana 7 str., 05-400 Otwock, Poland

Solid State Nuclear Track Detectors (SSNTDs) are widely used for dosimetry applications, as air radon concentration dosimeters, for neutron monitoring and in space research for investigations of the depth distribution of radiation in different organs of astronauts during long duration missions. These measurements are characterized by long–term exposure of up to a few months. It is known that exposure during space missions leads to the fading of CR–39 sensitivity. For practical applications the detectors require a calibration procedure which must be represented in the sensitivity measurements of the dose. How much ageing (non–irradiated samples), fading (irradiated samples) and other factors can affect the calibration factor and in consequence the precision of the measurements is a fundamental question.

Beginning from the moment when the polyallyl–diglicol–carbonate (PADC) called CR–39 was introduced by B.G. Cartwright et al. as a nuclear track detector, many authors have studied the influence of environmental conditions before, during and after irradiation of this type of detector by charged projectiles. This includes manufacturing processes, thermal annealing treatments, electromagnetic radiation exposure etc..

Radon monitoring or space physics laboratories take into consideration that the detector sensitivity is affected by different environmental conditions and modify their analysis systems in order to compensate the change in sensitivity due to storage before (ageing) after (fading) and during long–term exposures.

The aim of this work is first to show these effects by using the change in track diameters of ions of different energies during some period of storage time (a few years), and second to understand the mechanism of the sensitivity function, $V = V_T/V_B$, value variation. This work is a product of our long–term studies of PADC detector properties.

TOWARDS A FAST CALCULATOR FOR ATOMIC EMISSION PROCESSES OF PHOTONS AND ELECTRONS FROM RELATIVISTIC HEAVY-ION-ATOM COLISSIONS

M O Herdrich[ab], G Weber[b]

[a] Institut für Optik und Quantenelektronik, Friedrich-Schiller-Universität, 07743 Jena, Germany;

[b] Helmholtz-Institut Jena, 07743 Jena, Germany

The study of heavy-ion systems at the GSI Helmholtz-center for Heavy-Ion Research in Darmstadt has proven to provide a deep insight into atomic structures and interactions processes in the presence of extreme field-strengths [1]. The FAIR project which is currently being built at the site of the GSI and especially its High-Energy Storage Ring (HESR) give raise to new opportunities for heavy-ion experiments with the full range of charge-states and energies reaching up to the GeV/u regime [2]. The planning of future heavy-ion-atom collision experiments at relativistic energies at the HESR's internal gas-target may profit from the availability of a fast calculator for the emission characteristics of the occurring interactions. In particular, those processes are of great importance, which give rise to the emission of high energy photons and electrons that may contribute to the background of a broad range of planned experiments.

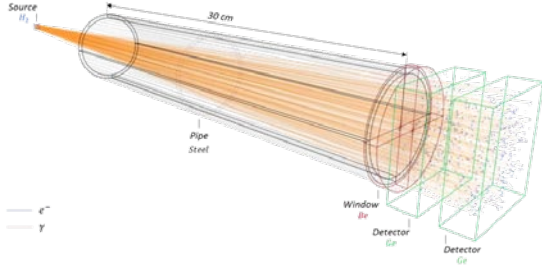

Figure 1: Simulation of REC-photons in a simple experiment geometry in GEANT4.

As a starting point for such a universal calculator, we recently begun to assemble results of theoretic physics concerning relativistic heavy-ion-atom interactions [3-5] into a set of tools that was used to create a database: Precise results on Radiative Electron Recombination, Bremsstrahlung and Binary Encounter processes in a vast parameter range can be found within seconds using the resulting database. The results were used in first simulations on possible day-zero-experiments at the HESR (see Fig. 1).

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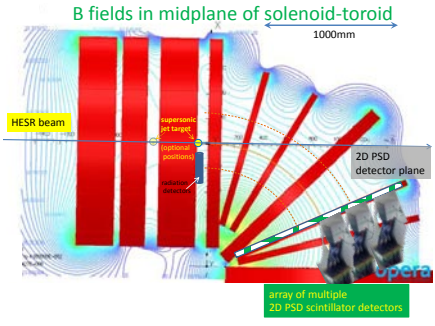
A NEW BROAD-BAND ELECTRON-POSITRON PAIR SPECTROMETER

S. Hagmann[1], P.M. Hillenbrand[1, 3], Y. A Litvinov[1], U. Spillmann[1], K. Stiebing[2], Th. Stöhlker[1, 4, 5]

[1] GSI Helmholtzzentrum Darmstadt, [2] Inst. für Kernphysik, Universität Frankfurt, [3]Universität Giessen,[4]Helmholtz Institut Jena, [5]Fakultät für Physik, Universität Jena

The surprisingly high cross sections observed for pair production in relativistic heavy-ion atom collisions [1, 2] have aroused new interest in this process even in the accelerator design community as capture from pair production has been identified as a critical, potentially luminosity limiting process in relativistic heavy ion colliders. The enormous cross sections observed can be traced [1] to the large transverse electric fields $E_{transv} \sim \gamma$. Theory predicts a scaling of the total cross section for free-free pair production [1, 3] $\sigma_{free\text{-}free} \sim (Z_{proj})^2 (Z_{tar})^2 \ln^3\gamma$ and a very complex relation between the angular emission patterns of electron and positron[4]. The future relativistic storage ring HESR at FAIR with a collision energy range up to $\gamma \sim 6$ will be best suited to study for ion-induced pair-production all channels which may be distinguished experimentally [3]. A corresponding future experimental investigation of the dynamics of the heavy-ion induced free-free pair creation up to $\gamma \sim 6$



$$X^{Z+} + A \longrightarrow X^{Z+} + \{A^*\} + e^+ + e^- \qquad (1)$$

is the motivation for the current spectrometer design study: a coincident detection of both outgoing leptons and their vector momenta as constitutive in a complete description of free-free pair production is not practically possible with instruments covering only a small solid angle for each lepton.

Figure 1:Cut through midplane of coil assembly of a toroidal magnetic lepton spectrometer for lepton energies up to 20 MeV.

We have therefore employed OPERA-3D[5] to study the electro-optical properties of a magnetic toroidal spectrometer where e^- and e^+ are momentum-dispersed perpendicular to the bend plane of the toroid; the very large effective solid angle enables coincident detection of the vector momenta of electrons and positrons from a free-free pair (see fig. 1). We show how the complete emitter frame emission pattern of a lepton pair may thus be determined by coincident detection of leptons in the detector plane for a choice of a few appropriate B-field settings.

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BAYESIAN STATISTICS FOR ATOMIC PHYSICS

MartinoTrassinelli[a]

[a]Institut des NanoSciences de Paris, CNRS, Sorbonne Universités UPMC Univ Paris 06, Paris, France

In certain cases of analysis of experimental data, the standard probability theory reaches its limitations. As an example, in the low statistics atomic spectrum with unresolved peaks as in Fig. 1 left, how can we objectively determine the number of contributions? In other words, given a set of experimental data, how can we test different hypothesis and assign them a probability? This type of problem is often encountered, like in particular in astrophysics and cosmology where experiments cannot be repeated, as in the recent discovery of gravitational waves, where only one observation is available (at present). In these cases,a different approach to define probability has to be applied using data analysis methods based on the work of Th. Bayes, P.-S. Laplace, H. Jeffreys, etc. commonly called *Bayesian statistics* [1].

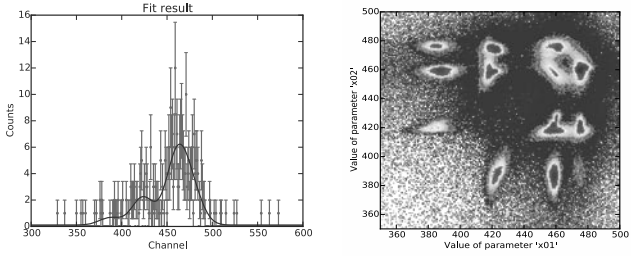

Figure 1: Left: High-resolution X-ray spectrum of He-like uranium intrashell transition from Ref. [2] and the result of the fit assuming the presence of four peaks. Right: 2D histogram of the probability distribution of 2 parameters corresponding to the positions of 2 different peaks.

We present here some practical uses of Bayesian methods for cases often encountered in atomic physics. In particular, we will show how it is possible to calculate, for low-statistic data presented in Fig. 1 (left), the most likelihood number of peaks and how to choose the correct shape to be adopted and how to extract accurately its position (with the associated uncertainty) even if the choice of the shape is not unambiguous. In all examples, we use a newly developed computational tool called `Nested_fit` that will be presented as well. This program is based on the nested sampling algorithm [3]; for a given data set and chosen model, it provides (i) the *Bayesian evidence* for the comparison of different hypotheses and (ii) the parameter probability and correlation distributions. In Figure 1, we show some typical outputs of `Nested_fit` for the low-statistic spectrum discussed before, assuming a four-peak model.

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THE STATUS OF THE MICRO-CALORIMETER AT SHANGHAI EBIT

Y Shen[a,b]，**J Xiao**[a,b], K Yao[a,b], Y Yang[a,b] , D Lu[a,b] ,R Hutton[a,b], and Y Zou[a,b]
[a] The Key Laboratory of Applied Ion Beam Physics, Ministry of Education, 200433 China
[b] Shanghai EBIT laboratory, Institute of Modern Physics, Fudan University, Shanghai, 200433 China

We present an overview of recent work on the micro-calorimeter at Shanghai EBIT laboratory. The micro-calorimeter was established by the collaboration between the Shanghai EBIT laboratory and the Smithsonian Astrophysical Observatory (SAO)[1]. The calorimeter has an array of eight pixels: four 7 μm thick pixels made of tin for the 0.1~10 keV photon energy region and four 90 μm thick pixels of tin for operation up to at least 60 keV.

Figure 1 is the first micro-calorimeter spectra from the Shanghai EBIT. The ADR could run for 12 hours at 50 mK between magnetize-demagnetize circles and the accumulation time of the spectra is 5 hours. The resolution at 3 keV is around 20 eV, which is not as good as it was tested. Anyway, the w and z line of Ar XVII can be distinguished and this micro-calorimeter is still a high-performance instrument for a broad range of EBIT experiments.

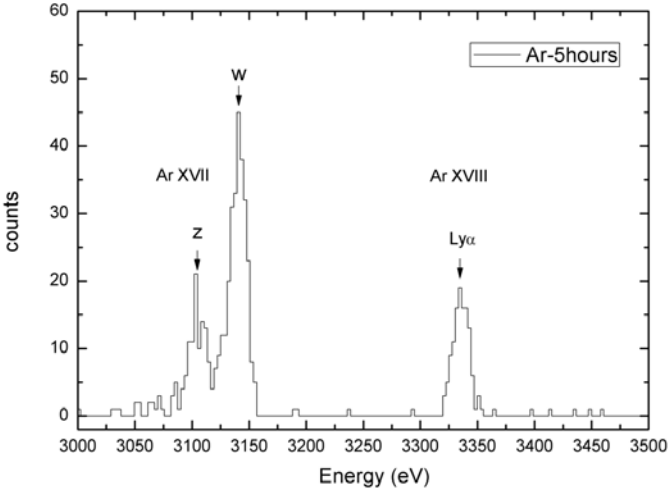

Figure 1: Micro-calorimeter spectra of K-shell emission of highly ionized Ar XVII/XVIII at Shanghai EBIT. The electron beam energy is 7keV and the current is 59mA.

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THE FISIC PROJECT FOR N-BODY QUANTUM DYNAMICS STUDY IN FAST ION - SLOW ION COLLISIONS: STATUS AND PROGRESS

E. Lamour[*], T. Stöhlker[§], J. Rangama[‡], A. Gumberidze[(•)†], L. Adoui[‡], A. Bräuning-Demian[†], H. Bräuning[†], J.Y. Chesnel[‡], R. Geithner[§], C. Hahn[§], A. Lévy[*], S. Macé[*], A. Méry[‡], C. Prigent[*], P. Rousseau[‡], J.-P. Rozet[*], U. Spillmann[†], S. Steydli[*], N.A. Tahir[†], M. Trassinelli[*], D. Vernhet[*], G. Weber[§]

* INSP Sorbonne Universités, CNRS, UPMC Univ Paris 06, Paris, France

§ Friedrich-Schiller-Universität Jena, Helmholtz-Institut, Jena, Germany

‡ CIMAP, CEA/CNRS/ENSICAEN/Université de Caen Basse-Normandie, Caen, France

† GSI, (•) ExtreMe Matter Institute, Darmstadt, Germany

When a few MeV/u ions collide with a few keV/u ions, a hitherto unexplored collision regime is reached: a regime where the ion energy transfer is at its maximum. There, all the primary electronic processes, like electron capture, loss and excitation, reach their optimum leading, for instance, to possible interference effects. Measurements and reliable theoretical predictions are completely lacking in this intermediate collision regime corresponding therefore to a real "terra incognita" for atomic physics.

The forthcoming availability of MeV energy, intense and stable ion beams of high optical quality at French and German Large Scale Facilities (SPIRAL2 and CRYRING) opens new opportunities towards the intermediate collision regime. With the FISIC project [1], we propose an experimental crossed-beam arrangement with an ultimate control of experimental conditions to measure absolute cross sections. The goal is to span from a pure three-body problem to a collision system between dressed partners (study of the effect of a controlled number of additional electrons). A lot of technical barriers have to be overcome. Solution/progress for several of them will be presented at the conference, namely:

- The *stripping issue* of intense ion beams delivered by the SPIRAL2 accelerator. First, an upstream work has been accomplished to extend the ETACHA code [2] so as to determine the most appropriate stripper nature and thicknesses with respect to the desired ion charge state. Second, the technical issue of the stripper thermal load during beam irradiation will be overcome by fixing the thin solid strippers on a rotating wheel [3].
- The *collision chamber* has been designed in order to ensure UHV conditions and to monitor the intensity profile of the high-energy ion beam upstream and downstream from the interaction zone.
- The *high energy ion detectors*. New detector prototypes capable to cope with some MHz count rates and to withstand the accompanying radiation damage are required. Solutions that rely on polycrystalline diamond devices and crystal scintillators such as YAP:Ce are currently tested.
- The *control and detection of the slow ion charge state*. An arrangement of two 180° spherical electrostatic analyzers used as a purification system, prior to the interaction, has been designed. A charge state analyzer, which includes movable electrodes and/or movable detectors is currently under study.

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COMMISSIONING OF THE RIKEN CRYOGENIC ELECTROSTATIC STORAGE RING (RICE)

Yuji Nakano,[1] Y. Enomoto,[1] T. Masunaga,[1] S. Menk,[1] P. Bertier,[1, 2] and T. Azuma[1, 3]

[1] Atomic, Molecular and Optical Physics Laboratory, RIKEN, Saitama 351-0198, Japan

[2] Institut de Physique Nucléaire de Lyon, Université de Lyon, Université de Lyon 1, CNRS/IN2P3, Villeurbanne, France

[3] Department of Physics, Tokyo Metropolitan University, Tokyo 192-0397, Japan

A new electrostatic storage ring, RIKEN cryogenic electrostatic ring (RICE), has been developed [1,2]. The first cryogenic operation of the RICE was successfully performed in 2014 August with a 15 keV Ne^+ beam produced in an ECR ion source NANOGUN. The beam was stored under the 5 K ambient temperature for more than 30 minutes with a decaying time constant of several minutes. Installation of the molecular ion sources and a cryogenic pre-cooling ion trap is currently in progress. In parallel, preparation of the neutral beam injector is also ongoing to realize the in-ring merged-beam collision experiment. The study of slow HCI-neutral collision is planned as one of the experimental programs at the merged-beam section. An up-to-date status of the development and experimental progresses will be reported.

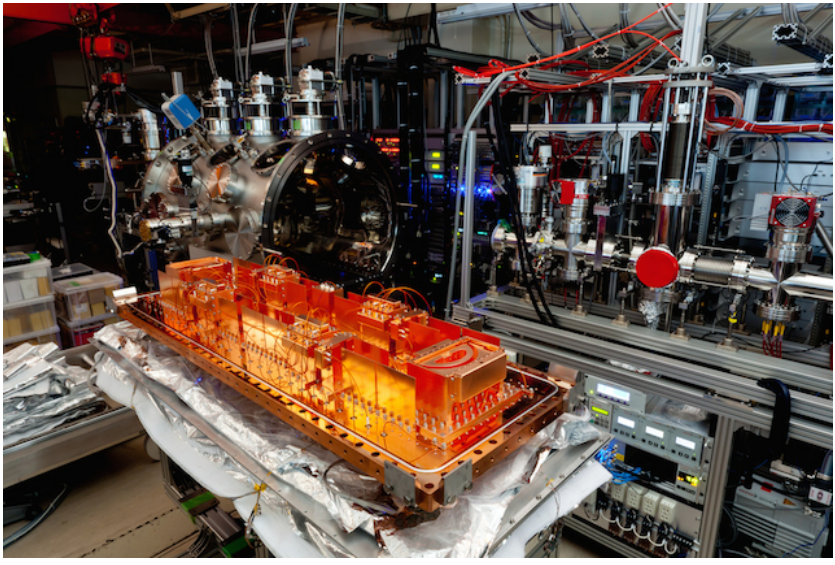

Figure 1: Photograph of the RICE cryogenic chamber and electrostatic components.

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ACCELERATING MONTE CARLO EVENT GENERATOR IN GRAPHICS PROCESSING UNITS

F. D. Colavecchia[a], M. Schulz[b], T. Kirchner[c] and M. F. Ciappina[d]

[a]División Física Atómica, Molecular y Óptica y Consejo Nacional de Investigaciones Científicas y Técnicas, Centro Atómico Bariloche , 8400 San Carlos de Bariloche, Argentina.

[b]Department of Physics and LAMOR, Missouri University of Science & Technology, Rolla, MO 65409, USA

[c]Department of Physics and Astronomy, York University, Toronto, Ontario M3J 1P3, Canada

[d]Max-Planck-Institut für Quantenoptik, Hans-Kopfermann Str. 1, D-85748, Garching, Germany

The Monte Carlo Event Generator (MCEG) is a numerical technique that is able to compute differential cross sections for a variety of complex ionization collisions, usually involving three and four body systems [1]. It simulates the experimental setup of a given collision, while including advanced theoretical distorted wave methods to compute the events. MCEG computes cross sections for random, but physically plausible final kinematical conditions, and chooses favorable events among them according to the usual Monte Carlos rules. Convolution of these events with experimental resolutions of detectors gives accurate representation of many ionization processes [2]. The main shortcoming of this scheme is that it is usually necessary to compute billions of cross sections in order to get a reasonable count of favorable events. However, each calculation for a particular kinematical condition is independent of the others. From a numerical point of view, this problem enters in the so-called *embarrasingly parallel* ones. Therefore, it perfectly suits the new computational features provided by latest generations of Graphical Processing Units (GPUs).

In this work we report benchmarks and speed ups of a GPU implementation of the MCEG method. In this code, each thread computes one cross section for a given random kinematical condition. The code proceeds in two steps. First, a set of cross section is computed, and second, favorable events are selected from this set. These two steps can be repeated to obtain a given number of events. The code is written in C language using the Compute Unified Device Architecture (CUDA) extensions [3], the Thrust library to perform sorting and reductions [4], and the Philox parallel random number generator [5]. We compute differential cross sections for double ionization of Neon by electron impact using a two step Born Approximation [6]. Our preliminary results show that the MCEG is accelerated in the GPU more than ten times, compared to the standard CPU code.

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TOWARDS THE PRODUCTION AND ISOLATION OF HIGHLY CHARGED IONS WITH LOW IONIZATION THRESHOLD

A.S. Naing[a], S.F. Hoogerheide[b], J.M. Dreiling[b], and J.N. Tan[b]

[a]University of Delaware, Department of Physics and Astronomy,
217 Sharp Lab, Newark, Delaware 19716, USA

[b]National Institute of Standards and Technology (NIST),
100 Bureau Drive, Mail Stop 8422, Gaithersburg, Maryland 20899, USA

In addition to the central role that highly charged ions play in the study of radiative and collisional processes occurring in laboratory and astrophysical plasmas [1], recent theoretical studies indicate that certain highly charged ions, such as Pr^{9+} and Nd^{10+}, are potentially useful for interesting applications, such as the development of next-generation atomic clocks, quantum information processing, or the search for variation in the fine-structure constant [2]. Highly charged ions can be produced in an electron beam ion source/trap (EBIS/T) with a strong magnetic field. However, lower magnetic fields are more suitable for abundantly producing the proposed candidate ions, as well as other interesting ions with relatively low ionization thresholds (100 eV to 2000 eV). We are developing a room-temperature miniature EBIS/T (mini-EBIS/T) for improving the production of such ions with low ionization threshold, as well as for bunched ion extraction into a capture trap. This work presents new features in the design and the construction of the mini-EBIS/T, as well as related experiments on the production and isolation of xenon ions (in the charge state range from +8 to +15) in a unitary Penning trap and an RF trap that are attached to the EBIT at NIST via an ion extraction beamline. Xenon ions with lower ionization thresholds (e.g., Xe^{8+}, Xe^{9+}, Xe^{10+}) have similar charge-to-mass ratios to ions of interest (Pr^{9+}, Nd^{10+}) and are thus useful in aiding the design of a mini-EBIS/T and its related ion optics and ion traps.

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A NEW MULTIHIT RIMS AND CHARGE STATE ANALYSER FOR FRAGMENTATION STUDIES OF PAH MOLECULES @TIFR-ECRIA

S. Biswas, D. Misra and **L. C. Tribedi**

Tata Institute of Fundamental Research, Colaba, Mumbai-400 005, India

In ion-molecule collision physics, coincident measurement of different collision products and their kinematic analysis are used to explore the details of the collision dynamics. Recoil ion momentum spectroscopy is one of such techniques, which is capable of providing all three momentum vectors of the recoil ions produced in a collision reaction [1].In the intermediate energy region (~keV/u), electron capture and transfer ionization. The TIFR-ECRIA [2] is capable of providing varieties of low energy ions for such collision studies at intermediate energies. To distinguish the different channels, post collision projectile charge state analysis is also required. Here we report the design and development of recoil ion momentum spectrometer (RIMS) with multihit capability, coupled with a projectile charge state analyser (CSA), which is being used to study ion induced fragmentation dynamics of different molecules. The spectrometer provides the momentum information of all recoil ions by measuring their time of flight (ToF) and the hit position on the 2D imaging detector. It is a Wiley-McLaren [3] type of spectrometer with a slight modification introduced by an electrostatic lens. This geometry ensures excellent time as well as space focusing simultaneously, which in turn ensure good momentum resolution. We have performed experiments for studying electron capture induced fragmentation of N_2 under the impact of 250 keV p [3]. The obtained typical KE spectrum for $N_2^{2+} \rightarrow N^+ + N^+$ [Fig.1] matches well with earlier works. From the coincidence analysis signatures of Coulomb fragmentation following ionization, transfer ionization (TI : N^+/N^+), transfer double ionization (TDI: N^{2+}/N^+) and transfer triple ionization (TTI: N^{3+}/N^+),)were found. To the best of our knowledge the TDI and TTI are observed for the first time. For each channel, detailed momentum analysis was done and the associated kinetic energy release (KER) distribution was determined. The fragmentation of a PAH molecule,Fluorene, ($C_{13}H_{10}$) under the p-impact in coincidence with single capture events will be presented.

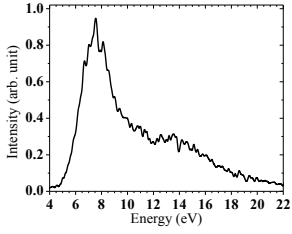

Figure1: KE spectrum for $N_2^{2+} \rightarrow N^+ + N$

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ELECTRON EMISSION FROM CORONENE AND FLUORENE: COLLECTIVE PLASMON RESONANCE PEAK

L. C. Tribedi[a], S. Biswas[a] and C. Champion[b]

[a]Tata Institute of Fundamental Research, Colaba, Mumbai 400005, India
[b]CENBG, Université Bordeaux 1, Chemin du Solarium, 33175 Gradignan, France

The polycyclic aromatic hydrocarbon molecules are organic compounds containing only carbon and hydrogen-that are composed of multiple aromatic rings. More than 20% of the carbon in the universe may be associated with PAHs. The PAHs are also considered to be possible starting material for the early life. The PAHs are of great interest in recent times because of their astrophysical absorption spectrum as well as technological importance. The fused benzenoid rings and electrons from each C atom forms a delocalized π-electron cloud over the C skeleton. It is expected to show collective excitation like plasmon resonance, as observed in case of fullerenes [1]. In general, the experimental detection of such collective state for the PAH molecules is relatively difficult because of its low oscillator strength compared to fullerenes. In case of PAH molecules such collective behavior, although predicted, has not been observed in e-emission

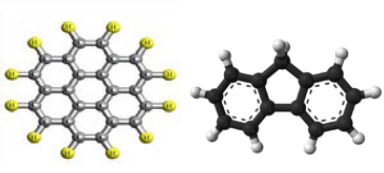

Fig.1: Coronene ($C_{24}H_{12}$) and Fluorene ($C_{13}H_{120}$).

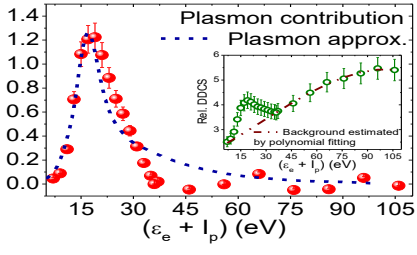

Fig.2: The ratio of forward-to-backward electron DDCS after background subtraction. Dashed line: theoretical prediction [3]. Inset: The ratio before background subtraction.

spectrum. Here, we present a manifestation of energy and angular distributions of electron emission upon deexcitation of the collective plasmon resonance in coronene, under fast (3.75 MeV/u) bare F-ion impact. The angular distributions of these electrons show an unusually enhanced forward-backward angular asymmetry, in contrast to the observed uniform distributions for simpler atomic (Ne) or molecular (CH4) targets. A simple model of photoelectron angular distribution from an oscillating dipolar plasmon, calculated including the first retardation term in the transition matrix element, provides excellent agreement with the observed linear distribution [2]. The DDCS ratio of forward-to backward angles clearly exhibits a broad peak which is in excellent agreement with the theoretical prediction of the plasmon peak. However a similar experiment conducted Fluorene ($C_{13}H_{10}$, m=166 amu), does not show the plasmon peak in the e-spectrum. Some of the recent relevant references [1-5] are given below from our work on large molecules.

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POSTER SESSION B

BOUND BETA-DECAY AND DECAY OF ISOMERIC STATES FOR NEUTRAL ATOMS AND CORRESPONDING MULTICHARGED IONS

A.V. Glushkov[a]

[a]Odessa State University-OSENU, P.O.Box 24a, Odessa-9, 65009, Ukraine

Many attempts have been made to influence on the nuclear decay rate by varying chemical environments etc or by applying strong electromagnetic fields. The situation is completely different in hot stellar plasmas where the ions are partially or fully ionized (multicharged ions). In this case it can be expected that the rates of nuclear beta decay and electron capture, as well as internal conversion, are strongly affected in comparison to those of neutral atoms [1]. In our paper the QED many-body perturbation theory is used to calculate the β decay parameters for a number of the beta-transitions. The relativistic calculation method is based on the optimized Dirac-Kohn-Sham formalism with taking into account the nuclear, radiative and exchange-correlation corrections [2]. We have calculated the probabilities of excitation to the final discrete states of $^{6}Li+$ (including to the doubly excited autoionizing states) as well as the total probabilities for single and double ionization. We have calculated beta decay parameters for a number of transitions: ^{33}P-^{33}S, ^{35}S-^{35}Cl, ^{63}Ni-^{63}Cu, ^{241}Pu-^{241}Am etc and show that the theoretical values agree quite well with some available experimental data. We have studied the chemical environment effect on parameters of the β transitions, in particular, $^{63}Ni^{(0)}$-$^{63}Cu^{(+1)}$, $Ni^{(+2)}$-$Cu^{(+3)}$, $^{241}Pu^{(0)}$-$^{241}Am^{(+1)}$, $Pu^{(+2)}$- $Am^{(+3)}$. The correct treatment of the chemical environment effect is shown to modify the beta decay parameters (the integral Fermi function, half-life period, probability). This modification is connected with account of a few factors (changing the integration limits in the Fermi function integral; the energy corrections for different chemical substances as well as the possibility of the bound or other decay channels). The estimates for a ratio λ_b/λ_c of bound-state (b) and continuum-state (c) beta decay rates for the case of bare $^{207}Tl^{81+}$ions and isomeric states of fully ionized ^{144m}Tb etc are given. The similar "multicharged ions" effects are also studied for ^{187}Re. It is found a giant increases of the half-lives of bare isomers by factors of up to 20 compared to their neutral counterparts. Such physical factors as a strong internal conversion, electron-capture (bound beta-decay) channels in the radioactive decay of these bare nuclei. The theoretical results are in a physically reasonable agreement with some experimental data [1].

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ADVANCED RELATIVISTIC ENERGY APPROACH TO CALCULATION OF THE RADIATION AND AUGER TRANSITION PROBABILITIES FOR MULTICHARGED IONS

A.V. Glushkov[a], O.Yu. Khetselius[a], P.A. Zaichko[a], M.Yu. Gurskaya[a] , T.A. Kulakli[a]

[a]Odessa State University-OSENU, P.O.Box 24a, Odessa-9, 65009, Ukraine

The accurate radiative decay widths and probabilities, oscillator strengths of atomic transitions are needed in astrophysics and plasma diagnostics, in fusion research and laser physics etc. Here we present an advanced relativistic approach to calculation of the radiation (oscillator strengths gf), Auger transitions probabilities in spectra of multicharged ions, based on energy approach [1-3] and relativistic many-body perturbation theory [4]. The key feature of the presented basis theory is an implementation of the optimized one-particle representation [3] into the frames of the S-matrix energy formalism. It provides a consistent approach to minimize gauge-non-invariant contributions to gf values and thus it make our approach significantly more advantagable in comparison with standard Hartree-Fock (HF), Dirac-Fock (DF) methods. We have carried out calculating energies, radiation and Auger transition probabilities for Li- and Zn-like ions (Z=10-70). It is checked that all gf values, obtained within our approach in different photon propagator gauges (Coulomb, Babushkin, Landau) are practically equal. As example in table below we list our results (REA) on gf of the $4s^2(^1S_0)$- 4s4p ($^1P^0_1$) transition in some Zn-like ions. For comparison the HF, DF, DF (with fitting to experiment) and model potential (MP) calculation data are presented too [4,5] (refs. therein).

Table 1. The exp. and theor. gf values for $4s^2(^1S_0)$- 4s4p ($^1P^0_1$) transition in the Zn-like ions.

Ion	Method	ΔE	f_L	f_V
Ga^+	DF	0.3351	1.89	1.98
	HF	0.2984	2.30	2.01
	DF (E_{exp})	0.3221	1.97	1.95
	MP	0.3076	1.68	1.73
	Our th.	0.3220	1.862	1.861
	Exp.	0.3221	1.85 ± 0.15	1.85 ± 0.15
Gd^{34+}	DF	4.6685	1.12	1.10
	Our th.	4.6294	1.01	0.99
Yb^{40+}	DF	6.2564	1.12	1.10
	Our th.	5.1788	0.97	0.96

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THEORETICAL ASPECTS OF WEAK DECAYS OF H-LIKE IONS

Francesco Giacosa

Institute of Physics, Jan Kochanowski University, Świętokrzyska 15, 25-406 Kielce, Poland

In this talk we discuss theoretical properties the weak electron-capture decay of an H-like ion into a neutrino and a nucleus. In particular, we show that oscillations in the decay rate cannot emerge due to fact that the emitted electron-neutrino is a superposition of mass eigenstates. This result is based on the application of the rules of Quantum Mechanics (including the projections generated by measurements). Namely, a measurement on the daughter state (the nucleus in this case) does not contain in the decay amplitude interference terms which could generate such an oscillation. As a next step, we present the emergence of oscillations in the decay law in the context of Quantum Mechanics when the energy distribution of the decaying state is 'cut' from the left and from the right. We then turn to the question if such a modification of the energy distribution is realistic for the case of the decay of highly charged ions.

X-RAY EMISSION FROM MULTICHARGED XENON IONS IN ELECTRON BEAM ION TRAP (EBIT)

D. Sobota[a], D. Banaś[a], Ł. Jabłoński[a], P. Jagodziński[b], A. Kubala-Kukuś[a], M. Puchała[a], I. Stabrawa[a], M. Pajek[a]

[a]Institute of Physics, Jan Kochanowski University, Świętokrzyska 15, 25-406 Kielce, Poland
[b]Departament of Physics, University of Technology, Aleja Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland

Multicharged ions are produced in the electron beam ion traps (EBIT) by sequential electron-impact ionization of atoms/ions in a strong magnetic field [1]. Depending on trap parameters, such as electron beam energy, electron beam current, confinement time, trapping potential, different ion charge state distributions are produced which affect in turn the x-ray emission from a trap. The measured x-ray spectra carry thus information on atomic processes taking place in the EBIT plasma, in particular, the electron impact ionization/excitation, radiative/nonradiative deexcitation and radiative recombination(RR) processes.

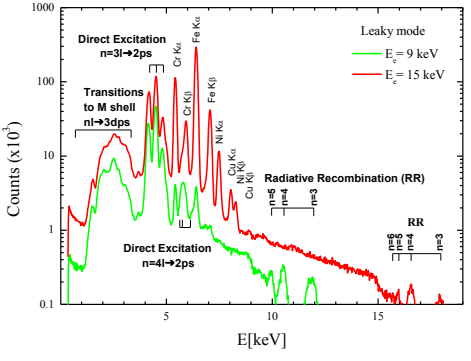

Figure 1: Measured X-ray spectra from highly charged xenon ions in the EBIT for electron beam energies 9 keV and 15 keV.

In this paper we report the results of measurements of x-ray emission from highly charged xenon ions trapped in an EBIT for different electron beam energies. The measurements were performed at the Kielce EBIS facility [1,2] consisting of an EBIT, dipole analyzing magnet and UHV experimental chamber for used for the studies of ion-surface interactions [3]. Highly charged Xe^{q+} ions were produced by an electron beam of energy 9-15 keV resulting in a wide distribution of charge states peaked at about q=36. The X-rays were measured by a semiconductor drift detector (SDD) mounted behind 50 μm beryllium window of the EBIT.

The measured spectra (Fig. 1) show the x-ray lines from radiative recombination into n=3-5 states and the M-shell and L-shell x-ray transitions in multicharged xenon ions. Additionally, the characteristic x-ray fluorescence from metallic components of a trap is clearly visible. The observed M-shell transitions in highly charged xenon with opened M-shell were identified as $n\ell \rightarrow 3spd$ with $n \geq 4$ and $q \leq 44$. The L-shell transitions were $n\ell \rightarrow 2sp$ with $n \geq 3$, but in this case they were excited by direct electron impact excitation of lower charge state Xe ions. The structure of observed x-ray transitions was explained assuming electric dipole selection rules for ℓ-states and available calculations [4,5] of x-ray energies in highly charged Xe ions.

Acknowledgements

The equipments was purchased thanks to financial support of the European Regional Development programs (WNP-POIG.02.02.00-023/08 and POPW.01.01.00-26-013/09-04)

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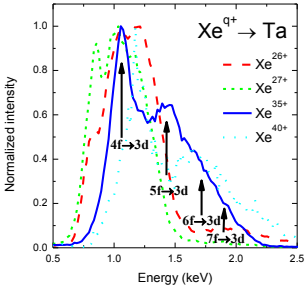
SPECTROSCOPY OF X-RAYS EMITTED IN INTERACTION OF HIGHLY CHARGED XENON IONS WITH BERYLLIUM FOIL

Ł. Jabłoński[a], D. Banaś[a], J. Braziewicz[a], J. Czub[a], P. Jagodziński[b], A. Kubala-Kukuś[a], D.Sobota[a], I. Stabrawa[a], M. Pajek[a]

[a]Institute of Physics, Jan Kochanowski University, Świętokrzyska 15, 25-406 Kielce, Poland
[b]Department of Mathematics and Physics, Kielce University of Technology, al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland

In the interaction of slow highly charged ions (HCI) with surfaces the so-called "hollow atoms" are formed [1-2]. In these exotic atomic states a large part of the electrons are in high Rydberg levels while inner shells remain empty. The X-rays and Auger electrons emitted in deexcitation of hollow atoms carry information about formation and the structure of this objects as well as the relaxation process.



In this work we report on the measurements of X-rays emitted in interaction of ~3 keV×q Xe^{q+} ions (q=26-40) with metallic Be foil. The ion beams were produced in EBIS-A facility [3-4] which consist of electron beam ion trap (EBIT), ion extraction and beam transport system, analyzing dipole magnet and UHV experimental chamber equipped with a manipulator to mount a sample. To measure the X-rays we used the XFlash silicon drift detector (SDD) having resolution of about 80 eV in 1-2 keV energy range studied.

Figure 1: Measured spectrum of X-rays emitted in interaction of Xe^{26+}, Xe^{27+}, Xe^{35+} and Xe^{40+} ions of energy ~3 keV×q with Be foil (the arrows indicate the energies of transitions in Xe^{35+})

The X-rays spectra measured for different charge states of ions were interpreted as a series of satellite and hypersatellite nℓ-3ℓ X-ray transitions (where n≥4). The energies of these transitions for different charge states were taken from [5], but more complex MCDF calculation are in progress. In order to reproduce the measured spectra, the experimental broadening of spectral lines have been taken into account. The observed line intensities yielded information about population of electrons in high n-states (n≥3). For Xe^{26+} with no M-shell vacancies the observed M X-rays may indicate an internal dielectronic excitation process[6].

Acknowledgments
The equipment was purchased thanks to financial support of the Europan Regional Development Fund in the framework of the Polish Innovative Economy Operational Program (Contact No. WNP-POIG.02.02.00-26-023/08).

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DETERMINATION OF TRANSITION ENERGY FROM ASYMMETRIC X-RAY LINEPROFILE IN PRECISION SPECTROSCOPY

Paweł Jagodziński[a], Marek Pajek[b], Dariusz Banaś[b], Thomas Stöhlker[c]

[a]Department of Mathematics and Physics, Kielce University of Technology, al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland

[b]Institute of Physics, Jan Kochanowski University, Świętokrzyska 15, 25-406 Kielce, Poland

[c]GSI Helmholtzzentrum für Schwerionenforschung, D-64291 Darmstadt, Germany

Progress in precision X-ray spectroscopy of high-Z few-electron ions [1,2] and theoretical atomic structure calculations [3] give new perspectives for sensitive tests the higher-order QED effects in heavy few-electron ions. For He-like ions, which are the simplest many-electron structures, the energy levels and transition energies are still not well known (e.g. He-like U^{90+}) and the theoretical predictions differ from each other up to 1 eV [3]. The QED effects in few-electron heavy ions can be studied by applying high-resolution diffraction spectrometers with energy resolution of about 1 eV [4]. However, due to low efficiency of these instruments, a spectrometer with a large crystal bent in a focusing (sigittal) plane, additionally to its bending in a dispersive (meridional) plane, should be used for this purpose. Both assumptions are satisfied in a spherical crystal Johann-type spectrometer [4].

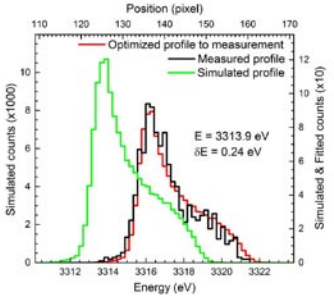

Fig. 1: Simulated profile of $1s2p\ ^3P_2 \rightarrow 1s2s^3S_1$ in He-like uranium simulated for spherical Johann spectrometer.

The energy profile of X-rays measured with Johann spectrometer exhibits a pronounced asymmetry (called Johann bump) shown on Fig. 1, which is caused by non-perfect focusing in this geometry. Such a profile can be characterized by its full width at half maximum (FWHM), which is interpreted as the energy resolution of a spectrometer, as well as some additional parameter, full width at tenth of maximum (FWTM), characterizing its width at the tail. The FWHM energy resolution of a dedicated spherical crystal spectrometr designed for a measurement of $1s2p\ ^3P_2 \rightarrow 1s2s^3S_1$ transition in He-like uranium ions was simulated to be 1.9 eV [5], including x-ray source extension and Doppler effect. However, the X-ray transition energy can be determined in this case with better accuracy. This can be achieved, first, by precise modeling of asymmetry of x-ray profile using ray-tracing simulations and, second, by optimizing the energy offset of observed and calculated profile (with assumed transition energy). In this procedure the uncertainty of x-ray energy determination was estimated to be 0.24 eV [5], which allows a study QED effects in He-like uranium.

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TUNGSTEN SPECTROSCOPY RESEARCH USING LOW ENERGY EBITS AT THE SHANGHAI EBIT LABORATORY

J Xiao[a,b], W X Li[a,b], Z Z Zhao[a,b], M L Qiu[a,b], Y Yang[a,b], T Brage[c], C Y Chen[a,b], R Hutton[a,b], and Y Zou[a,b]

[a] The Key Laboratory of Applied Ion Beam Physics, Ministry of Education, 200433 China

[b] Shanghai EBIT laboratory, Institute of Modern Physics, Fudan University, Shanghai, 200433 China

[c] Division of Mathematical Physics, Department of Physics, Lund University, Sweden

We present an overview of recent work on the spectroscopy of tungsten ions, related to tokamak edge plasma. Tungsten spectra were recorded from the SH-HtscEBIT[1] in the Shanghai EBIT laboratory. In the visible spectrum range, we have studied the spectra of W^{13+},W^{25+} to W^{28+} .By analyzing the spectra with the help of accurate theoretical calculations, using state-of-the-art techniques, we were able to identify term and fine structure splittings in the ground and the first excited configuration for a number of charge states. The theoretical models included a careful study of correlation and showed an excellent agreement with our experimental results for transition energies and rates. Some metastable levels which have extremely long lifetime and high population were found, and the influences of these levels on the charge state distribution of tungsten ions in tokamaks are discussed. In the EUV spectrum range, we have studied the spectra from W^{11+} toW^{15+}. The charge states and spectra transitions were identified by comparison with calculations using a detailed relativistic configuration interaction method and collisional-radiative model, both incorporated in the flexible atomic code.

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DYNAMICS OF Pm-LIKE Bi ATOMIC SYSTEMS

J. P. Marques[a,b], M. C. Martins[b], J. P. Santos[b], P. Indelicato[c], F. Parente[b,a]

[a]BioISI - Biosystems & Integrative Sciences Institute, Departamento de Física, Faculdade de Ciências da Universidade de Lisboa, Campo Grande, C8, 1749-016 Lisboa, Portugal

[b]Laboratório de Instrumentação, Engenharia Biomédica e Física da Radiação (LIBPhys-UNL), Departamento de Física, Faculdade de Ciências e Tecnologia, FCT, Universidade Nova de Lisboa, 2892-516 Caparica, Portugal

[c]Laboratoire Kastler Brossel, UPMC-Sorbonne Universités, CNRS, ENS-PSL Research University Collège de France

Kobayashi *et al*. [1] showed experimentally, using an EBIT, that the more intense resonance lines in Pm-like bismuth are the ones corresponding to the $4f^{13}5s5p - 4f^{13}5s^2$ transitions, due to the presence of the $[4f^{13}5s^2]_{7/2}$ metastable level, contrary to the earlier prediction of Curtis and Ellis [2].

We used the multi-configuration Dirac-Fock (MCDF) code of Desclaux and Indelicato [3,4] to calculate the excitation cross section, transition energy, and probability values for this system and were able to obtain the relative line intensities, for different values of electron energies and densities.

Furthermore, we have developed a method to predict the time evolution of the population of the pertinent levels (Fig.1) until equilibrium is reached.

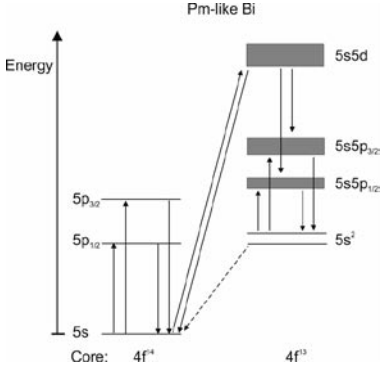

Figure 1: Level scheme of Pm-like Bi

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NE-LIKE HEAVY IONS AS AN ATOMIC LIFETIME LABORATORY: FE XVII

E. Träbert[a,b], **P. Beiersdorfer**[a], J. R. Crespo López-Urrutia[c]

[a]Physics Division, PLS, LLNL, Livermore, CA 94550, USA
[b]AIRUB, Ruhr-Universität Bochum, 44780 Bochum, Germany
[c]MPI für Kernphysik, 69117 Heidelberg, Germany

The four lowest excited levels in Ne-like ions, $2p^5 3s$, feature lifetimes of very different order of magnitude and of very different isoelectronic scaling because of the underlying decay mechanisms. The resonance and intercombination decays of the two J=1 levels (by electric dipole (E1) decay) in moderately high ion charge states have been subject of systematic studies using the beam-foil technique [1,2]. The SuperEBIT electron beam ion trap at Livermore has served to cool a cloud of Ne-like ions of Cs (Cs^{45+}) so much that the thermal line broadening was reduced below the natural linewidth of n=3 levels and a picosecond level lifetime could be determined [3].

The Fe XVII emission spectrum (Ne-like spectrum of Fe) comprises several very prominent X-ray lines that play an important role in the study of many astrophysical objects, including three transitions emanating from a 3s level. Two of the four 3s levels are metastable (J=0,2), which means they have a rather long radiative decay time compared to collisional processes. The (M2) decay rate of the $2p^5 3s$ J=2 level has recently been measured at the Livermore EBIT facility, and the scatter of predictions by a factor of 1.7 has been reduced to a measurement uncertainty of merely a few percent [4]. An even longer-lived level is the $2p^5 3s$ J=0 level. Theory predicts that it decays exclusively by magnetic dipole (M1) decay at 1153 Å to the $2p^5 3s$ J=1 level. We have used the Livermore electron beam ion trap facility to measure the M1 decay rate of the $2p^5 3s$ J=0 level. We find a value of 14,500 $\pm$ 1500 s^{-1} [5], which is in agreement with available calculations.

Work performed under auspices of U.S. D.o.E. by DE-AC52-07NA27344 and supported by NASA's APRA program under Interagency Agreement NNG13WF991.

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NONPERTURBATIVE TREATMENT OF THE ZEEMAN EFFECT IN HIGHLY CHARGED IONS WITH NONZERO NUCLEAR SPIN

Anna M. Volchkova[a,b], Dmitry A. Glazov[a,b]

[a]Department of Physics, St. Petersburg State University,
Universitetskaya nab. 7/9, 199034 St. Petersburg, Russia
[b]State Scientific Centre "Institute for Theoretical and Experimental Physics"
of National Research Centre "Kurchatov Institute",
B. Cheremushkinskaya st. 25, 117218 Moscow, Russia

Investigations of the Zeeman splitting of the hyperfine-structure levels in few-electron ions can serve for precise determination of the nuclear magnetic moments [1,2]. We present relativistic calculations of the g-factor and the coefficients of the Breit-Rabi formula for $n = 1$ and $n = 2$ energy levels in few-electron ions. In contrast to previous calculations [3-6], where the magnetic interaction was treated as a perturbation, we start with Dirac equation in the presence of external magnetic field, which is solved within the dual-kinetic-balance approach [7]. The results for $1s$ and $2s$ states are in agreement with the previously published values [3-5]. The results for $2p_{1/2}$ and $2p_{3/2}$ states provide the theoretical basis for future experiments with boron-like ions.

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HYPERFINE INDUCED EFFECTS ON THE ANGULAR DISTRIBUTION OF THE DIELECTRONIC HYPERSATELLITE LINE

V.A. Zaytsev[a], A. Surzhykov[b], S. Fritzsche[b,c], V.M. Shabaev[a]

[a]Department of Physics, St. Petersburg State University, 7/9 Universitetskaya nab., St. Petersburg, 199034, Russia

[b]Helmholtz-Institut Jena, Fröbelstieg 3, 07743 Jena, Germany

[c]Universität Jena, Institut für Theoretische Physik, 07743 Jena, Germany

Strong progress in the x-ray detector techniques presently allows one to regard the angular and polarization measurements as a powerful tool for exploring highly-charged ions [1-4]. Nowadays, the possibility of applying this instrument for studying the nuclear properties and the hyperfine (HF) induced effects is tested. An opportunity of investigating the HF induced effects on the polarization of the x-ray emission was first pointed out in Ref. [5]. In that work, it was experimentally found that the polarization of the photons being emitted from He-like scandium ($Z = 21$) is significantly affected by the hyperfine interaction (HFI). Though this work was published two and a half decades ago, the similar studies are presented quite sparsely in the literature.

In the present work, we investigate the influence of the nuclear spin I and the nuclear magnetic dipole moment μ on the properties of the x-ray emission following the dielectronic recombination (DR) of an electron with a heavy Li-like ion. Specifically, the effects induced by the HF structure and the HFI on the angular distribution are studied. Here we suppose that the levels of the HF structure are not resolved that corresponds to the most realistic situation. The interest to initially Li-like ions is explained by the fact that in such systems one can populate a particular fine structure level [6] and, as a consequence, identify the HF induced effects more explicitly. Nevertheless special attention is paid to the case when even fine structure levels are assumed to be unresolved. In both situations the angular distribution appears to be sensitive to variation of I and μ. Thus one can expect that the accurate measurement of the x-ray angular distribution can be regarded as an independent tool for the determination of the nucleus parameters.

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ENERGY LEVELS, TRANSITION RATES AND LIFETIMES OF 1s2s(^{3}S)3ℓ STATES FOR Li-LIKE IONS WITH $Z \leq 10$

J. P. Santos[a], J. P. Marques[b,a], M. C. Martins[a], P. Indelicato[c], E. P. Benis[d], I. Madesis[e] , T. J. M. Zouros[e], F. Parente[a,b]

[a]Laboratório de Instrumentação, Engenharia Biomédica e Física da Radiação (LIBPhys-UNL), Departamento de Física, Faculdade de Ciências e Tecnologia, FCT, Universidade Nova de Lisboa, 2892-516 Caparica, Portugal
[a]BioISI - Biosystems & Integrative Sciences Institute, Departamento de Física, Faculdade de Ciências da Universidade de Lisboa, Campo Grande, C8, 1749-016 Lisboa, Portugal
[c]Laboratoire Kastler Brossel, UPMC-Sorbonne Universités, CNRS, ENS-PSL Research University Collège de France
[d]Department of Physics, University of Ioannina, GR 45110 Ioannina, Greece
[e]Department of Physics, University of Crete, P.O Box 2208, GR 71003 Heraklion, Greece

The study of the selective enhancement of 1s2snℓ states populated by cascades in single-electron transfer collisions of ions with He and H_2 targets have been studied by Zouros *et al*. [1]. In this work, we present the energy levels, transition rates and lifetimes for Li-like ions with $Z \leq 10$ in the 1s2s(^{3}S)3ℓ states calculated using the multiconfiguration Dirac-Fock (MCDF) code of Desclaux and Indelicato [2, 3]. The preliminary results obtained for the 1s2s3p levels are displayed in Figure 1.

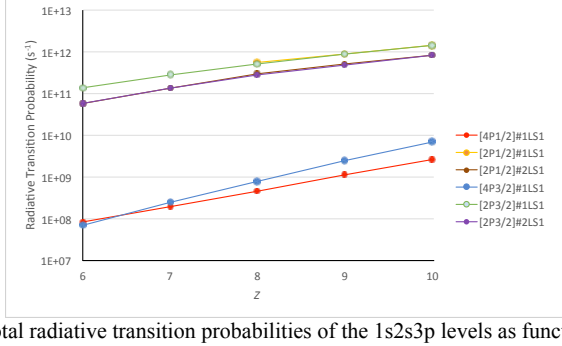

Figure 1: Total radiative transition probabilities of the 1s2s3p levels as function of the *Z*.

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DOUBLE AND SINGLE ELECTRON TRANSITIONS IN He-LIKE IONS WITH EMPTY K SHELL

L.Natarajan[a*] and Anuradha Natarajan[b]

[a]Department of Physics, University of Mumbai, Mumbai, India
[b]Department of Physics, SIWS college, Wadala, Mumbai,India
*corresponding author :ln@physics.mu.ac.in

Fully relativistic configuration interaction calculations in the active space approximation [1]have been carried out to study the one-electron one- photon (OEOP) and the unusually intense two-electron one-photon (TEOP) electric dipole transitions from the states of 2s3s configuration in He-like ions [2,3] with $13 \leq Z \leq 74$. As the TEOP transitions are correlatition sensitive, care has been taken to include all significant contributions to correlation . The branching ratios of the OEOP and TEOP transitions are reported for the first time tp the best of our knowledge. The effects of Breit interaction and quantum electrodynamics on the transition probabilities have been analyzed in detail.The results are compared with other available data[3].

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SOLAR WIND CHARGE EXCHANGE IN LABORATORY - OBSERVATION OF FORBIDDEN X-RAY TRANSITIONS -

Naoki Numadate[a], Kunihiro Okada[b], Nobuyuki Nakamura[c] , Hajime Tanuma[a]

[a]Department of Physics, Tokyo Metropolitan University, 1-1 Minami-Ohsawa, Hachioji, Tokyo 192-0397, Japan

[b]Department of Physics, Sophia University, 7-1 Kioicho, Chiyoda, Tokyo 102-8554, Japan

[c]Institute for Laser Science, University of Electro-Communications, 1-5-1 Chofugaoka, Chofu, Tokyo 182-0021, Japan

In this 30 years, soft x-ray emissions from the solar system have been observed by X-ray observatory satellites [1]. Now it has been recognized that a part of these emissions stems from charge exchange collisions between highly charged ions in solar wind and neutrals in the solar system [2]. These reactions are called solar wind charge exchange (SWCX). In the SWCX spectra, the forbidden transition from the metastable O^{6+}, 1s2s $^3S_1$, is observed as the main component [3]. However, it is very difficult to observe the forbidden transition with a long lifetime of millisecond from the ion having the solar wind velocity of 300-900 km/s in the laboratory. Nonetheless we succeded in observation of the long-lived forbidden transition by trapping metastable O^{6+} ions after charge exchange reactions of $O^{7+}(1s) + He \rightarrow O^{6+}(1snl) + He^+$.

We reproduced the SWCX by injecting highly charged O^{7+} ion beam into a collision cell filled with helium gas. After the collision, only O^{6+} ions were introduced and trapped in a Kingdon ion trap, and soft X-ray emissions from them ware observed with a silicon drift detector. Figure 1 shows an observed forbidden line (solid line). The peak energy of this line is 560 eV, which is corresponded to the transition of $1s^2\ ^1S_0$ - 1s2s $^3S_1$. We had observed the resonance lines of O^{6+} with the same set-up (dotted line). When the intensities are normalized at the peaks, we show the reasonable energy difference of about 10 eV between two peaks.

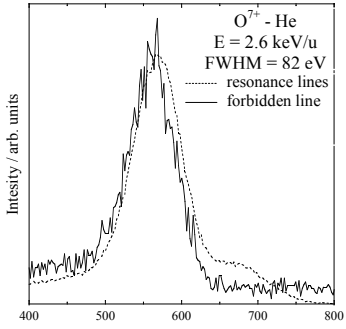

Figure1. Forbidden and resonance line spectra from O^{6+} ions.

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PRELIMINARY OBSERVATION OF X-RAY SPECTROSCOPIC LINES FROM TUNGSTEN 45+, 46+ IONS BY A FLAT-CRYSTAL SPECTROMETER IN SHANGHAI EBIT

Yang YANG[a,b], Jacek RZADKIEWICZ[c], Jun XIAO[a,b], Roger HUTTON[a,b], Yaming ZOU[a,b]

[a]Shanghai EBIT Laboratory, Institute of Physics, Fudan University, Shanghai, China
[b]The Key Lab of Applied Ion Beam Physics, Ministry of Education, China
[c]National Centre of Nuclear Research, 7 Andrzeja Sołtana str., Otwock-Świerk, Poland

The W45+ and W46+ 3p–4d inner shell excitation lines in addition to Mo32+ 2p–3s lines, in the wavelength range 5.0-5.35 Å, have been identified from the spectrum taken by an upgraded high-resolution x-ray spectrometer designed for ITER-like wall experiments at JET[1,2]. The urgent need for interpretation of these spectra comes primarily. It is an advantage for an Electron Beam Ion Trap device to generate one of or both these tungsten and molybdenum ions in its trap, and let them experience a quasi-monoenergetic or an equivalent-maxwellian energy distribution electron beam[3], whose energy can be controlled precisely as well as its electron density and an external magnetic field at the trap. A series experimental observation and theoretical simulation are proceeding in Shanghai EBIT Laboratory, aiming at clarifying the relation between intensities of these spectral lines and electron energy/ temperature, as well as relative abundances of these ions in the plasma. Some preliminary observations were done at Shanghai EBIT lab, by using a flat-crystal spectrometer[4], one of which is presented in Figure 1, acquired at an electron beam energy of 3.75 keV and beam current of 36.7mA and magnetic field of 3T.

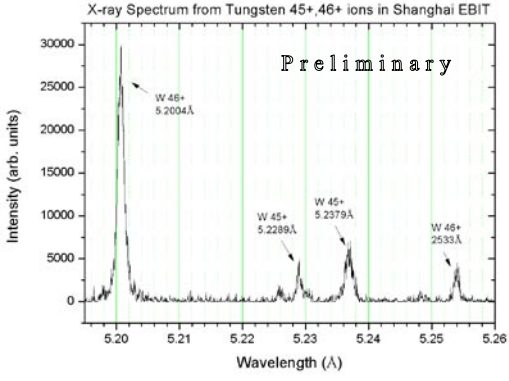

Figure 1: A preliminary tungsten spectrum in Shanghai EBIT from a flat crystal spectrometer with resolving power (λ/Δλ) around 4000.

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SPECTROSCOPY OF HIGHLY CHARGED IONS SUITABLE FOR NEW OPTICAL FREQUENCY STANDARDS

Hendrik Bekker[a], Alexander Windberger[a], José R. Crespo López-Urrutia[a]
[a]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

In recent years, various highly charged ions with optical transitions have been proposed for implementation in next generation optical frequency standards in view of their advantageous low sensitivity to external perturbations. In particular, Ir^{17+} ($Z = 77$) also offers optical transitions with a strong dependence on variation of the fine-structure constant due to a $4f$–$5s$ level crossing. Unfortunately, the accuracy achieved by predictions is unsuitable for laser spectroscopic searches. To resolve this issue, we produced and trapped Re^{15+}, Os^{16+}, Ir^{17+}, and Pt^{18+} ions of the Nd-like isoelectronic sequence in the Heidelberg electron beam ion trap (EBIT). Emission spectra were measured with grating spectrometers sensitive in the optical and the extreme ultraviolet (EUV) range [2, 3]. Several optical transitions could be identified by their known scaling with atomic number Z^2. Identifications were also based on the characteristic line shapes due to the Zeeman splitting of involved fine-structure levels in the strong magnetic field (8 T) of the EBIT, see Fig. 1.

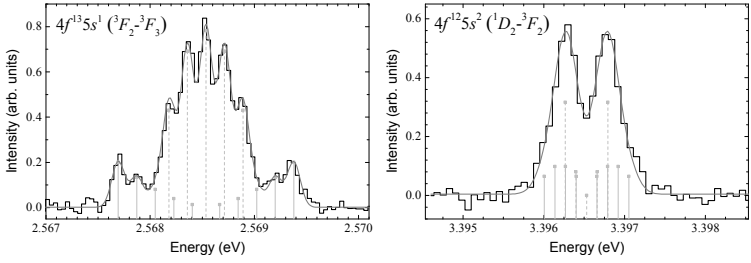

Figure 1: Two examples of well resolved M1 lines of Ir^{17+} that could be identified by their characteristic Zeeman line shapes. The smooth gray line shows a fit of the Zeeman line shape model to the data (black). The vertical lines show the energies of the individual Zeeman components (dashed $\Delta m = 0$, solid $\Delta m = \pm 1$).

The interpretation of the EUV spectra in the range from approximately 16 to 23 nm was supported by predictions from a collisional-radiative model. In the Pm-like iso-electronic sequence Re^{14+}, Os^{15+}, Ir^{16+}, and Pt^{17+} the long sought-after alkali-like $5s_{1/2}$–$5p_{3/2}$ transitions were identified. Further identifications in both Pm-like and Nd-like ions could be used to benchmark and improve the accuracy of atomic theory for these complex, not well-understood, systems. Moreover, the obtained results are an important step towards laser spectroscopy that could be performed with sympathetically cooled HCI in cryogenic Paul traps such as CryPTEx [4].

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ISOTOPE SHIFTS OF THE $2p_{3/2}$-$2p_{1/2}$ TRANSITION IN B-LIKE IONS

N. A. Zubova[1,2], A. V. Malyshev[1,2], I. I. Tupitsyn[1], V. M. Shabaev[1], Y. S. Kozhedub[1], G. Plunien[3], C. Brandau[4,5,6], and Th. Stöhlker[4,7,8]

[1]Department of Physics, St. Petersburg State University, 7/9 Universitetskaya nab., St. Petersburg 199034, Russia
[2]SSC RF ITEP of NRC "Kurchatov Institute", Bolshaya Cheremushkinskaya 25, Moscow, 117218, Russia
[3]Institut für Theoretische Physik, TU Dresden, Mommsenstrasse 13, Dresden, D-01062, Germany
[4] GSI Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany
[5] ExtreMe Matter Institute EMMI and Research Division, GSI Helmholtzzentrum für Schwerionenforschung, D-64291 Darmstadt, Germany
[6] Institut für Atom- und Molekülphysik, Justus-Liebig-University Giessen, Leihgesterner Weg 217, D-35392 Giessen, Germany
[7] Helmholtz-Institut Jena, D-07743 Jena, Germany
[8] Institut für Optik und Quantenelektronik, Friedrich-Schiller-Universität Jena, D-07743 Jena, Germany

High-precision measurements of the isotope shifts in heavy ions, that are anticipated at the FAIR facilities, will give a unique possibility for tests of QED in a new region: strong-coupling regime beyond the Furry picture. In addition, these studies will allow determination of the nuclear charge radius differences for radioactive isotopes with a lifetime longer than about 1 min. These investigations require high-precision calculations of the isotope shifts, including the relativistic and QED effects. Such calculations for Li-like ions were performed in Ref. [1]. In this paper we present the corresponding calculations for B-like ions [2].

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DIELECTRONIC RECOMBINATION WITH HE-LIKE IONS OF URANIUM

K.N. Lyashchenko[*,1], **O.Yu. Andreev**[*]

[*]Department of Physics, St. Petersburg State University, 7/9 Universitetskaya nab., St. Petersburg, 199034, Russia

Abstract

Calculation of the differential cross section for the dielectronic recombination with He-like ions of uranium within the framework of QED is presented. Contributions of the Breit interaction and the interference of the photon multipoles are investigated.

We presented a study of dielectronic recombination with He-like uranium [1], where the initial state is given by a two-electron ion of uranium being in its ground state and by an incident electron. We investigate energy regions where the energy of the initial state is close to the energies of doubly excited states: $(1s,(2s)^2)$, $(1s,2s,2p)$, $(1s,(2p)^2)$. The final state is given by an emitted photon and a Li-like ion in one of the ground state or the single-excited states: $((1s)^2,2s)$, $((1s)^2,2p)$. The process of dielectronic recombination is a resonant process. The resonances in the cross section correspond to the doubly excited states. In the resonant area the dielectronic recombination gives the main contribution to the cross section.

The calculations are performed with employment of the line-profile approach [2-4]. The one-photon exchange correction for the low-lying states is taken into account in all orders of the QED perturbation theory. The electron self-energy and vacuum polarization corrections are considered in the first order of the perturbation theory. We present results of the calculation of the total and differential cross section. The polarization properties are also considered and the Stokes parameters are calculated. The contribution of the Breit interaction to the cross section and to the Stokes parameters is investigated in details.

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[1]E-mail: laywer92@mail.ru

SATELLITE AND HYPERSATELLITE Lγ X-RAY LINES OF THORIUM

M. Polasik[a], K. Słabkowska[a], J. Starosta[a], M. Czarnota[b], D. Banaś[b], M. Pajek[b], J.-Cl. Dousse[c], J. Hoszowska[c]

[a] Faculty of Chemistry, Nicolaus Copernicus University in Toruń, 87-100 Toruń, Poland
[b] Institute of Physics, Jan Kochanowski University, 25-406 Kielce, Poland
[c] Physics Department, University of Fribourg, CH-1700 Fribourg, Switzerland

The subject of this study are the line shapes of $L\gamma_1$ (L_2–N_4), $L\gamma_2$ (L_1–N_2), $L\gamma_3$ (L_1–N_3) and $L\gamma_6$ (L_2–O_4) diagram and satellite x-ray transitions of thorium. The dynamics of the multiple ionization and the structure of the M- and N-shell satellites can be explained only taking into account the extensive multiconfiguration Dirac-Fock calculations [1]. For every calculated type of lines the theoretical stick spectra (line positions with their relative intensities) have been presented. For every line two theoretical spectra have been foreseen, one as a sum of the Lorentzian natural line shapes and the other one, as a convolution of the Lorentzian natural line shapes sum with the Gaussian instrumental response (see Figure 1).

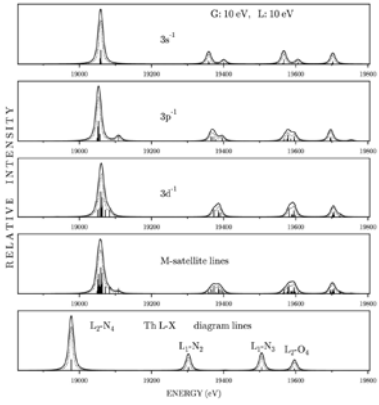

Figure 1: MCDF calculations (stick spectra) and theoretically constructed diagram and satellite x-ray spectra for the $L\gamma_1$, $L\gamma_2$, $L\gamma_3$ and $L\gamma_6$ transitions of thorium. Partial spectra corresponding to different subshell of M-shell spectator vacancy configurations are also presented in the three top panels.

Presented results have been already used for the interpretation of experimental high-resolution Lγ x-ray spectra of thorium generating in the collisions with 360 MeV oxygen ions [2]. We plan to show on the conference the preliminary results of the decomposition of this experimental Lγ x-ray spectrum of thorium on the contributions corresponding to the MCDF predictions for particular hole configurations. The good agreement between the theoretical (MCDF) predictions and the details of experimental spectrum have been achived.

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QED CALCULATIONS OF THE IONIZATION ENERGIES OF BORONLIKE IONS

Aleksei V. Malyshev[a,b], Dmitry A. Glazov[a,b], Andrey V. Volotka[a,c], Ilya I. Tupitsyn[a], Vladimir M. Shabaev[a], Guenter Plunien[d]

[a]Department of Physics, St. Petersburg State University, Universitetskaya nab. 7/9, 199034 St. Petersburg, Russia

[b]State Scientific Centre "Institute for Theoretical and Experimental Physics" of National Research Centre "Kurchatov Institute", B. Cheremushkinskaya st. 25, 117218 Moscow, Russia

[c]Helmholtz-Institut Jena, Fröbelstieg 3, D-07743 Jena, Germany

[d]Institut für Theoretische Physik, Technische Universität Dresden, Mommsenstraße 13, D-01062 Dresden, Germany

Ionization energies for the $1s^2 2s^2 2p_{1/2}$ and $1s^2 2s^2 2p_{3/2}$ states of boronlike ions with nuclear charge number in the wide range $16 \leq Z \leq 96$ are rigorously evaluated. The approach applied [1] merges *ab initio* QED treatment in the first and second orders of the perturbation theory in the fine-structure constant α with the third- and higher-order electron-correlation contributions evaluated within the Breit approximation [2]. To formulate the QED perturbation theory the two-time Green function method is employed [3]. The nuclear recoil effect is taken into account. The accuracy of the ionization energies obtained is significantly improved in comparison with previous calculations.

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HCI COLLISIONS WITH LARGE MOLECULES : NUCLEOBASES AND WATER

Lokesh C Tribedi[a]

[a]Tata Institute of Fundamental Research, Colaba, Mumbai 400005, India

Present-day atomic collision physics is closely related to interdisciplinary science. Collisional interaction of fast ions with large biomolecules, PAH and fullerenes [1-8] is an active field of research. The secondary electron emission from nucleobases and water is an important parameter to estimate the radiation damage caused by the fast ions. A recently installed 14.5 GHz ECR based ion-accelerator on 400 kV deck and the existing 14 MV Pelletron tandem accelerator in TIFR are being used to investigate many body effects on collision products and varieties of other processes[1-8]. The collision energy varies between (20 keV-80 MeV). In particular the angular distribution and angular asymmetry in the electron double differential cross sections and total ionization cross section in case of water [3,5] or biomolecules (such as uracil and Adenine) provides a very crucial input regarding the many-body aspects. The dramatically large forward backward asymmetry in electron emission for uracil [4,6,7] compared to small molecules indicates a size effect. At the total cross section level a clear deviation from the q^2-dependence have been established from a series studies. The best known quantum mechanical model although comes closer to the water data at high energies, at intermediate energies it fails. Inclusion of transfer-ionization mechanism improves the agreement with a suitable scaled model. A large enhancement in e-emission from a nano-solvated bio-molecule has also been quantitatively determined only recently. The studies involve HCIs of C, O, F and Si of varieties of energy ~keV/u -MeV/u. The detailed data for these molecules has been used to develop a scaling rule of ionization in terms of velocity and charge states, which will have input for the model calculation for radiation damage at hadron therapy. The C60 fullerene is used as a benchmark system which manifests the giant plasmon resonance in electron DDCS spectrum. The collective excitation peak alone explains~50% of the total cross section. These results imply the large influence on the low energy e-emission of the many body processes and must be inclluded in the radiation damage modeling. A similar plasmon-electron emission in the PAH and C_{60} molecules has been demonstrated only recently [1,2]. Some relevant examples will be presented, mostly based on the work done in our laboratory [1-8], from recent experiments on electron spectroscopy and time-of-flight recoil-ion mass spectroscopy.

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POLARIZATION CORRELATIONS IN BREMSSTRAHLUNG

R. A. Müller[a,b], R. H. Pratt[c], A. Surzhykov[a,b]

[a]Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany

[b]Technische Universität Braunschweig, 38106 Braunschweig, Germany

[c]Department of Physics and Astronomy, University of Pittsburgh, Pennsylvania 15260, USA

During the recent years advances have been made in the generation of electron beams with polarization purities larger than 80%. Moreover high-precision detectors have been developed to measure the polarization direction and degree of light with photon energies in the MeV-regime. In view of bremsstrahlung, which is the inelastic scattering of an electron by an atom or ion under simultaneous photon emission, these techniques are used to investigate how the incident electron and outgoing photon polarizations are correlated (Ref. [1] and references therein). The connection between the polarization of the in- and outgoing particles can be described using the so-called correlation-parameters C_{ij}. In bremsstrahlung, where the incident electron is prepared in a certain polarization state and only the emitted photon is observed, there are seven nonzero C_{ij}'s, where i and j specify the polarization of the ingoing electron and outgoing photon, respectively. In this contribution we will show detailed calculations of these parameters and discuss their dependence on the nuclear charge and the energies of the incident and scattered electrons. Moreover we show that the seven C_{ij} are not independent, but fulfill the sum rule $R = C_{03}^2 + C_{11}^2 + C_{12}^2 + C_{20}^2 + C_{31}^2 + C_{32}^2 - C_{23}^2 = 1$ if the outgoing electron is in a $s_{1/2}$-state [2]. The latter condition is only met in the so called tip region, where the incident electron transferres almost all of its energy to the emitted photon. Additionaly our calculations, as presented in Fig. 1, show that the sum rule is fulfilled best ($R \approx 1$) for low nuclear charges and high electron energies.

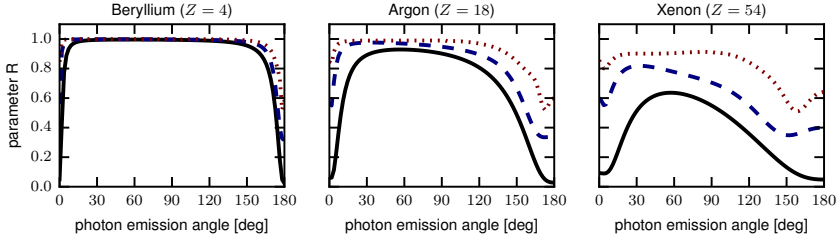

Figure 1: Sum of squared polarization correlations R as a function of the photon emission angle for three incident electron energies ($E_i = 100$kev: black solid line, $E_i = 500$keV: blue dashed line, $E_i = 1000$keV: red dotted line) and three different nuclear charges ($Z = 4$: left panel, $Z = 18$: center panel, $Z = 54$: right panel). The energy of the outgoing electron is 1eV.

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RELATIVE BIOLOGICAL EFFECTIVENESS OF DOUBLE ION BEAM CONTAINING CARBON AND OXYGEN IONS

Joanna Czub[a], Janusz Braziewicz[a,b], Dariusz Banaś[a,b], Marian Jaskóła[c], Urszula Kaźmierczak[d], Andrzej Korman[c], Anna Lankoff[e,f], Halina Lisowska[e], Zygmunt Szefliński[d], Andrzej Wójcik[e,g]

[a] Institute of Physics, Jan Kochanowski University, Kielce, Poland
[b] Holycross Cancer Centre, Kielce, Poland
[c] National Centre for Nuclear Research, Świerk, Poland
[d] Heavy Ion Laboratory, University of Warsaw, Warsaw, Poland
[e] Institute of Biology, Jan Kochanowski University, Kielce, Poland
[f] Institute of Nuclear Chemistry and Technology, Warsaw, Poland
[g] CRPR, MBW Department, Stockholm University, Sweden

Relative biological effectiveness (RBE) is an important parameter used in ion radiotherapy and radiobiology. RBE value depends on the biological test and dose, hence it is important to determine RBE values for various experimental conditions. Generally, there is a lack of data on the RBE of mixed beams of radiations that have different LET (linear energy transfer) values.

In this study the RBE value was estimated for CHO-K1 cells which were irradiated by double ion beam containing carbon ions and oxygen ions. These two ions were used because these ions appears during neon ion radiotherapy as components of fragmentation process. Biological response of cells were estimated by the clonogenic survival test (Figure 1). RBE value was evaluated as a function of cell surviving fraction and dose of mixed beam. Double ion beam was accelerated by cyclotron situated in the Heavy Ion Laboratory, Warsaw, Poland.

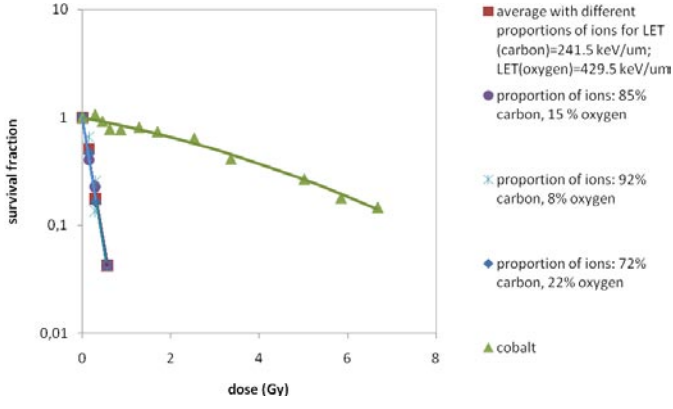

Figure 1: Survival fraction of CHO-K1 cells irradiated by double ion beam.

EFFECT OF PROJECTILE CHARGE ON ELECTRON AND POSITRON IMPACT SINGLE IONIZATIO CROSS SECTION OF H_2O

Prithvi Singh[1] , G. Purohit[1] & C. Champion[2]

1. Department of Physics, School of Engineering, Sir Padampat Singhania University, Bhatewar, Udaipur-313 601, India
2. Centre d'Etudes Nucléaires de Bordeaux Gradignan, CENBG, CNRS/IN2P3, Gradignan, Université de Bordeaux, France

The charged particle impact ionization studies of fundamental atomic and molecular systems have been of great interest since the early days of quantum mechanics. Extensive theoretical and experimental investigations have been carried out to understand the electron and positron impact single ionization processes of various targets. [1-6]. Such type of studied is important in many areas, such as understanding the processes in the earth's upper atmosphere, in the development of new lasers and novel forms of lighting, as well as in the treatment of cancers that use radiotherapy. Accurate cross sections for Water molecule target ionization by low energy electron and positron impact are very important for the understanding of the radiation damage in biological samples [7].

Triple differential cross section calculations for the ionization of $3a_1$orbitals of the water molecule by low energy electron, and positron impact are reported. The present investigation is done in the modified distorted wave born approximation using post collision interaction and polarization of target with inclusion of second order term (DWBA2). We found a very good agreement with the experimental data of Nixon and Murray [8] in case of the $3a_1$ orbital of water molecule. By changing the projectile's charge, significant differences were observed between the electron and positron impact ionization cross section of water molecules.

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ELECTRON IONIZATION CROSS SECTIONS OF C_2H_6 MOLECULE

Rajeev Kumar

Department of Physics, D.J. College, Baraut, Baghpat (U.P.), India-250611

Ethane is important in a large number of applications involving interaction with energetic electromagnetic radiation. Here we have studied the partial and total Integral Ionization Cross Sections of ethane from ionization threshold to 1000eV by using modified Jain Khare semi-empirical approach [1-5]. The major input data for this approach are oscillator strengths, we have used this data (oscillator strengths) from Brion et al [6]. Partial ionization cross sections of ethane were not available till now. Available [7-8] total (sum of partial ionization cross sections) ionization cross sections show good agreement with our data. We have also evaluated Ionization Rate Coefficients for evaluated data by using Maxwell-Boltzmann distribution[9-10].

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MAGNETIC FIELD EFFECT IN RADIATIVE RECOMBINATION OF BARE URANIUM IONS WITH COOLING ELECTRONS

D. Banaś[a], A. Gumberidze[b], P. Jagodziński[c], M. Pajek[a], Th. Stöhlker[b,d]

[a] Institute of Physics, Jan Kochanowski University, 25-406 Kielce, Poland
[b] GSI Helmholtzzentrum für Schwerionenforschung, D-64-291 Darmstadt, Germany
[c] Department of Physics, Kielce University of Technology, 25-314 Kielce, Poland
[d] Helmholtz-Institut, Jena, D-07743 Jena, Germany

The influence of magnetic field on radiative recombination (RR) of bare ions with cooling electrons, which was observed in experiments in ion storage/cooler rings [1-3] have attracted a wide interest to interpret this observation [4, 5]. As it was found experimentally the measured RR rates for very low electron-ion energies exceed the standard quantum mechanical predictions, which, on the other hand, agree with experiments for higher relative energies. This, so called, enhancement effect was studied in more details experimentally in Ref. [1], where the scaling of excess of RR rates on the magnetic guiding field in the electron cooler and the electron beam temperatures, characterizing a flattened distribution of electron velocities, was established. However, the existing interpretations [4, 5] of the RR enhancement effect still do not fully explain the observations.

In order to investigate the effect of magnetic field on RR in more details, the state-selective x-ray RR experiment has been performed in the electron cooler of the ESR storage ring with decelerated bare U^{92+} ions recombining with electrons for relative electron-ion energies in the range 0-1000 meV [6] . In this experiment the x-ray K-RR photons emitted from radiative recombination into the K- and L-shells were measured in coincidence with recombined U^{91+} ions. By comparing the measured RR rate coefficients with fully relativistic RR calculations, which reproduce the data for higher relative electron-ion energies quite well, the enhancement of RR for the lowest n=1 and n=2 states was derived for the cooling condition, i.e. the zero average relative energy. This result is a strong argument against interpretation of the RR enhancement as a results of recombination into high Rydberg states followed by decay of these intermediate states.

In this paper we discuss the observed enhancement of RR as a result of the guiding magnetic field in the electron cooler, which affects the electron trajectories. First, we present a simplified model of radiative recombination in strongly magnetized cold plasma, which explains the main features of the observed RR enhancement, including the scaling with magnetic field and electron beam temperatures. Second, the effect of the magnetic field was studied in a more detailed manner by performing the Monte Carlo simulations of RR for helical electron trajectories. The calculations show the RR enhancement particular and its observed scaling with the magnetic field. In particular, the effect of impact parameter cut-off, which is crucial for final interpretation of the simulations, is considered here in details. Finally, the proposed interpretation of the enhancement effect will be discussed in a context of the RR experiment for bare uranium ions interacting with cooling electrons.

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SPIN-ORBIT EFFECT ON THE QUANTUM-MECHANICAL CALCULATION OF MOBILITY OF CARBON IONS C^+ IN COOLED HELIUM GAS

Lamia Aissaoui[a], Moncef Bouledroua[b], Kamel Alioua[c]

[a]Laboratoire de Physique des Rayonnements et de leurs interactions avec la matière, Lahadj Lakhdar University, Batna, Algeria

[b]Département de Médecine and Laboratoire de Physique des Rayonnements, Badji Mokhtar University, Annaba, Algeria

[c]Laboratoire de Physique des Rayonnements, Badji Mokhtar University, Annaba,Algeria

According to the recent results of the mobility of carbon ions $C^+(^2P°)$ and $C^+(^4P)$ moving in a cooled buffer helium gas [1,2], we have aimed to show the effect of the spin-orbit interaction on the full quantum mechanical calculations of the mobility calculations. For this reason, we calculate the interaction potentials corresponding to ground $C^+(^2P)$-$He(^1S)$ state and the metastable-excited $C^+(^4P)$-$He(^1S)$ state which are achieved with MORPLO with adding for each potential the spin-orbit interaction. Then we use the computed quantum-mechanical transport cross sections in the Viehland gram-char Fortran code as to get the mobility of C^+ ions at several gas temperatures. A good agreement is acquired with the experiment.

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L-SHELL X-RAY EMISSION FROM ATOMS MULTIPLE IONIZED BY FAST S^{q+} IONS WITH ENERGY OF 0.4–3.8 MeV/amu

M. Jaskóła[a], I. Fijał-Kirejczyk[a], A. Korman[a], D. Banaś[b], J. Braziewicz[b], J. Choiński[c], U. Majewska[b], M. Pajek[b], J. Semaniak[b], W. Kretchmer[d], G. Lapicki[e], T. Mukoyama[f], D. Trautmann[g]

[a] National Centre for Nuclear Research, 05-400 Świerk/Otwock, Poland
[b] Institute of Physics, Jan Kochanowski University, 25-406 Kielce, Poland
[c] Heavy Ion Laboratory, Warsaw University, 02-097 Warsaw, Poland
[d] Physikalisches Institut, Universität Erlangen-Nürnberg, D-91058 Erlangen, Germany
[e] Department of Physics, East Carolina University, Greenville, NC 27858, USA
[f] Kansai Gaidai University, Hirakata, 573-1001 Osaka, Japan
[g] Institut für Physik der Universität Basel, Switzerland

X-ray emission in collisions of heavy ions of MeV energies with atoms is strongly affected by the multiple ionization process, which is increasingly important for stronger Coulomb field of the projectile. The multiple ionization leads to appearance of x-ray satellites which, for a limited energy resolution of the x-ray spectrometer, results in shifting and broadening of observed x-ray lines. Additionally, the inner-shell atomic decay rates can be drastically changed in multiply ionized atoms. Consequently, the interpretation of x-ray emission in collisions of heavy ions with atoms needs special efforts to agree with experimental results.

The present paper summarizes our experimental results on L-shell x-ray emission in collisions of S^{q+} (q=4-14) ions of energy 9.6-120 MeV with thin (10-80 $\mu g/cm^2$) films of metallic Ta, Os, Au, Bi and U deposited on carbon backings (10-20 $\mu g/cm^2$). The x-ray spectra measured with a Si(Li) detector were analyzed taking into account x-ray line shifts and broadening (see Ref. [1]), which allowed to extract both the ionization probabilities and ionization cross sections. In this short paper the results obtained for gold are discussed in more details, in particular, the ionization probabilities for the M- and N-shell at the zero impact parameter which were extracted from the measured L-x-ray spectra. The corresponding L-subshell ionization cross section for sulfur ions were partly discussed elsewhere [2].

The measured ionization probabilities for M- and N-shell for Au bombarded by 10-120 MeV S ions are in the range 3-15% and 65-45%, respectively. They were compared with the theoretical predictions based on the "geometrical model" (GM) [3] and the semiclassical calulations (SCA) [4] using different electronic wave functions, namely the nonrelativistic hydrogenic (SCA-HYD), relativistic (Dirac) hydrogenic (SCA-DH) and selfconsistent relativistic Dirac-Hartree-Fock (SCA-DHF) wave functions. In these calculation the electron binding effect was treated both in the separated- and united-atom limits. A comparison of the measured ionization probabilities with the presented calculations will be discussed in details.

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DYNAMICS OF N_2 DISSOCIATIVE IONIZATION BY ELECTRON IMPACT

X. Wang, Y. Zhang, D. Lu, R. Hutton, Y. Zou and B. Wei

Institute of Modern Physics, Department of Nuclear Science and Technology,
Fudan University, Shanghai 200433, China
brwei@fudan.edu.cn

Dissociative single, double and triple ionizations of N_2 by 200, 400 and 1000 eV electron impact are studied using cold target recoil-ion momentum spectroscopy technique in Shanghai [1]. In collisions with electrons, N_2 molecules in most cases undergo dissociation processes as a subsequence of multiple ionization, accompanied with certain kinetic energy release (KER). In recent years, the combination of three dimensional (3D) momentum measurement with the coincident detection technique has rendered the KER measurement possible [2, 3], which can provide an important and efficient tool to retrieve information concerning molecular ion geometry and structure, reaction energetics and dynamics.

For the unstable dications, there are two breakup channels via charge symmetric dissociation (CSD, $N_2^{2+} \rightarrow N^+ + N^+$) or charge asymmetric dissociation (CAD, $N_2^{2+} \rightarrow N^{2+} + N$) channel. As demonstrated in Figure 1, the KER for CSD of N_2^{2+} exhibits three major contributions, namely two peaks *a* and *b* at 6.9, 9.2 eV and a "shoulder" *c* at 12.5 eV. It is interesting to notice that in contrast to that of KED of N^+ changing with electron energy increasing from 200 to 1000 eV, the profile of KER for CSD of N_2^{2+} does not change. More detail will be provided at the conference.

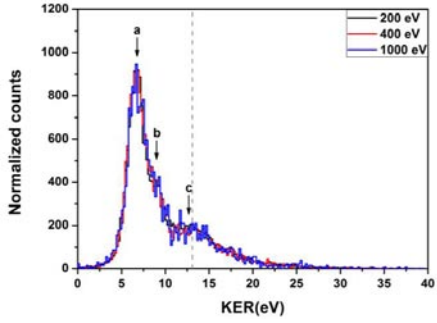

Figure 1: Normalized KER spectra for the charge symmetric dissociation ($N_2^{2+} \rightarrow N^+ + N^+$) channel of N_2^{2+} taken at three different incident electron energies. The vertical solid line (position 13.08 eV) indicates the KER predicted by the Coulomb explosion model.

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ELECTRON-ION RECOMBINATION OF IONS WITH AN OPEN 4f SHELL: W^{19+}

N. Badnell[a], K. Spruck[b,c], C. Krantz[c], O. Novotný[c,d], A. Becker[c], D. Bernhardt[b], M. Grieser[c], M. Hahn[d], R. Repnow[c], D. W. Savin[d], A. Wolf[c], A. Müller[b], and **S. Schippers**[e]

[a]Department of Physics, University of Strathclyde, Glasgow G4 0NG, United Kingdom

[b]Institut für Atom- und Molekülphysik, Justus-Liebig-Universität Gießen, 35392 Giessen, Germany

[c]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

[d]Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027, USA

[e]I. Physikalisches Institut, Justus-Liebig-Universität Gießen, 35392 Giessen, Germany

Atomic collision processes with tungsten ions are of current interest for understanding the role of tungsten impurities in fusion plasmas [1]. For example, the charge balance of tungsten is determined by the interplay of electron-impact ionization and electron-ion recombination. Most of the required cross sections come from theoretical calculations which often bear large uncertainties and, thus, require benchmarking by experiment. To this end, we have focussed on tungsten ions with a particulary complex atomic structure. The present study extends our previous work on electron-ion recombination of W^{20+} [2,3] and W^{18+} [4] to $W^{19+}([\mathrm{Kr}]\,4d^{10}\,4f^{9})$ [5].

The experiment was carried out by employing the electron-ion merged-beams technique at the Heidelberg heavy-ion storage ring TSR. As in the previous cases of W^{18+} and W^{20+}, an unusually large W^{19+} recombination rate coefficient has been observed at low electron-ion collision energies leading to a plasma rate coefficient that is larger by up to almost three orders of magnitude than the rate coefficient from the ADAS [6] data base. According to our present understanding, this is caused by resonant recombination involving many-electron processes which cannot fully be treated by the standard theory for electron-ion recombination. Nevertheless, they can be accounted for in a coarse manner by statistical theory [7]. Different variants of statistical theory have already been applied successfully to electron-ion recombination of W^{20+} [3,8] and W^{18+} [4]. Also our present calculations for W^{19+} are in good agreement with the experimental findings. This adds to the confidence that statistical theories will be able to provide reliable electron-ion recombination rate coefficients also for other complex ions.

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SHAKEOFF IONIZATION NEAR COULOMB BARRIER DURING ION-ATOM COLLISIONS

Prashant Sharma and **T. Nandi**

Inter University Accelerator Centre, Aruna Asaf Ali Marg, New Delhi 110067, India.

The effects of interaction responsible for any physical processes depend on the interaction range and the coupling constant, which are vastly different for electromagnetic and strong forces. Therefore, the atomic and the nuclear phenomena are not expected to interfere with each other. To explore the nuclear effects on atomic processes, if any, we have measured the projectile ion x-rays in the ion-atom collisions as a function of the beam energies around the Coulomb barrier. The variation of the projectile ionization with the ion-beam energies exhibits an unexpected jump resulting in a resonance type structure in the derivative spectrum near the Coulomb barrier as shown in Figure 1. Such a behaviour cannot originate from primary atomic processes alone and therefore, indicates the interference of nuclear interaction. The long lived orbiting di-nuclear complex [1] is formed under the effect of the Coulomb as well as the nuclear potential, which gives rise to the shakeoff ionization [2] of the projectile ion manifesting the resonance. At the barrier and above the barrier energies, the di-nuclear system formed disturbs the electron configuration of the ions, initiates shakeoff ionization and pushes the ions in higher ionic stage thereby causing an increase in x-ray transition energy. The present finding has been validated with three asymmetric, inverse kinematics, viz. ^{12}C(^{56}Fe,^{56}Fe), ^{12}C(^{58}Ni,^{58}Ni) and ^{12}C(^{63}Cu,^{63}Cu). This study opens up new channels for interdisciplinary research comprising of atomic and nuclear physics.

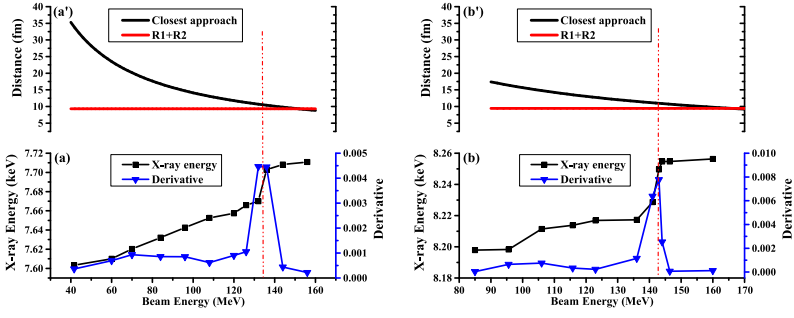

Figure 1: Centroid of the projectile x-ray energy peaks versus beam energies in lab frame (a) ^{58}Ni beam and (b) ^{63}Cu beam on C-foil & distance of closest approach and touching distance versus beam energy for two body systems of (a') ^{58}Ni on ^{12}C and (b') ^{63}Cu on ^{12}C. The distance of closest approach is calculated using the formulation given elsewhere [3]. Error bars are tiny and within the symbol size. All solid lines are to guide eye only. The dash-dot vertical lines represent the centroid of the observed resonance type structure.

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HIGHLY CHARGED ARGON IONS BY HE^{+} AND HE^{+2} IMPACT

C. C. Montanari[a], J. E. Miraglia[a]

[a]Instituto de Astronomía y Física del Espacio (CONICET-UBA), Buenos Aires, Argentina

The multiple ionization is a complex many-electron process where direct ionization and post-collisional electron emission contribute to the final charge state. Electron-electron correlation and changes in the target potential play a role [1]. For certain targets, such as He or even Ne, it may be decisive, for others as Kr or Xe it is negligible [2]. The intermediate cases deserve deeper study, this work is a step in this direction. We used the continuum distorted-wave eikonal initial state [3] and the independent electron model to describe the multiple ionization of Ar by He^{2+} and He^{+} in the energy range 0.1-10 Mev/amu, including Auger-like post collisional ionization (PCI). As shown in the Figure 1(a), the results agree well with the experimental data at high energies where the PCI is the main contribution. At intermediate impact energies the description is also good but it tends to overestimate the triple and quadruple ionization data. We also compare with recent TDDFT calculations by Zhang *et al* [4], considering ionization plus capture, Figure 1(b). These results are closer to the experimental measurements for triple ionization of Ar. Unfortunately, TDDFT values go up to 300 keV/amu. The extension to higher energies would be very interesting. The Ar K and L-shell ionization cross sections are also calculated and compared with the experimental data available and with the ECPSSR values [5].

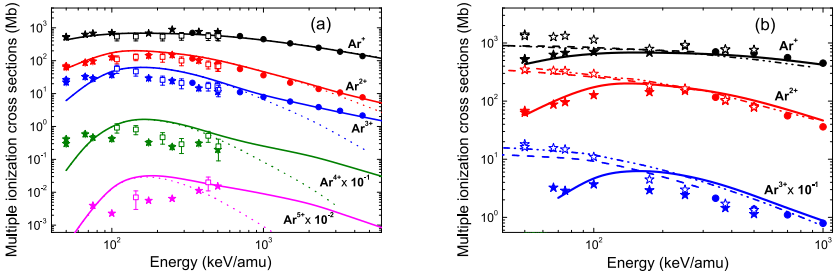

Figure 1: Multiple ionization cross section of Ar by He^{2+}. Curves: solid and dotted lines, present *pure* ionization with and without PCI; dashed and dashed-dotted lines, capture and ionization by Zhang *et al* [4] and Kirchner *et al* [6], respectively. Symbols, experimental data: full circles, Andersen *et al* [7]; full(open) stars, DuBois [8] excluding (including) capture; open squares, Li^{2+} impact data [9].

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ELECTRON-IMPACT IONIZATION OF BERYLLIUM-LIKE CARBON IONS

B. Ebinger[1,2], A. Borovik Jr. [1,2], S. Schippers [1,2] and A. Müller [2]

[1]I. Physikalisches Institut, Justus-Liebig-Universität Gießen, 35392 Giessen, Germany

[2]Institut für Atom- und Molekülphysik, Justus-Liebig-Universität Gießen, 35392 Giessen, Germany

Reliable atomic data are of crucial importance for the modeling of ionized-matter environments. Cross sections for electron-impact ionization of atoms and ions are particularly important. Besides the fairly well understood direct ionization process, indirect ionization mechanisms such as excitation-autoionization (EA) and resonant-excitation double autoionization (REDA) can significantly contribute to net single-ionization [1]. Benchmark experiments uncovering fine structures that arise from indirect ionization processes in few-electron systems provide guidance for theoretical efforts to adequately describe total single ionization by electron collisions. Here, we present measurements of electron-impact single-ionization cross sections of the C^{2+} ion, i. e., of a fairly simple four-electron system (Figure 1). Complications arise, however, from the presence of both $1s^2\,2s^2\ {}^1\mathrm{S}_0$ ground-level and $1s^2\,2s\,2p\ {}^3\mathrm{P}_{0,1,2}$ metastable-level ions in the experiment. Employing the well-established fine-step energy-scan technique [2], contributions of indirect-ionization processes invoked by excitation of the K-shell were uncovered with a statistical uncertainty of less than 0.03% thus helping to disentangle the various cross-section contributions.

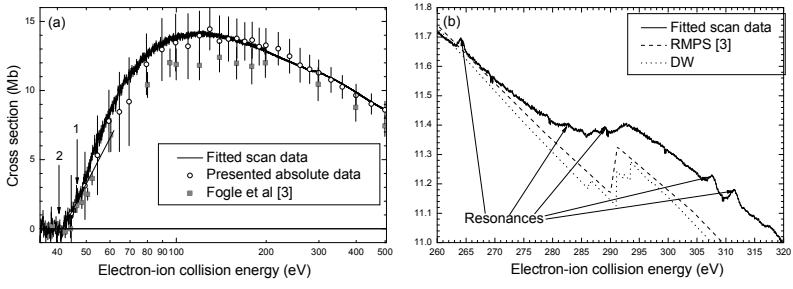

Figure 1: (a) Measured cross section for electron-impact ionization of C^{2+} ions in comparison with earlier data. The difference on the absolute scale is explainable by a higher fraction of metastable-level ions present in our experiment ($\sim$70% vs. $\sim$46% in Ref. [3]). The numbers label the ionization threshold of the ground (1; $1s^2 2s^2$) and metastable level (2; $1s^2 2s 2p\ {}^3P$) respectively. (b) The measured cross section between 260 and 320 eV compared with theoretical calculations. Contributions from indirect ionization processes resulting in a step (arising from EA) and several resonances (arising from REDA) can be clearly seen.

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OFF-SHELL DISTORTION OF MULTICHANNEL PROCESSES IN ION-ION COLLISIONS

C. F. Clauser, R. O. Barrachina

Centro Atómico Bariloche and Instituto Balseiro, Comisión Nacional de Energía Atómica y Universidad Nacional de Cuyo, Av. Bustillo 9500, 8400 Bariloche, Río Negro Argentina.

Any multichannel problem can be reduced to a succession of two-body events [1-2]. However, these basic building blocks of many-body theories do not correspond to elastic processes but are off-the-energy-shell, meaning that their initial, intermediate and final energies are not necessarily equal to each other.
In view of this difficulty, the great majority of the Distorted-Wave models includes a subsidiary approximation where these off-shell terms are arbitrarily forced to lie on the energy shell. In fact, the very same definition of the initial and final states, where the two-body distortions are incorporated as multiplicative factors instead of convolutions over some intermediate momenta, is an unmistakable fingerprint of this on-shell assumption. At a first glance, since the energy deficiency is negligible for high enough velocities [3], the on-shell assumption seems to be completely justified. Therefore, except for some few exceptions [4], these off-shell effects have been largely discarded or simply ignored. However, for the case of Coulomb interactions, the two-body off-shell distortions have branch-point singularities on the half of the energy shells (i.e. when two of the characteristic energies are equal to each other) [5]. In this communication we show that these singularities might produce sizeable distortions of multiple scattering amplitudes, mainly when dealing with ion-ion collisions. Finally, we propose a method of approximating these distortions that might lead to better results that removing them completely.

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ASYMMETRIES OF THE ELECTRON CUSP IN HEAVY-ION ATOM COLLISIONS

P.-M. Hillenbrand[a], S. Hagmann[a], Yu. A. Litvinov[a], and Th. Stöhlker[a,b,c]

[a]GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany
[b]Helmholtz-Institut Jena, 07743 Jena, Germany
[c]Institut für Optik und Quantenelektronik, F.-Schiller-Universität Jena, 07743 Jena, Germany

In collisions of heavy highly-charged projectile ions with atomic targets, the energy distribution of the emitted electrons is a characteristic observable for the underlying elementary charge-transfer processes. At the experimental storage ring ESR of the heavy-ion accelerator facility GSI, a dedicated magnetic electron spectrometer was installed downstream from the supersonic gas-jet target, which enables the measurement of high-energetic electrons emitted in ion-atom collisions, with electron velocities similar to the projectile velocity, emitted within a small cone in the forward direction. This provides the ability to extend the well known study of cusp electrons towards heavy-ion atom collisions at near-relativistic projectile energies. Through the electron-loss-to-continuum (ELC) cusp, double-differential cross sections of projectile ionization can be studied even for the heaviest few-electron projectiles [1]. But also a new channel opens up, the radiative electron capture to continuum [2], which can be directly compared to its non-radiative counterpart [3]. Using the electron spectrometer in combination with detectors for emitted x rays and charge-exchanged projectiles, the study of the collision system $U^{88+} + N_2$ @ 90 MeV/u revealed three processes, each characterized by a unique shape of the electron cusp [4].

Furthermore, the process of ELC was investigated for multi-electron projectiles in the collision systems

$$U^{28+} + H_2 \rightarrow U^{29+} + [H_2]^* + e^-,\ U^{28+} + N_2 \rightarrow U^{29+} + [N_2]^* + e^-,\ U^{28+} + Xe \rightarrow U^{29+} + Xe^* + e^-.$$

The experimental data revealed a significant electron cusp asymmetry, which increases towards heavier targets. This observation is inconsistent with presently available theories [5].

As a next step, an experimental study of ELC for U^{89+} ions colliding with different gaseous targets is envisaged, at a projectile energy just above the threshold for electron impact ionization. For these collision systems, relativistic CDW calculations predict a deviation of the electron energy distribution from first-oder perturbation theory due to the effect, that the electron emitted by the projectile is attracted by the target nucleus.

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UNRAVELING THE FRAGMENTATION DYNAMICS OF EXCITED POSITIVELY CHARGED AMINO ACIDS INDUCED BY COLLISIONS WITH HIGHLY-CHARGED IONS.

Dariusz Grzegorz Piekarski[a], R. Delaunay[b], S. Maclot[b], A. Domaracka[b], L. Adoui[b], B. A. Huber[b], P. Rousseau[b], F. Martín[a,c,d], M. Alcamí[a,d], S. Díaz-Tendero[a,c]

[a]Departamento de Química, Universidad Autónoma de Madrid, 28049 Madrid, Spain.

[b]Normandie Université-CIMAP-UMR 6252 CEA/CNRS/ENSICAEN/UNICAEN, Boulevard Henri Becquerel BP 5133-14070 Caen cedex 5, France.

[c]Condensed Matter Physics Center (IFIMAC), Universidad Autónoma de Madrid, Cantoblanco 28049 Madrid, Spain.

[d]Instituto Madrileño de Estudios Avanzados en Nanociencias (IMDEA-Nanociencia), Cantoblanco 28049 Madrid, Spain.

In the radiation damage of biological tissues a bunch of secondary particles is produced: electrons, ions and radicals. They are responsible of the molecular degradation and cell death in hadron-therapy (an ion-based therapy). Nowadays, an important research activity focuses on understanding these processes at the molecular level [1]. In this communication we present a combined experimental and theoretical study of the fragmentation of excited doubly ionized amino acids as glycine [2], beta-alanine [3] and gamma-aminobutyric acid [4] in the gas phase induced by collision with highly charged ions. Multicoincidence mass spectroscopic techniques together with ab initio molecular dynamics simulations and density functional calculations allow us to observe several processes in competition with the expected Coulomb repulsion. Hydrogen and hydroxyl group migration are important processes that have to be considered to get a complete picture of the complex fragmentation dynamics in the gas phase. We thus show that the combination of theory and experiment is crucial to understand the early stages of radiation damage. We also present results for clusters of amino acids. The knowledge of the stability and the structure of excited clusters of beta-alanine molecules is essential to understand the ionization and fragmentation after collisions with highly charged ions.

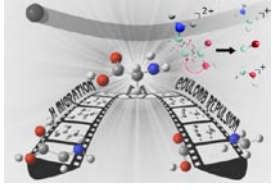

Figure 1: Illustrative competition between Coulomb explosion and H migration in glycine [2] and OH migration in β-alanine [3].

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FIRST OBSERVATION OF RDEC FOR GAS (N_2) TARGETS WITH F^{9+}

P. N. S. Kumara[a], D. S. La Mantia[a], A. Simon[b] , A. Kayani[a], J. A. Tanis[a]

[a]Department of Physics, Western Michigan University, Kalamazoo, MI 49008, USA.
[b]Department of Physics, University of Notre Dame, Notre Dame, IN 46556 USA.

In the radiative double electron capture (RDEC) process two electrons are captured from a target atom to one or two bound states of a fully-stripped projectile along with simultaneous emission of a single photon. The emitted photon energy is about twice the energy of the well-known process of radiative single electron capture (REC). RDEC involves electron correlation since two electron capture with single photon emission requires communication between the captured electrons.

Three experiments [1,2,3] at GSI and two experiments [4,5] at Western Michigan University have been conducted in attempts to observe RDEC. The first observation of RDEC was reported in 2010 [4] for collisions of O^{8+} projectiles on a thin carbon foil done at WMU.

Here we report the first RDEC observation for bare fluorine colliding with a gas (N_2) target. X-ray events were observed for both single and double electron capture coincident x-ray emission as shown in figure 1. The upper bound for the RDEC cross section (170 mb) obtained from the data is in better agreement with the most recent theoretical calculations [6].

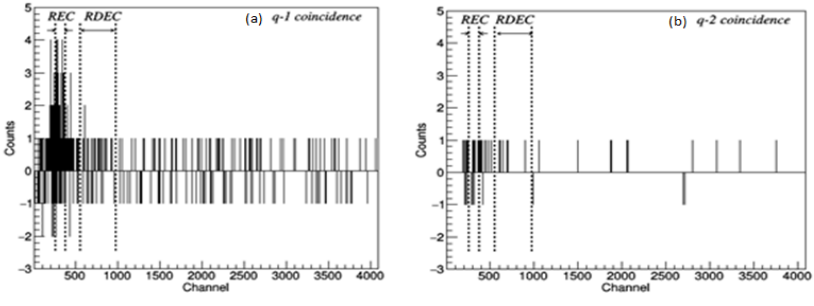

Figure 1: Coincidence X-ray spectrum of (a) single electron capture and (b) double electron capture for 2.3 MeV/u F^{9+} + N_2 collisions

Since RDEC has a very small cross section, this experiment with a gas target requires comparatively more counting time than a thin foil target to get sufficient statistics to observe RDEC. The experiment is being continued at WMU. This research project is funded by NSF.

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THE ROLE OF THE WAVEPACKET COHERENCE ON THE IONIZATION CROSS SECTION OF HE BY p^+ AND C^{6+} PROJECTILES

F. Navarrete[a], M.F. Ciappina[b], M. Schulz[c], L. Sarkadi[d], R.O. Barrachina[a]
[a]Centro Atómico Bariloche and Instituto Balseiro, Comisión Nacional de Energía Atómica and Universidad Nacional de Cuyo, Av. Bustillo 9500, 8400 Bariloche, Argentina
[b]Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748 Garching, Germany
[c]Department of Physics and LAMOR, Missouri University of Science & Technology, Rolla, MO 65409, USA
[d]Institute for Nuclear Research of the Hungarian Academy of Sciences (MTA Atomki), P.O. Box 51, H-4001 Debrecen, Hungary

In the last few years there have been an increasing interest on the projectile beam coherence effects in ion-atom and ion-molecule collisions [1−8]. In the traditional way to compute the (multiply) differential cross section [9] the projectile beam is considered as a plane wave, though a more realistic model has proved to be necessary to account for the discrepancies found between theory and experiment.

In a recent work, Sarkadi *et al.* [10] developed a method for calculating the doubly differential ionization cross section of an hydrogen atom and an H_2 molecule by proton impact, including the projectile beam coherence properties. This approach has shown good agreement with experimental data for the same process studied in [4] and [1]. Although this scheme was used for calculating inelastic scattering of 75-keV protons, it was based on the recent theory of Karlovets *et al.* [11] developed for the elastic scattering of wave packets of particles off a potential field.

In the present work, we use the theory developed in [10] to perform calculations for fully differential ionization cross section of He by p^+ and C^{6+} impact at 1 MeV and 100 MeV/amu, respectively. Our method consist of a convolution that takes into account additional degrees of freedom, compared to those used in [10]. We contrast our results with the available experimental data [3,12,13].

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SINGLE AND DOUBLE CAPTURE RESULTING IN TARGET K-SHELL IONIZATION FOR F^{9+} + AR COLLISIONS

David La Mantia[a], Nuwan Kumara[a], Asghar Kayani[a], Anna Simon[b], and John Tanis[a]

[a]Department of Physics, Western Michigan University, Kalamazoo, MI 49008-5252 USA
[b]Department of Physics, University of Notre Dame, Notre Dame, IN 46556-5670 USA

Cross sections for single and double electron capture resulting in the emission of target Ar K shell x rays, as well as the total cross sections for single and double electron capture, have been measured for incident $\sim$2 MeV/u F^{9+} ions. This work was performed at Western Michigan University using the tandem Van de Graaff accelerator. A beam of fully-stripped fluorine ions was collided with argon gas molecules in a differentially pumped cell. A Si(Li) x-ray detector, placed at 90^o to the incident beam, detected the x rays, while silicon surface barrier detectors were used to observe charge changed projectiles following magnetic analysis. Coincidences between the detected x rays and the charge changed projectile ions were recorded as shown in Figure 1. The total capture cross sections are compared to previously measured cross sections in the literature [1] [2].

Preliminary analysis of the data indicates total cross sections for single electron capture have values on the order of tens of megabarns with the double capture cross sections being about an order of magnitude smaller as expected. On the other hand, the same cross sections for coincidences with target K-shell x-ray emission, despite being about 10^4 times smaller, are approximately equal to each other. This somewhat surprising fact is being analyzed and possible reasons for this behaviour will be discussed. The variation of total and coincidence cross sections with the beam energy will also be presented and discussed.

This work was supported in part by the NSF under Grant No. PHY-1401429.

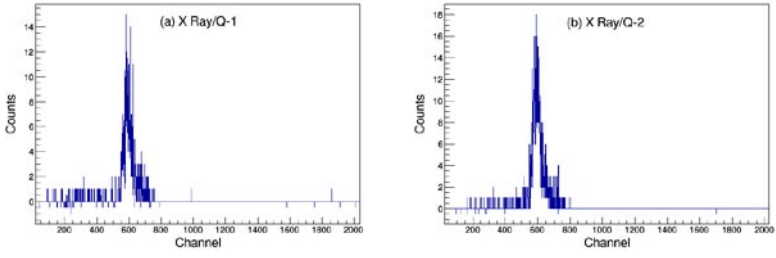

Figure 1: Coincidence x-ray spectra with (a) single electron capture and (b) double electron capture for 45 MeV F^{9+}+ Ar at a pressure of 4μ

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QUASI-EQUILIBRIUM IN CHARGE-STATE EVOLUTION FOR SEVERAL MeV/u IONS AFTER C-FOIL PENETRATION

Alex M Imai[a], Sataka Masao[b,c], Satoru Okayasu[b], Makoto Matsuda[b], Kiyoshi Kawatsura[d], Katsumi Takahiro[e], Ken-ichiro Komaki[f], Hiromi Shibata[g], Katsuhisa Nishio[b]

[a]Department of Nuclear Engineering, Kyoto University, Nishikyo, Kyoto 615-8540, Japan
[b]Japan Atomic Energy Agency (JAEA), Tokai, Ibaraki 319-1195, Japan
[c]University of Tsukuba, Tsukuba, Ibaraki 305-8573, Japan
[d]Theoretical Radiation Research Laboratory, Sakyo, Kyoto 606-0966, Japan
[e]Kyoto Institute of Technology, Sakyo, Kyoto 606-8585, Japan
[f]RIKEN, Wako, Saitama 351-0198, Japan
[g]The Institute of Scientific and Industrial Research, Osaka University, Osaka 567-0047, Japan

After a series of measurements of pre-equilibrium and equilibrium charge-state distributions for 2.0 MeV/u S^{q+} (q = 6-16) and C^{q+} (q = 2-6) ions after penetrating C-foils of 0.9-200 μg/cm^2 in thickness [1], we claim quasi-equilibrium in charge-state evolution has been systematically observed, *i.e.*, charge-state distributions, mean charge-sates, and distribution widths for projectile ions without K-shell holes, S^{q+} (q = 6-14) and C^{q+} (q = 2-4), once merge at target thickness of 6.9 and 5.7 μg/cm^2 respectively, showing quasi-equilibrium, and simultaneously evolve to establish the real equilibrium as the foil thickness is increased further. On the other hand, those for projectile ions with K-shell hole(s), $S^{15+,16+}$ and $C^{5+,6+}$, evolve differently and directly to the real equilibrium established at ~150 and ~10 μg/cm^2 for S and C ions, respectively. These results have directly represented a suggestion of Majewska and Braziewicz *et al.* [2,3] in measuring K x-ray spectra of S ions passing through C-foils that the equilibrium charge-state for L and higher shells can be achieved in a much shorter path of the projectile inside the carbon target than in the case of the K-shell. Simulations with ETACHA code [4,5] have shown that the quasi-equilibrium is brought by differences between reaction-rates of K- and L-shell processes.

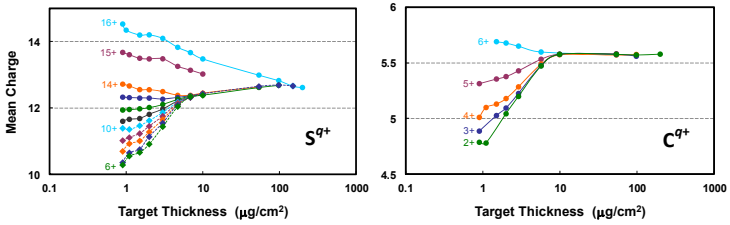

Figure 1: Mean charge-states of 2.0 MeV/u S^{q+} (q = 6-16) and C^{q+} (q = 2-6) ions after C-foil.

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PHOTORECOMBINATION OF BERYLLIUMLIKE AND BORONLIKE SILICON IONS

D. Bernhardt[a], A. Becker[b], C. Brandau[c,d], M. Grieser[b], M. Hahn[e], C. Krantz[b], M. Lestinsky[d], O. Novotný[b,e], R. Repnow[b], D. W. Savin[e], K. Spruck[a,b], A. Wolf[b], A. Müller[a], **S. Schippers**[c]

[a]Institut für Atom- und Molekülphysik, Justus-Liebig-Universität Gießen, 35392 Giessen, Germany

[b]Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany

[c]I. Physikalisches Institut, Justus-Liebig-Universität Gießen, 35392 Giessen, Germany

[d]GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany

[e]Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027, USA

We report measured rate coefficients for electron-ion recombination of Si^{10+} forming Si^{9+} and of Si^{9+} forming Si^{8+}, respectively [1]. The measurements were performed using the electron-ion merged-beams technique at the Heidelberg heavy-ion storage ring TSR. Electron-ion collision energies ranged from 0 to 50 eV for Si^{9+} and from 0 to 2000 eV for Si^{10+}, thus, extending previous measurements for Si^{10+} [2] to much higher energies (Fig. 1). Experimentally-derived rate coefficients for the recombination of Si^{9+} and Si^{10+} ions in a plasma are presented along with simple parameterizations. These rate coefficients are useful for the modeling of the charge balance of silicon in photoionized plasmas (Si^{9+} and Si^{10+}) and in collisionally ionized plasmas (Si^{10+} only). In the corresponding temperature ranges, the experimentally-derived rate coefficients agree with the latest corresponding theoretical results within the experimental uncertainties.The storage-ring techniques allows for the preparation of ions in well defined energy levels. This has been exploited in particular for reducing the Si^{10+} ion beam contamination by long-lived $2s\,2p\,{}^3P$ metastable levels to almost insignificance.

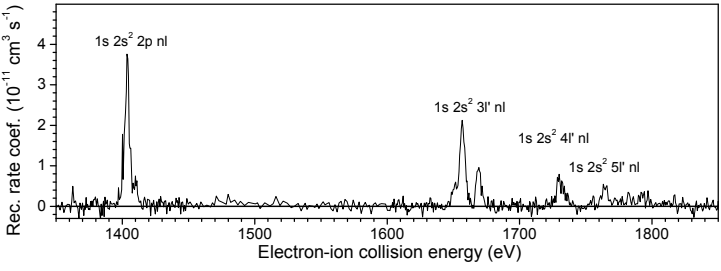

Figure 1: High-energy part of the measured merged-beams rate coefficient (solid black line) for photorecombination of Si^{10+} in the energy range of DR resonances associated with K-shell excitations. Resonance groups are labelled by the according $1s^2\,2s^2 \rightarrow 1s\,2s^2\,N'l'$ core excitations. The figure has been taken from Ref. [1].

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WATER FRAGMENTATION BY BARE AND DRESSED LIGHT IONS WITH MEV ENERGIES

W Wolff[c] R Schuch[d], H Luna[c], N D Cariatore[b], S Otranto[b], F Turco[a], D Fregenal[a] G Bernardi[a] and S Suárez[a]

[a]Centro Atómico Bariloche, CONICET, S. C. de Bariloche, Río Negro, Argentina
[b]IFISUR, CONICET, Dpto de Física, Universidad Nacional del Sur, Bahía Blanca, Argentina.
[c]Instituto de Física, Universidade Federal de Río de Janeiro (IF-UFRJ), Brazil
[d]Department of Physics, Stockholm University, Alba Nova University Center, Stockholm, Sweden

The report presents data on the ionization and fragmentation of water induced by H^+, $Li^{0-3+,}$ and $C^{1,2+}$ impact in the intermediate energy range of 1.6 to 5.8 MeV, with focus on the energy and time-of-flight distributions of water ionic fragments (fig.1). Two experimental approaches based on an electrostatic spectrometer were applied to investigate the fragmentation channels, in one case fragment-ion energy distributions were recorded, while in the second setup, the Pelletron accelerator was operated in pulse mode and the spectrometer acted as a time of flight spectrometer. The experimental findings were compared to a model based on Classical Trajectory Monte Carlo calculations which were married to a Coulomb Explosion Model.
The combined experimental and theoretical study reveals isotropic production of charged ions and show, besides the most abundant H^+ ions, highly-charged O^{q+} fragments with charges up to 5+. From the ion energy distribution and time of flight spectra relative yields of the dissociation resulting from multiple-ionization were extracted as function of neutral to bare projectiles, for several projectile energies, and fragment-ions energies, probing distinct scopes of the water fragmentation. The calculations indicate that close collisions between the projectile and the target atoms lead to multiple ionization and can be related to the O^{q+} population. Although there are studies concerning the influence of the velocity and charge state of the projectile on the dissociation of water [1], a detailed knowledge of features of the dissociation pattern leading to the formation of multiply charged ion-pairs in the intermediate energy range remains scarce.

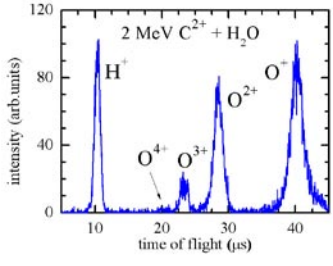

Figure 1: Time of flight spectrum recorded for 2 MeV C^{2+} ion beam at the detection angle of 10 degrees. Fragment-ions of O^{q+} with q from 1 to 4, and H^+ with 2eV/q were measured.

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M-SHELL IONIZATION CROSS SECTIONS OF HEAVY ELEMENTS BY CHARGED-PARTICLE IMPACT

Takeshi Mukoyama

Institute for Nuclear Research of the Hungarian Academy of Sciences (ATOMKI),
Bem tér 18/C, H-4026 Debrecen, Hungary

The M-subshell ionization cross sections of heavy elements by charged-particle impact have been calculated in the binary-encounter approximation. The calculations were made in the manner similar to the previous works for protons on Au [1]. The cross section based on the classical dynamics is averaged over velocity distribution of the target atomic electron. The velocity distribution is obtained by the Fourier-Bessel transformation of atomic wave functions. We considered three atomic models for target elements: the nonrelativistic and relativistic hydrogenic models and the Hartree-Fock-Roothaan model.

In Fig. 1, M_5-shell ionization cross sections for protons on U with the nonrelativistic (BEA) and relativistic (RBEA) hydrogenic wave functions and the Hartree-Fock-Roothaan (HFR) wave functions are shown. For comparison, the results of the relativistic plane-wave Born approximation (RPWBA) and the RPWBA with corrections for the binding-energy and the Coulomb-deflection effects (RPWBA-BC) [2] are also plotted.

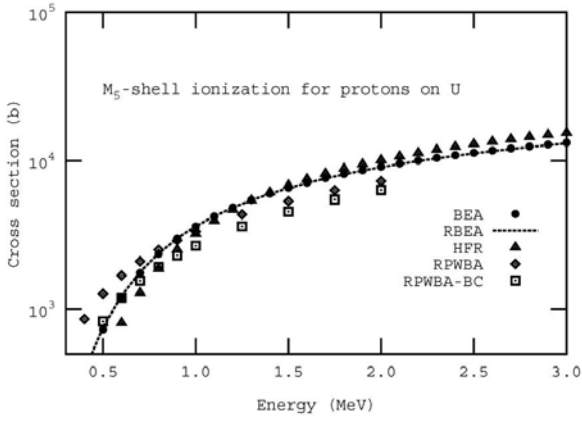

Figure 1: M_5-shell ionization cross sections for protons on U.

It is clear that the electronic relativistic effect plays a minor role, but there is small wave-function effect, i.e. difference between the BEA and HFR. The obtained results are used to compare with the experimental data for M-shell x-ray production cross sections.

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TILDA-V: PROTON TRACK-STRUCTURE IN BIOLOGICAL MATTER

Michele A. Quinto[a,c], Juan M. Monti[a], Philippe F. Weck[b], Omar A. Fojon[a], Jocelyn Hanssen[a], Roberto D. Rivarola[a] and Christophe Champion[c]

[a]Instituto de Física Rosario, CONICET, Universidad Nacional de Rosario, Rosario, Argentina
[b]Sandia National Laboratories, Albuquerque, NM 87185, USA
[c]Université de Bordeaux, CNRS/IN2P3, Centre d'Etudes Nucléaires de Bordeaux Gradignan, Gradignan, France

Whether it is in radiobiology to identify the DNA critical lesions or in medicine to adapt the radio-therapeutic treatment protocols, an accurate knowledge of the charged particle induced interactions in living matter is required. To do that, Monte-Carlo track-structure codes represent the most suitable and powerful tools, in particular for modeling the full slowing-down of ionizing particles in biological matter. In the current work, we detail our *homemade* Monte Carlo code - called *TILDA-V* - based on a complete set of multiple-differential and total cross sections for describing all the inelastic and elastic processes occurring throughout the slowing-down of protons in water and DNA [1]. *TILDA-V* (an acronym for Transport d'Ions Lourds Dans Aqua & Vivo) refers to an extension of the *TILDA* code previously developed by Champion *et al.* [2]. It is based on a complete set of quantum-mechanical cross sections for all the electron- and proton/hydrogen-induced interactions in water as well as in biological targets including the DNA nucleobases and the sugar-phosphate backbone [1]. A realistic description of the biological medium is considered by modeling a typical nucleotide equivalent unit of hydrated DNA, namely, a nucleobase-pair plus a sugar phosphate group both surrounded by a hydration shell composed by 18 water molecules.

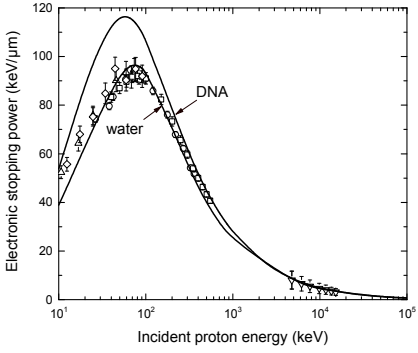

Figure 1: Electronic stopping power (induced by H^+/H^0) in water and hydrated DNA.

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DEFORMATION OF MULTIPLY CHARGED C_2H_2 IONS PRODUCED IN CHARGE-CHANGING COLLISIONS OF 0.8-MEV C^+ IONS

S. O. Yoshida[a], T. Majima[ab], T. Asai[a], M. Matsubara[a], H. Tsuchida[ab], M. Saito[a] and A. Itoh[ab]

[a]Department of Nuclear Engineering, Kyoto University, Kyoto 615-8540, Japan
[b]Quantum Science and Engineering Center, Kyoto University, Uji 611-0011, Japan

Structural deformation and subsequent fragmentation are fundamental processes of highly charged molecular ions generated by fast ion collisions [1, 2]. In this study, we focus on three body fragmentations of $H^{+/0} + C_2^+ + H^{+/0}$ as a function of the charge state r of the intermediate $C_2H_2^{r+*}$ ions for r = 1–3. Kinetic energy (KE) distributions of C_2^+ fragment ions are supposed to reflect sensitively imbalance of momentum vectors of two $H^{+/0}$ fragments. Thus, it can be a good probe to examine deformation of the intermediate $C_2H_2^{r+*}$ ions from the initial symmetric linear structure.

We have performed collision experiments between gas-phase C_2H_2 molecules and 0.8-MeV C^+ ions under single electron (1*e*)-loss and 1e-capture conditions. The experimental procedure is given elsewhere [3], except for the time-resolved 3D momentum imaging technique employed in the present experiment. The KE of each product ion was obtained by using this newly introduced technique. We also measured the number of emitted electrons to analyze the charge state r of the intermediate $C_2H_2^{r+*}$ ions before fragmentation.

Figure 1 shows mean KEs of C_2^+ fragment ions produced from $C_2H_2^{r+}$* for r = 1–3. The fragmentation pathways are written as $C_2H_2^{+*} \rightarrow H^0 + C_2^+ + H^0$, $C_2H_2^{2+*} \rightarrow H^+ + C_2^+ + H^0$ and $C_2H_2^{3+*} \rightarrow H^+ + C_2^+ + H^+$, respectively. The mean KEs at r = 2 are higher than those at r = 1 because of the Coulomb repulsive force between C_2^+ and H^+. In 1*e*-capture collisions, the mean KE at r = 3 becomes lower than that at r = 2. This is reasonably considered as a result of collinear dissociation with the symmetric charge distribution. On the other hand, in 1*e*-loss collisions, the mean KE increases at r = 3. The higher KE of C_2^+ can be explained by a geometrical effect of fragmentation through a bent structure. This result indicates that molecular deformation is enhanced by a higher internal energy deposited in 1*e*-loss collisions.

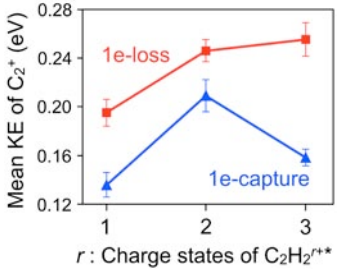

Figure 1: Mean kinetic energies of C_2^+ as a function of the intermediate charge state r of the parent $C_2H_2^{r+*}$ in a single electron loss and capture collisions with 0.8-MeV C^+ ions.

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PARTIAL IONIZATION CROSS SECTIONS FOR SiF_4 BY ELECTRON IMPACT

Neeraj Kumar and Satyendra Pal

Department of Physics, M.M.H. College, Ghaziabad-201001 (U.P.) INDIA

Silicon tetra fluoride (SiF_4) and free radicals SiF_n (n = 1 – 3) are widely used in plasma, plasma-assisted etching and deposition of silicon layers in the fabrication of microelectronic components and other high technological devices. The highly reactive fluorine atoms and ions present in the etching plasma interact with the surface and produce the volatile products such as SiF_4 and SiF_2 which are further diffused back into the plasma where they are dissociated and ionized by the plasma electrons and the resultant fragments are transported and re-deposited on the silicon surface [1-2].

The present work reports the calculations for differential cross sections as a function of secondary and or ejected electron energy in the ionization of SiF_4 by electron collision corresponding to the production of various cations viz. singly charged ions SiF_n^+ (n=0-4) and F^+ and doubly charged ions SiF_3^{+2} and SiF_2^{+2} through direct and dissociative ionization processes at a fixed incident electron energy of 200 eV. The modified Jain-Khare semi-empirical formalism [3] based on oscillator strength has been employed for evaluation of cross sections. In absence of the experimental and/ or theoretical data for comparison of the differential cross sections, the corresponding derived integral cross sections (Fig.1) in terms of the partial ionization cross sections for these cations in the energy range varying from ionization threshold to 1000 eV, revealed a reasonably good agreement with the available data [4].

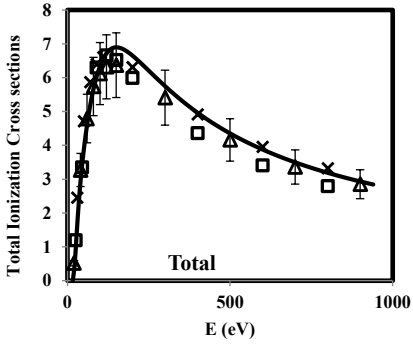

Figure 1- Total ionization cross sections (sum of partial ionization cross sections) in the units of $10^{-16}cm^2$ for electron impact ionization of SiF_4 in comparison with the various experimental and theoretical data sets (see for instant [4]).

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EUV EMISSION SPECTRA IN COLLISIONS OF HIGHLY CHARGED TANTALUM AND BISMUTH IONS WITH NITROGEN AND OXYGEN MOLECULES

Hajime Tanuma[a], Naoki Numadate[a], Yoshiyuki Uchikura[a], Kento Shimada[a], Takuto Akutsu[a]
Elaine Long[b], Gerry O'Sullivan[b]

[a]Department of Physics, Tokyo Metropolitan University, 1-1 Minami-Ohsawa, Hachioji, Tokyo 192-0397, Japan

[b]School of Physics, University College Dublin, Belfield, Dublin 4, Ireland

Charge exchange spectroscopy is a powerful method used to observe emission lines of highly charged ions and to measure charge transfer cross sections in collisions of highly charged ions with neutral atoms/molecules. We had performed this type of spectroscopy on multiply charged Sn and Xe ions to provide the atomic data for the development of an extreme ultraviolet (EUV) light source which is necessary for the next-generation of semiconductor lithography [1, 2].

In this work, we observed the EUV emission spectra from collisions of highly charged Ta and Bi ions with N_2 and O_2. Ta ions were produced in a 14.25 GHz electron cyclotron resonance ion source with the insertion of Ta sheet into the plasma chamber of this ion source because the melting point of Ta is extremely high at about 3300 K. Bi, on the other hand, has a relatively low melting point at around 540 K. We therefore profuced the Bi ions by placing the Bi sample onto a Ta sheet and inserting them into the plasma. We used oxygen gas to stabilise the plasma in the chamber.

Ions produced in the hot plasma at about 10^6 K were extracted with an electric potential of 15 kV, and the charge-state selected ion beam with an analysing magnet was directed into a collision cell filled with target gas. EUV emissions from the collision cell were observed with a compact flat-field grazing-incident spectrometer equipped with a variable-line-spacing (ca. 1200 lines/mm) grating. A CCD camera with a Peltier cooling system was installed in the spectrometer to observed emission lines in the wavelength region of 5–30 nm.

In the collisions of Bi^{q+} (q =15–22), we observed not only many discrete lines, but also several unresolved transition arrays (UTAs). On the other hand, in collisions of Ta^{q+} (q = 14-19), only UTAs were observed. However, we observed emission lines from multiply charged N and O ions, namely N^{3+} and O^{3+}, produced during collisions with N_2 and O_2 target gases, respectively. We consider that the multiply charged atomic fragments might be produced in an inner-shell electron capture or an inner-shell ionisation by close collisions of heavy, highly-charged ions.

Emissions from the target are sometimes observed in collisions of highly charged ions with neutral targets [3]. However, the mechanism of these processes is not yet clear and is worth investigating further.

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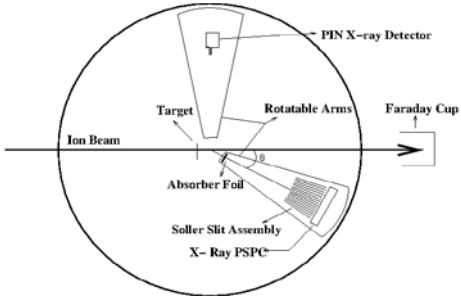
STUDY OF He- & Li-LIKE Fe, Ni & V USING MCDTS SETUP

Ranjeet K Karn[a], Deepak Swami[b], Gaurav Sharma[c], Basu Kumar[d], C P Safvan[b] and T Nandi[b]

[a]Dept. Of Physics, Jam. Co-operative College, Jamshedpur – 831036, India
[b]Inter University Accelerator Centre, New Delhi - 110067, India
[c]Dept. of Applied Physics, Delhi Technological University, Delhi – 110042, India
[d]Jai Prakash University, Chapra - 841301, India

Precision spectroscopy of highly charged ions provides a powerful tool to study many unexplored realms of physics, shedding light on many astrophysical, quantum electrodynamic, atomic collision and spectroscopic mysteries. Beam-foil spectroscopic technique is one of the most elegant tools to study highly charged ions for the measurement of both transition energies and lifetime. However this technique suffers from inherent cascading and blending problem. If the level under study is repopulated by the decay of higher levels, then this is called cascading effect. Cascading problem is inherent to BFS, and hence independent of detectors spectral resolution. On the other hand the presence of nearby transitions (below the detector resolution i.e. ~150 eV at 5.9 keV) in same ion species causes intra-ion blending, where as similar transitions from neighbouring ion species give rise to inter-ion blending also called satellite blending. In contrast to the problem imposed by cascading effect, intra-ion and inter-ion blending effect imposes problem due to experimental limit of detector resolution. To eradicate this problem, we have designed and developed high resolution multi channel Doppler tuned spectrometer (MCDTS) setup coupled with high precision foil movement system at IUAC New Delhi [1].



165, 170 and 150 MeV beam of ^{56}Fe, ^{170}Ni, and ^{51}V ions, respectively from the 15 UD Pelletron accelerator at IUAC, New Delhi was used in this experiment. When a well focussed beam interacts with thin Carbon foil, various electron stripping and capture process take place, which produce the excited H-, He- and Li-like Fe ions. We have resolved the $1s2s\ ^3S_1 - 1s^2\ ^1S_0$ (M1) transition in He-like from its satellite $1s2s2p\ ^4P^0_{5/2} - 1s^22s\ ^2S_{1/2}$ (M2) transition in Li-like with reasonably high precision by using MCDTS setup energetically. Details of experimental setup and result of Fe will be discussed in details along with priliminary result of Ni and V.

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EXPLAINING THE "DARK MATTER X-RAY LINE" AT 3.53 keV BY CHARGE EXCHANGE BETWEEN S^{16+}, S^{15+} AND NEUTRALS

Stepan Dobrodey[a], Chintan Shah[a], Sven Bernitt[a,b], René Steinbrügge[a], José R. Crespo López-Urrutia[a]

[a]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
[b]IOQ, Friedrich-Schiller-Universität, Max-Wien-Platz 1, 07743 Jena, Germany

Speculations about a possible dark matter origin of a weak x-ray transition at $3.53\,\mathrm{keV}$ have generated excitement in the scientific community and given rise to a tide of publications attempting to explain the possible cause for this unidentified transition. Cautiously, Gu and Kaastra *et al.* [1] have pointed to a clear explanation for this phenomenon: charge exchange (CX) between bare sulphur S^{16+}, hydrogen-like S^{15+} and hydrogen. By populating states in high principal quantum numbers n_{cx}, the process drives a radiative cascade directly feeding the $n = n_{\mathrm{cx}}$ to $n = 1$ transitions as well as other x-ray lines. Charge exchange studies carried out at the LLNL EBIT [2-5] and other laboratories [6] at both low and high resolution have shown discrepancies in quantitatively modelling this process while confirming the basic principle. Since S^{16+}, S^{15+} ions are present in the astrophysical objects where the $3.53\,\mathrm{keV}$ transition appears, an accurate model would be needed to scrutinize the relative intensity of the CX-fed transition. We approach the problem experimentally by generating S^{16+} and S^{15+} ions in FLASH-EBIT and letting them recombine with residual gas with the electron beam turned off while collecting x-ray spectra with a resolution of FWHM $\sim 150\,\mathrm{eV}$. By varying the production conditions we change the relative populations of the two ions of interest and distinguish their respective contributions. We also compare the present CX data with results obtained using an ion-beam setup [7]. The 3.53 keV transition shows clearly up in the spectra under a wide variety of conditions and agrees with the astrophysical observations and the predictions of Gu and Kaastra [1].

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GUIDING OF ELECTRONS THROUGH GROOVED SIO_2 PARALLEL PLATES WITHOUT ENERGY LOSS

Yingli Xue, Deyang Yu, Junliang Liu, Mingwu Zhang, Bian Yang, Yuezhao Zhang and Xiaohong Cai

Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China

For electrons guiding through isolating capillaries, it reported that the transmission efficiency was significantly low [1,2] and that large portion of the transmitted electrons suffered significant energy-loss [2-4]. The guiding mechanisms are controversial and are far from clearly understood [5,6]. We present that 800–2000 eV electron beams were guided by a pair of grooved SiO_2 parallel plates, in which almost all of the *transmitted* electrons (not the secondary electrons) did not suffer energy loss. It shows that the transmitted electrons are guided by a self-organized repulsive electric field, demonstrating that the self-organized charge-up mechanism does also work in guiding of electrons through some specially designed isolating assemblies.

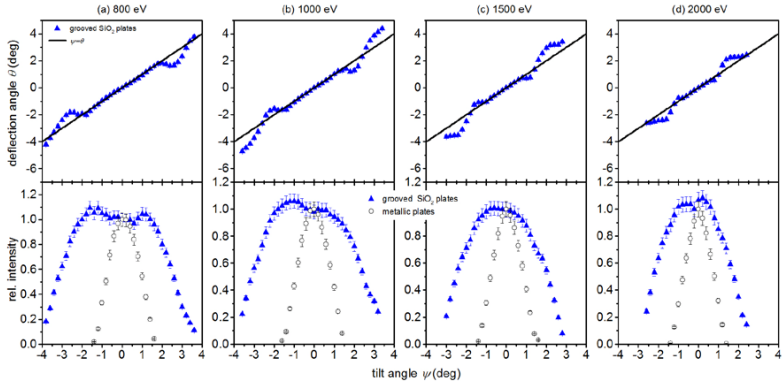

Figure 1: Deflection angle (upper panels) and relative transmission intensity (lower panels) as functions of the tilt angle for (a) 800, (b) 1000, (c) 1500 and (d) 2000 eV electrons passing through the grooved SiO_2 parallel plates. The transmission intensity is normalized to the value at ψ=0°, which is estimated to be about 50–70%. The solid lines in the upper panels represent $\psi=\theta$, while the open circles in the lower panels are transmission intensity for metallic parallel plates. For details, see [7].

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EFFECTS OF THE SUDDEN ELECTRON-HOLE PAIR CREATION AND OF THE LIFE TIME OF THE RESIDUAL HOLE ON PLASMON EXCITATIONS IN AUGER AND X-RAY PHOTOEMISSION SPECTROSCOPY

J. Garcia Gallardo[1], J. L. Gervasoni,[1, 2, 3] and L. Kover[4]

[1]Bariloche Atomic Center (CNEA), 8400 Bariloche, Rio Negro, Argentina.
[2]Balseiro Institute (Bariloche Atomic Center (CNEA) and Nat. Univ. of Cuyo (UNC), Argentina.
[3]Consejo Nacional de Investigaciones Cientificas y Tecnologicas (CONICET), Argentina.
[4]Institute for Nuclear Research of the HAS (MTA ATOMKI), 18/c Bem ter, H-4026 Debrecen, Hungary

The use of systems of spectroscopy and analysis of surfaces have had an important impact in the development of this area [1]. The various types of electron spectroscopies can be divided in two groups. In the first, the surface is bombarded with an electron beam and the scattered (or emitted) electrons are analyzed in angle or energy (secondary electrons). A very popular technique included inside this sub-group is the Auger Electron Spectroscopy (AES). In the second group of electron spectroscopy, they are produced by means of the irradiation of the material with photons generated by an external source. This technique has attracted great interest, stimulated by the possibility of having continuous sources of synchrotron radiation. Nevertheless, most experiments are still made with conventional non-continuous sources. This is the reason why we can distinguish X-ray photoemission spectroscopy (XPS) for fixed energies in the range of KeV [1].

Although these techniques of electron spectroscopy are used with success in surface physics, we must take into account that the use of electrons as carriers of information about surfaces has some inherent limitations. One of these comes from the definition of the surface that we want to study. In this work we study the effect of the sudden electron-hole pair creation and of the life time of the residual hole on plasmon excitations in surfaces, for both processes: XPS and Auger, and its corresponding plasmon excitations.

We treat the electron emission in a very simplified manner in order to be able to develop analytical expressions accounting for surface and bulk plasmon excitations. A detailed description of the photoelectron process was done in ref. [2,3]. Regarding the electron emission, it will be schematized as a sudden creation of a static positive charge a= +e (XPS); +2e (AES) and a moving negative charge $q_- = -e$, which is located at the same site as the positive charge at the moment of creation (See Figure 1). But now the hole has a given life time, given place to some novel behavior that we study in detail.

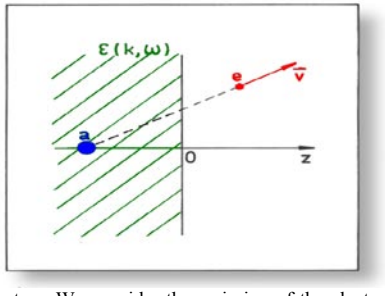

Figure 1. Squeme of the system. We consider the emission of the electron **e** with velocity **v**, from a depth $\mathbf{z}_0$ inside the surface. The hole **a** is created in $\mathbf{z}_0$.

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DAMPING OF PLASMONS IN METALS: A PRAGMATIC APPROACH FOR THE QUANTIFICATION OF A COMPLEX PROCESS

Néstor R. Arista,[1,2] J. L. Gervasoni,[1,2,3] S. Segui[1,3]

[1]Centro Atómico Bariloche (CNEA). Av. Bustillo 9500, 8400 S. C. de Bariloche, Argentina.
[2]Instituto Balseiro (CNEA - UNCuyo). Av. Bustillo 9500, 8400 S. C. de Bariloche, Argentina.
[3]Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina.

The excitation of plasmons and their subsequent decay is of great interest in many branches of fundamental and applied physics. In particular, the shape of the plasmon peaks in energy loss spectra of charged particles is determined to a large extent by way the plasmons interact with the electron gas of the medium and ultimately decay.
In the present work we address the problem of quantifying this process within the framework of the dielectric formalism. We use various methods to define and assess the damping constant γ appearing in the Drude's model for the dielectric constant, ranging from empiric fittings to the calculation of quantum-transition probabilities. We compare the results with the data found in the literature.

EXPERIMENTAL EVIDENCE OF BEAM-FOIL PLASMA CREATION DURING ION-SOLID INTERACTION

Prashant Sharma, Tapan Nandi

Inter University Accelerator Centre, Aruna Asaf Ali Marg, New Delhi 110067, India.

During the typical ion-solid collisions, the complex dynamic interactions between projectile ions and target atoms significantly alter the charge states of the corresponding atomic system. In the present work, charge state evolution of energetic projectile ions (^{56}Fe, ^{58}Ni and ^{63}Cu) during the passage from thin carbon foils has been revisited in the 1.51-2.69 MeV/u energy range using the x-ray spectroscopy technique [1]. Contributions from the bulk and the target surface in charge changing processes have been segregated by measuring the charge state distribution (CSD) of the projectile ions right at the ion-solid interaction zone. The measured projectile mean charge states (MCS) in the present work are found to be higher than the obtained MCS from empirical formalism [3] and experimental electromagnetic methods [4,5] as shown in the Fig. [1], which can be attributed to the multi-electron capture from the exit surface of the target [2]. Interestingly, CSD measured in the bulk exhibits Lorentzian profile in contrast to the well-known Gaussian structure observed using electromagnetic methods [4,5] and theoretical predictions [3,6], shown in the Fig. [1]. The occurrence of such behaviour suggests that ion-solid collisions constitute high-density localized plasma in the bulk of the solid target, called beam-foil plasma. This beam-foil plasma is similar to the high-density solar and astrophysical plasma, which may have practical implications in various fields, in particular, plasma physics and nuclear astrophysics. Further, present work suggests modification in the theoretical CSD predictions by incorporating plasma coupling effects during the ion-solid interactions.

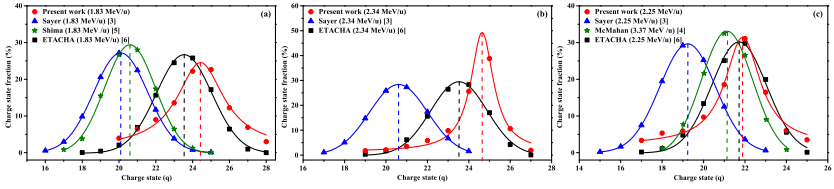

Figure 1: Comparison of the charge state distribution and the mean charge states in the case of (a) ^{63}Cu on ^{12}C (b) ^{58}Ni on ^{12}C and (c) ^{56}Fe on ^{12}C for different beam energies. The figure shows Lorentzian fit to the present work and Gaussian fit to all the others. Errors are embedded in the symbol itself. The vertical lines represent the mean charge states.

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RADIATIVE DEEXCITATION OF INITIALLY SLOW HIGHLY CHARGED IONS TRANSMITTED THROUGH GRAPHENE

R.A. Wilhelm[a], E. Gruber[a], J. Schwestka[a], R. Heller[c], R. Kozubek[b], A. Hierzenberger[b], M. Schleberger[b], S. Facsko[c], F. Aumayr[a]

[a]Institute of Applied Physics, TU Wien, Wiedner Hauptstr. 8-10, 1040 Vienna, Austria
[b]Faculty of Physics, University of Duisburg-Essen, Lotharstr. 1-12, 47057 Duisburg, Germany
[b]Institute of Ion Beam Physics and Materials Research, Helmholtz-Zentrum Dresden-Rossendorf, Bautzner Landstr. 400, 01329 Dresden, Germany

The interaction of slow highly charged ions with solid surfaces is associated with many different phenomena. One of them is the formation of a hollow atom or ion already in front of the surface due to resonant electron transfer above the Coulomb barrier between the ion and the surface [1]. A hollow atom is a highly excited neutral particle, which will rapidly de-excite by either radiative or non-radiative processes [2,3].
Here we study the former process when Xenon and Argon ions with charge states up to Q=40 and Q=18, respectively, are transmitted through a freestanding single layer of graphene. Emitted x-rays are detected with a Bruker XFlash detector with an energy resolution of 140eV. Transmitted ions are also detected with an electrostatic analyzer, allowing charge exchange and energy loss measurements. Both ion and x-ray detection can be performed in coincidence in order to clearly distinguish between x-rays emitted from ions transmitted through graphene and ions impinging on the surrounding target holder (see Fig. 1).

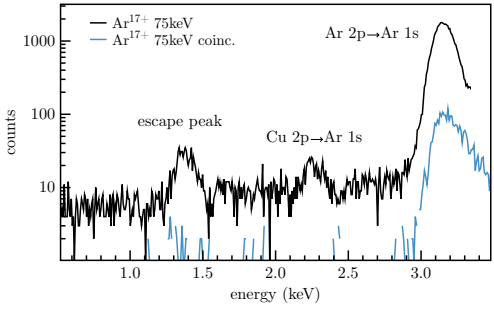

Figure 1: x-ray emission spectra from Ar^{17+} ions at 75keV transmitted through graphene. The black line shows all emitted x-rays (above a threshold of 500eV), whereas the blue line shows the spectrum in coincidence with transmitted ions. In the latter case the Cu 2p -> Ar 1s signal is not visible as it results from ions impinging on the target holder.

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ABSORPTION OF ATOMS AND MOLECULES OF HYDROGEN AND NITROGEN IN TUNGSTEN, IN SIMILAR CONDITIONS TO THOSE FOR A FUSION REACTOR

Beneitez, S.S.[1], Gervasoni J. L[1,2], Furnari J. C.[3]

[1] Centro Atómico Bariloche, CNEA (Comisión Nacional de Energía Atómica).
[2] CONICET (Consejo Nacional de Investigaciones Científicas y Técnicas).
[3] Centro Atómico Ezeiza, CNEA (Comisión Nacional de Energía Atómica).

This work is a preliminary study of the absorption of H, N, H2, N2, on a surface of tungsten from the crystallographic direction (001), (DFT), through the first beginning implemented, based on the density funtional theory implemented in the Open-Source Code Quantum Espresso [http://www.quantum-espresso.org/].

We model the tungsten surface in the direction (001), the adsorption energy was analyzed for atoms of H, N, and molecules of H2, N2. We determine this absorption sites and orientation for these molecules. In the case of H_2 molecule we study in detail the mechanism of "dissociative adsorption".

LIFETIME QUENCHING DUE TO SURFACE WAKE FIELD

G. Sharma[a], D. Swami[b], B. Kumar[c], N. K. Puri[a], and T. Nandi[b]

[a]Dept. of Applied Physics, Delhi Technological University, New Delhi-110042, India
[b]Inter University Accelerator Centre, JNU New Campus, New Delhi-110067, India
[c]Jai Prakash Vishvidyalaya, Chapra, Bihar-841301, India

Energy loss field in bulk of the foil is so large that can blend the fine structure sub levels completely. However, small surface wake field (SWF) [1] induced mixing leads to partial admixture of $2s\ ^2S_{1/2}$ and $2p\ ^2P_{1/2}$ in H-like ions that quenches the $2s\ ^2S_{1/2}$ lifetime to a great extent [2]. In order to study this effect in various ion species, we have used the beam energy above the Coulomb barrier to obtain the spectrum from projectile and projectile-like ions in a single beam-foil experiment as shown in Fig.1. The four peaks observed can be assigned to He-like Ti, Cr, Fe and H-like Co ions [4] as the peak of radiative electron capture disappears from the delayed spectra. Infact, the x-ray lines from projectile-like ions are much weaker than the one from the projectile-ion; a special technique [3] is adopted to record them. Upper level lifetime measurements were carried out using the beam-foil time-of-flight technique with 110 MeV Ti ions with a flight distance of only 0-3 mm for the short lived levels as given in the Table 1. The lifetimes obtained cannot be attributed to a pure metastable state in the corresponding ion. Hence, effect of the Stark mixing of closely spaced $1s2p\ ^3P_1$ and $1s2s\ ^3S_1$ in He-like ions and $2p\ ^2P_{1/2}$ and $2s\ ^2S_{1/2}$ in H-like ions need to be considered. The prescription given elsewhere [2] have been followed to obtain the SWFs, which fall in the order of 10^7 V/cm. It is thus much smaller than the field required for complete mixing ($\sim 10^{10}$ V/cm) the above mentioned states. Further, the results show that the SWF decreases linearly with the atomic number of the corresponding ion species.

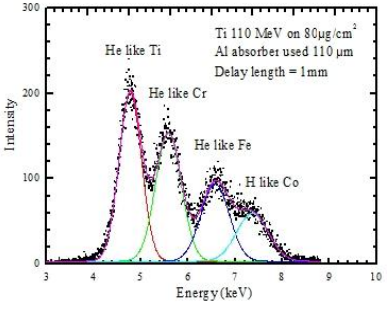

Table1: Measured (τ) and theoretical (τ') lifetimes of the projectile and projectile like ions are compared. The mixing parameter ε and corresponding SWF responsible for the mixing (E_f) [2] are given.

Ion	E keV	τ (ps)	τ'(ns) [4]	ε x10^{-2}	E_f(V/cm) x10^{+07}
Ti^{20+}	4.73	67.1	26.6	3.74	9.2
Cr^{22+}	5.50	61.9	10.7	2.63	6.4
Fe^{24+}	6.51	129.5	4.7	1.32	3.2
Co^{26+}	7.36	78.3	2.0	0.61	1.5

Figure 1: The X-ray spectrum of 110 MeV Ti on 80 µg/cm^2 C target. The lines from projectile ion and projectile like ions are resolved using 110 µm Al absorber before the detector.

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PHOTOIONIZATION AND PHOTOFRAGMENTATION OF $Lu_3N@C_{80}^{q+}$ IONS (q = 1, 2, 3)

J. Hellhund[a], A. Borovik Jr.[b], K. Holste[b], S. Klumpp[c], M. Martins[c], S. Ricz[d], **S. Schippers**[b], and A. Müller[a]

[a]Institut für Atom- und Molekülphysik, Justus-Liebig-Universität Gießen, 35392 Giessen, Germany

[b]I. Physikalisches Institut, Justus-Liebig-Universität Gießen, 35392 Giessen, Germany

[c]Institut für Experimentalphysik, Universität Hamburg, 22761 Hamburg, Germany

[d]Institute for Nuclear Research, Hungarian Academy of Sciences, 4001 Debrecen, Hungary

We have measured cross sections for photoionization and photofragmentation of endohedral fullerene ions $Lu_3N@C_{80}^{q+}$ (q=1,2,3) [1] employing the photon-ion merged-beams technique at the PIPE end-station [2] of beamline P04 of the PETRA III synchrotron at DESY in Hamburg, Germany. The photo-reaction channels $Lu_3N@C_{80}^{q+} \rightarrow Lu_3N@C_{80-2r}^{p+}$ ($q = 1, 2, 3; p = 2, 3, 4, 5, 6; r = 0, 1, 3, 4$) were investigated in the photon energy ranges 280–330 eV around the carbon K-shell threshold, 380–435 eV around the nitrogen K-Shell threshold, and 1500–1700 eV around the lutetium M-shell threshold. As an example, Figure 1 shows two of the measured cross sections together with peak-fit results. The present work extends recent studies on (endohedral) fullerenes [3-6] to a heavier and more complex species as well as to higher photon energies.

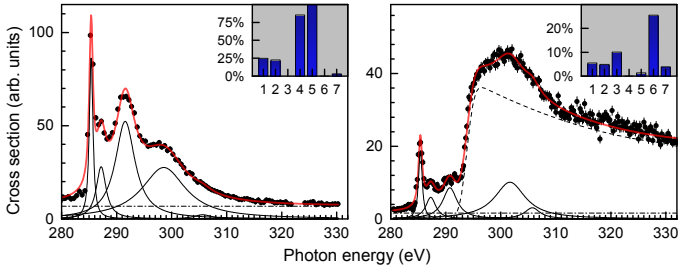

Figure 1: Measured (symbols) and fitted (lines) cross sections for single (left) and double (right) photoionization of $Lu_3N@C_{80}^{+}$. The insets display the relative contributions of the seven peak functions fitted to the spectra.

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MULTIPLE IONIZATION OF Ne^+ IONS BY PHOTOABSORPTION NEAR THE K EDGE

A. Müller[a], D. Bernhardt[a], A. Borovik Jr.[a,b], T. Buhr[a,c], J. Hellhund[a], K. Holste[a,b], A. L. D. Kilcoyne[d], S. Klumpp[e], M. Martins[e], S. Ricz[a,f], J. Viefhaus[g], S. Schippers[a,b]

[a]Institut für Atom- und Molekülphysik, Justus-Liebig-Universität Gießen, 35392 Giessen, Germany

[b]I. Physikalisches Institut, Justus-Liebig-Universität Gießen, 35392 Giessen, Germany

[c]Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany

[d]Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

[e]Institut für Experimentalphysik, Universität Hamburg, 22761 Hamburg, Germany

[f]Institute of Nuclear Research, Hungarian Academy of Sciences, 4001 Debrecen, Hungary

[g]FS-PE, DESY, 22607 Hamburg, Germany

Single, double and triple photoionization of Ne^+ ions by a single photon have been investigated using the photon-ion spectrometer PIPE [1] at the PETRA III synchrotron radiation source in Hamburg. Absolute cross sections were measured employing the photon-ion merged-beams technique [2]. In the course of photon-energy calibration measurements, high-resolution K-shell ionization spectra were also measured for neutral neon by employing an ionization chamber. Natural widths of several prominent lines of neutral Ne and of Ne^+ ions including the Ne K_α transitions could be determined with high accuracy. For comparison with existing theoretical calculations photoabsorption cross sections were inferred by summing the measured partial ionization channels. Agreement between theory and experiment is of mixed quality. It is remarkable, though, that the available R-matrix calculations nicely reproduce fine details in the photoabsorption cross section where interference of double excitations with the channel of direct photoionization occurs. The observed resonances in the different final ionization channels reveal the presence of complex Auger-decay mechanisms. The ejection of three electrons from the lowest K-shell-excited $Ne^+(1s2s^22p^6\ ^2S_{1/2})$ level, for example, requires cooperative interaction of at least four electrons in a single event even if the final charge state is reached via a cascade of Auger decays. The statistical quality, the energy range and the number of channels investigated in the present experiment are unique in the context of K-shell excitation and ionization of ions [3]. Only a previous experiment with C^+ ions [4] has provided a similarly comprehensive, high-quality set of absolute cross section data for photon-ion interactions in the energy range around the K edge.

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HIGHLY CHARGED TUNGSTEN IONS GENERATED BY NANOSECOND PULSED LASER AND INFLUENCE OF MAGNETIC FIELD ON ION CHARGE STATE

S.A. Abbasi[a,d], A.H. Dogar[b], B. Ilyas[c], S. Ullah[a], M. Rafique[d] and A. Qayyum[a]
[a]Physics Division, Pakistan Institute of Nuclear Science and Technology, Islamabad, Pakistan
[b]National Institute of Lasers and Optronics, Nilore, Islamabad, Pakistan
[c]Optics Laboratories, P.O. Box 1021, Islamabad, Pakistan
[d]Department of physics, University of Azad Jammu & Kashmir, Muzaffarabad, Pakistan

Recently, it has been demonstrated that laser-solid interaction process can produce higher current densities of highly charged ions [1] as compared to electron cyclotron resonance (ECR) ion source, which is presently favored for ion accelerators. However, the understanding of the effects of laser parameters (laser fluence, pulse duration, wavelength, etc) and applied magnetic field on the charge state, energy and angular distribution of the ions is very rudimentary. In this work plasma is produced by irradiating a W target with 6 ns pulsed Nd:YAG (λ=1064 nm) laser. The laser fluence at the target was varied in the range of 3.5-19.4 J/cm^2. The ion signal from W plasma was characterized with the help of ion collector and time-of-flight electrostatic energy analyzer (TOF-EEA). The detail of experimental set is given elsewhere [2]. A typical TOF-EEA ion spectra measured at the laser fluence of 19.4 J/cm^2 is shown in Fig. (1a). The integrated ion charge increases from 0.1 to 0.4 μC, ion charge states from W^{1+} to W^{6+} and average ion energy from 0.38 to 1.45 keV with the increase of laser fluence from 3.5 to 19.4 J/cm^2. It was observed that the appearance threshold of a particular ion charge state can be measured and the number of emitted ion charge states can be controlled by the laser fluence.

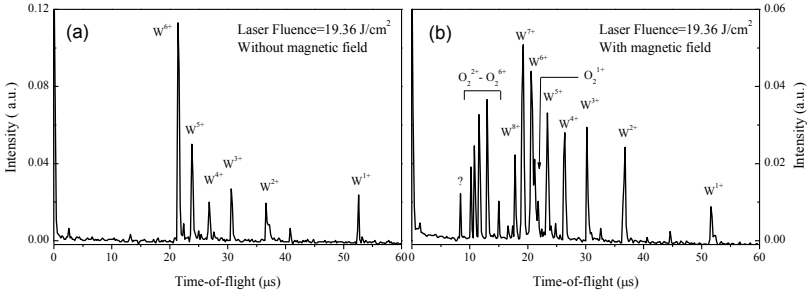

Figure 1. TOF-EEA spectra obtained by irradiating a W target with the laser fluence of 19.36 J/cm^2, (a) without magnetic field and (b) with 0.23 T magnetic field at the target surface.

By application of 0.23 T magnetic field at the target surface, the number of W ion charge states increased from 6 to 8 and in addition six ion charge states of molecular oxygen O_2^{n+} were observed. The observed effects of laser fluence and magnetic field on the properties of the ions are discussed.

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ENERGY SHIFT OF Ta's Kβ_2 LINE AS AN IONIZATION DIAGNOSTIC FOR THE $\geq 15\times$ IONIZED PLASMA IN THE PFRP

N. R. Pereira[a], B. V. Weber[b], E. Szymanska[c], K. Slabkowska[c], L. Syrocki[c] and M. Polasik[c]

[a]Ecopulse, Inc, 7844 Vervain Ct, Springfield, VA 22152 USA

[b]Naval Research Laboratory, Washington DC 20375 USA

[c]Chemistry Department, Nicolaus Copernicus University, Torun, Poland

For modest ionization levels in high-Z atoms, the energy of an ion's K-lines changes by a minute fraction: the $\simeq$ 10 eV higher energy of the $\simeq$ 63287 eV Kα_2 line from the KL_2 transition in Ir on ionization to $\sim$ Ir^{20+} was verified with a K-edge filter [1]. As a diagnostic this type of ionization energy shift does not work because different ionization levels give the same result.

For the higher-Z atoms, the Lβ_2 line at $\simeq$ 10 keV from the L_3N_5 transition has a larger ($\simeq$ 50 eV) and single-valued ionization energy shift that is suitable as an ionization diagnostic [2]. For such a measurement the Plasma-Filled Rod Pinch [3] is ideal because its plasma contains high-energy electrons from the high voltage ($\sim$ 2 MV), high current ($\sim$ 0.8 MA peak) pulse that ionizes a small ($\sim$ mg) amount of material. A detector behind a K-edge filter in a crystal spectrometer may allow a nanosecond-resolved measurement of the ionization energy shift. Suitable K-edge filter-Lβ_2 line combinations are Zn-Ta (with Ta's Lβ_2 $\simeq$ 9652 eV), and Se-Pb (with Pb's Lβ_2 $\simeq$ 12623 eV).

Figure 1 shows the energy of Ta's Lβ_2 line as function of ionization, with the nominal position of Zn's K-edge indicated by the thick dashed line at the origin. The thin short-dashed line suggests the $\simeq$ 12 eV difference in energy between the K-edge's nominal and the peak attenuation, and the measurement's range. The paper will present the analyses done by the time of the

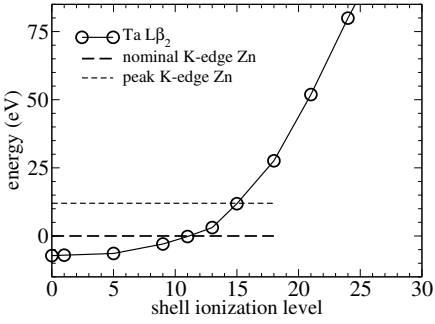

Figure 1: Ionization energy shift for Ta Lβ_2, and Zn's K-edge.

Conference, together with any available measurements (tentatively scheduled for May 2016).

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ZERO-ENERGY RESONANCE EFFECTS IN ION-ATOM IONIZATION COLLISIONS WITHIN A PLASMA ENVIRONMENT

C. F. Clauser, **R. O. Barrachina**

Centro Atómico Bariloche and Instituto Balseiro, Comisión Nacional de Energía Atómica y Universidad Nacional de Cuyo, Av. Bustillo 9500, 8400 Bariloche, Río Negro Argentina.

The effect produced by the surrounding medium on the interaction of charged particles within a plasma leads to atomic spectra and cross sections that differ from those in vacuum. Therefore, it is not possible to rely on atomic and scattering data measured or calculated in vacuum to represent what happens inside a plasma. This point becomes particularly crucial when these data are employed to analyze the performance and working conditions of fusion reactors, especially in the case of inertial confinement.

In this communication we investigate the emergence of zero-energy resonance effects in ion-atom ionization collisions occurring within a plasma. We demonstrate that this type of resonances might occur for particular conditions of density and temperature, whenever the relative energy of a pair of charged particles in the final states vanishes.

Finally we demonstrate that in low density plasmas these resonances might be blurred out by inhomogeneities in density and/or temperature; and the cross section for a pure Coulomb potential be recovered as an average effect. On the other hand, high density plasmas might be tuned to the conditions for a zero-energy resonance, producing sizable distortions of the cross sections, even order of magnitude larger than standard estimates. These results clearly show that the calculation of ionization collisions within a plasma should not been done with disregard to the corresponding screening effect.

OPACITY EFFECTS ON SOFT X-RAY SPECTRA FROM HIGHLY CHARGED LANTHANIDE IONS IN LASER-PRODUCED PLASMAS

Chihiro Suzuki[a], Takeshi Higashiguchi[b], Atsushi Sasanuma[b], Goki Arai[b], Yusuke Fujii[b], Yoshiki Kondo[b], Thanh-Hung Dinh[b], Fumihiro Koike[c], Izumi Murakami[a], Gerry O'Sullivan[d]

[a]National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan

[b]Utsunomiya University, 7-1-2 Yoto, Utsunomiya 321-8585, Japan

[c]Sophia University, 7-1 Kioi-cho, Chiyoda-ku, Tokyo 102-8554, Japan

[d]University College Dublin, Belfield, Dublin 4, Ireland

Soft X-ray emission spectra from highly charged lanthanide ions are of particular interest for basic atomic physics as well as applications to short wavelength light sources. It is well known that contributions from a number of charge states having open 4d subshells overlap at a similar wavelength region and form quasicontinuum bands, so-called unresolved transition arrays (UTA), the spectral feature of which strongly depends on the optical thickness of the emitting plasmas [1].

In this study, we have observed soft X-ray spectra from highly charged ions of seven lanthanide elements from Z=60 (Nd) to 70 (Yb) in laser-produced plasmas (LPPs) using CO_2 and Nd:YAG laser systems, the wavelengths of which are 10.6 μm and 1.06 μm, respectively. The optical thickness of a CO_2 LPP is much smaller than that of a Nd:YAG LPP because of the difference in critical density. As a result, the spectral feature is very different in the two types of LPPs, as shown in figure 1. Broad UTA features, the centre wavelength of which systematically moves to shorter wavelength as Z increases, are observed in Nd:YAG LPPs. In contrast, the UTA widths are narrower in the CO_2 LPPs, and have sharp peaks coinciding with the strongest resonance line of Pd-like ions for lower Z elements. The results are also discussed based on comparison with atomic structure calculations for open 4d and 4f subshell ions.

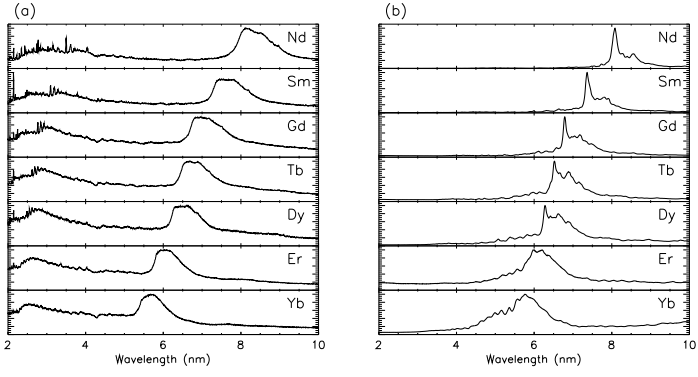

Figure 1: Normalized soft X-ray spectra from highly charged ions of seven lanthanide elements from Z=60 (Nd) to 70 (Yb) observed in (a) Nd:YAG and (b) CO_2 LPPs.

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TUNGSTEN L, M AND N X-RAY SPECTRA MODELING FOR WEST TOKAMAK PLASMAS

Ł. Syrocki[a], E. Szymańska[b], K. Słabkowska[b], M. Polasik[b]

[a]Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University in Toruń, 87-100 Toruń, Poland
[b]Faculty of Chemistry, Nicolaus Copernicus University in Toruń, 87-100 Toruń, Poland

In the future International Thermonuclear Experimental Reactor (ITER) the interaction between the plasma and the tungsten chosen as the plasma-facing wall material imposes that the hot central plasma loses energy by x-ray emission from tungsten ions. But on the bright side the registered x-ray spectra provide alternative diagnostics of the plasma itself. X-ray spectra originating from highly ionized tungsten are extremely complex and demand exhaustive theoretical studies that can be specific to a particular tokamak. Such detailed studies will be especially important for proper interpretation of Soft X-Ray (SXR) plasma radiation (0.1-20 keV) from future ITER-like machines, i.e. WEST project.

The modeling of the soft N, M and L x-ray spectra structures for tungsten in high-temperature tokamak plasmas have been performed within the framework of Collisional–Radiative model using the Flexible Atomic Code package [1,2] for electron temperatures and densities relevant to WEST tokamak. In the package the full-relativistic Dirac-Fock-Slater iteration method and the configuration interaction method are used for the calculation of atomic structures, and the distorted-wave approximation method is used for electron collision cross sections.

Presented results concern the modeling of the very soft N → N and M → M transition line structures and N, M and L x-ray lines structures in the tungsten SXR radiation expected to be emitted from WEST tokamak plasmas. SXR radiation emitted in WEST will be register by the diagnostic based on the GEM detector system [3]. The simulations have been performed in the wide photon energy range using the FAC package for various electron temperatures and electron density, relevant for the central plasma in WEST tokamak.

We believe that the results of our modeling presented here will be useful for the proper design and optimization of the GEM detector system. The further theoretical study on the tungsten spectra modeling for different WEST scenarios is in progress.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This scientific work was partly supported by Polish Ministry of Science and Higher Education within the framework of the scientific financial resources in the year 2015 allocated for the realization of the international co-financed project. This work was also done under Grant No. 2011/01/D/ST2/01286 of the Polish National Science Centre.

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DIAGNOSTICS OF PLASMA PARAMETERS BASED ON THE K AND L X-RAY LINE POSITIONS FOR 3D, 4D AND 4F ELEMENTS

E. Szymańska[a], K. Słabkowska[a], Ł. Syrocki[b], K. Sawicka[a], M. Polasik[a]

[a]Faculty of Chemistry, Nicolaus Copernicus University in Toruń, 87-100 Toruń, Poland
[b]Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University in Toruń, 87-100 Toruń, Poland

Outer-shell ionization of various elements in plasmas is mainly a function of the plasma parameters. Therefore, it can affect the energy positions and shapes of characteristic x-ray lines in radiation emitted from plasmas, what should be useful in plasma diagnostics. Until 2011 the knowledge concerning the influence of outer-shell electron stripping on the K, L and M x-ray lines, based on the results of systematic studies has not been hitherto known in scientific literature. Lack of this knowledge caused serious difficulty in the interpretation of the complex x-ray registered spectra structures, emitted by mid-Z and heavy elements in the hot plasma in recent years. This situation have encouraged us to perform the series of detailed theoretical studies concerning the influence of outer-shell electron stripping on the K, L and M x-ray lines for many elements [1-8]. Part of the performed results have been already used in order to obtain the information about some of plasma parameters [5, 6].

The main objective of presented studies has been to provide an exhaustive set of theoretical predictions about the effect of outer-shell electron stripping on the positions of the K and L x-ray lines for selected 3d, 4d and 4f elements, which can be of vital importance in designing new diagnostics of plasma parameters by the interpretation of x-rays spectra emitted from the plasma generated in various sources. Diagnosing plasmas by these ionization energy shifts depends essentially on computations that can now be performed with sufficient accuracy, i.e. using the multiconfiguration Dirac-Fock method.

The results of these studies will enabling diagnostics of low and high temperature plasma parameters by the interpretation of x-rays emitted from the plasma produced in various sources, e.g. by discharge pulsed power machine (plasma-filled rod pinch diode - PFRP, plasma-focus device like PF-1000), short-pulsed high power lasers and by world's most powerful pulsed-power facility and x-ray generator - Sandia Z-machine.

This work was supported by the Polish National Science Centre under grant no. 2011/01/D/ST2/01286.

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INDIVIDUAL M X-RAY LINE CONTRIBUTIONS ORIGINATING FROM TUNGSTEN IONS FOR VARIOUS PLASMA PARAMETERS

K. Słabkowska[a], Ł. Syrocki[b], E. Szymańska[a], M. Polasik[a]

[a]Faculty of Chemistry, Nicolaus Copernicus University in Toruń, 87-100 Toruń, Poland
[b]Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University in Toruń, 87-100 Toruń, Poland

In this work we present the results of modeling of the M x-ray line structures for tungsten in high-temperature plasmas predicted with temperatures relevant to tokamak JET. The simulations have been performed using the Flexible Atomic Code (FAC) package within the framework of Collisional-Radiative model approach [1-3]. In the package the full-relativistic Dirac-Fock-Slater iteration method and the configuration interaction method are used for the calculation of atomic structures, and the distorted-wave approximation method is used for electron collision cross sections.

From our preliminary attempt to interpretation [4-5] of the x-ray spectrum, registered by the high-resolution crystal KX1 spectrometer on the JET with an ITER-like wall, we have found that either the contribution for $4s^1$ subshell state and the sum of contributions (for $4s^1$, $4p^1$, $4d^1$ and $4f^1$ subshell states) are not able to properly reproduce the shape of the experimental spectrum. The reason of that problem seems to be a drastic overestimation (by the FAC package) of the contributions from occupied subshells with higher quantum number ℓ in transitions of the $3p^5 4\ell^1 4d^1 \rightarrow 3p^6 4\ell^1$ type, in comparison with those originating from the transitions of $3p^5 4s^1 4d^1 \rightarrow 3p^6 4s^1$ type. Therefore, to reproduce the high-resolution experimental spectra, it is necessary to evaluate the individual contributions not only from $4s^1$ states but also from $4p^1$ to $4f^1$ states as shown here for the W^{45+} ions. We found from our analysis that also in the case of W^{47+} it is important to take into account different M x-ray subshell contributions. In this case we have considered contributions from 4s and 4d subshells, which correspond to 4s → 3p and 4d → 3p transitions, respectively.

Moreover, it has been found that a detailed, quantitative interpretation of the high-resolution x-ray spectra registered for different discharge conditions on the JET tokamak need further comprehensive theoretical studies. Such research is in progress. We believe that the results of our modeling presented here are also important for ASDEX Upgrade tokamak and for tokamaks such as WEST and ITER, where tungsten plasma-facing components will be implemented and kept track of with a similar high-resolution x-ray diagnostic.

This work was supported by the Polish National Science Centre under grant no. 2011/01/D/ST2/01286.

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CHARACTERISTICS OF FEMTOSECOND LASER PULSES PROPAGATING IN MULTIPLE IONISED RARE GASES

Valer Tosa, Katalin Kovacs

National Institute for R&D of Isotopic and Molecular Technologies, Donat 67-103, 400293, Cluj-Napoca, Romania

We use a three dimensional non-adiabatic model [1] to characterize femtosecond pulse propagation in a gas medium under conditions of high intensities which creates high electron concentrations via multiple ionizations of the target gas medium.
Here we analyze the case of a 35 fs long pulse at 267 nm wavelength (third harmonic of 800 nm Ti:Sa laser) propagating in Ar at 30 torr, assumed constant along a 2 mm long static cell placed in the focus. A pulse energy of 2.6 mJ, a focal length of 4 m, and a beam waist at the focusing element of 3.2 mm yield a waist in the focus of 20 μm and an on-axis intensity at medium entrance of 1.1×10^{16} W/cm^2.
Assuming a Gaussian temporal shape as shown in the left panel of Fig. 1 we obtain the evolution in time of ionizing species Ar, Ar^+, …, Ar^{6+} which are fully depleted by the end of the pulse. If the initial Ar density is assumed to be n_0 then the final electron concentration will be $> 6n_0$. This is seen in middle panel of Fig. 1 where the electron concentration and laser fields are plotted against time. As one can note the electron concentration exhibits successive plateaus, corresponding to double, triple ionization and so on. This temporal variation of the electron concentration is also highly non-homogeneous in space thus one can foresee a complex spatio-temporal variation of the refractive index which causes interesting effects during propagation, which will be reported.
Strong modifications can be seen also in frequency domain, as shown in the right panel of Fig. 1. Initial spectrum is a Gaussian centered at 267 nm, while the spectrum at medium exit on-axis is heavily broadened, both towards shorter but especially toward longer wavelengths which are more sensitive to plasma effects. This broadening is the effect of plasma induced self-phase modulation but the range of broadening is smaller than that reported for 800 nm pulse propagation [1], as shorter wavelengths are more robust against plasma effects.

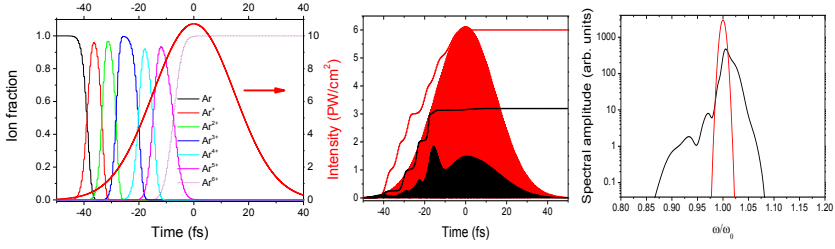

Figure 1: Ion species evolution (left), temporal (middle) and spectral (right) laser fields on-axis, before (red) and after (black) propagation in 30 torr of Ar gas

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SOLUTION OF THE TIME-DEPENDENT DIRAC-KOHN-SHAM EQUATIONS FOR MANY-ELECTRON ION EXPOSED TO A STRONG LASER FIELD

Dmitry A. Tumakov[a], Dmitry A. Telnov[a], Ilia A. Maltsev[a,b], and **Vladimir M. Shabaev**[a]

[a]Department of Physics, St. Petersburg State University, 7/9 Universitetskaya nab., 199034 St. Petersburg, Russia

[b]SSC RF ITEP of NRC "Kurchatov Institute", Bolshaya Cheremushkinskaya 25, 117218 Moscow, Russia

A method for study of many-electron highly charged ions exposed to intense laser fields is proposed. The time-dependent Dirac-Kohn-Sham equations for systems with axial symmetry are solved numerically. The method is used for calculations of ionization probabilities of many-electron ions. The interaction with the electromagnetic field is described within the electric dipole approximation. As a case study, ionization probabilities of many-electron atoms are calculated and compared with the corresponding non-relativistic results [1].

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STATUS OF THE INTERNAL MULTIPHASE TARGET SOURCE FOR STORAGE RING EXPERIMENTS

N. Petridis[a], R. E. Grisenti[a,b], Yu. A. Litvinov[a] and Th. Stöhlker[c]

[a]GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany
[b]Institut für Kernphysik, Johann Wolfgang Goethe-Universität, 60438 Frankfurt, Germany
[c]Friedrich-Schiller-Universität, 07737 Jena, Germany

Recent modification of the internal target source setup at the experimental storage ring (ESR) led to a significant improvement of its performance. In particular, a reliable operation of the light target gases helium and hydrogen at unprecedented area densities up to values of 10^{14} cm^{-2} was demonstrated [1]. In the course of these optimization efforts, a remarkably versatile target source was established, enabling operation over the whole range of desired target gases (from H_2 to Xe) and area densities ($\sim 10^{10}$ to $\sim 10^{14}$ cm^{-2}).

For more general, future applications at storage rings a completely new inlet chamber was proposed based on the experience gained during previous modification processes [2]. The much more compact chamber design will maintain the demanding storage ring vacuum requirements while enabling the operation of the target beam at an interaction length down to 1 mm. This is of paramount importance with respect to the realization of high precision experiments, e.g. by reducing the inaccuracy of the observation angle causing the relativistic Doppler broadening [3].

The new inlet chamber design is currently being assembled and commissioned at GSI. A thorough investigation of the exact target properties is mandatory prior to deployment at a storage ring. Experimental results obtained during the commissioning process of the new internal target chamber design will be presented. Further experimental prospects enabled for the first time by the novel multiphase target source will be discussed.

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THE S-EBIT PROGRAM OF THE HELMHOLTZ INSTITUTE JENA

Sergiy Trotsenko[a,b], Weidong Chen[b], Jessica Menssen[a,b,c], Gleb Vorobjev[b], Alexandre Gumberidze[b,d,e], Christophor Kozhuharov[b], Frank Herfurth[b], Reinhold Schuch[f] and Thomas Stöhlker[a,b,g]

[a]Helmholtz Institute Jena, D-07743 Jena, Germany
[b]GSI Helmholtzzentrum für Schwerionenforschung, D-64291 Darmstadt, Germany
[c]Hochschule Rhein Main, University of Applied Sciences, D-65428 Rüsselsheim, Germany
[d]ExtreMe Matter Institute EMMI, D-64291 Darmstadt, Germany
[e]Frankfurt Institute for Advanced Studies FIAS, Frankfurt a.M., Germany
[f]Stockholm Univercity, SE-10691 Stockholm, Sweden
[g]Fiedrich-Schiller-Universität Jena, D-07743 Jena, Germany

One of the goals of Helmholtz Institute Jena with respect to the Facility for Antiproton and Ion Research is to provide highly charged, low-energy ions by using the S-EBIT facility currently being installed at GSI [1]. This is of particular importance during the FAIR construction related shutdown period of the GSI accelerator complex, when little to no beam time can be provided. During this period the S-EBIT shall facilitate research and development works for SPARC experiments at FAIR. This accelerator-independent source of HCI will not only provide ions necessary for R&D of HITRAP [2] experimental stations but also serve as a standalone device for research and R&D activities (e.g. development of x-ray spectrometers, calorimeter detectors, x-ray optics etc. [3]). Further-more, the combination of S-EBIT with the available laser infrastructure e.g. JETI200 will be a unique platform for the study of highly charged ions subject to intense laser radiation [4] as it is planned at a later stage once the S-EBIT facility has been moved to Jena. An overview of the research program as well as the status of the current activities will be presented.

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HIAF -- NEW OPPORTUNITIES FOR ATOMIC PHYSICS WITH HIGHLY CHARGED HEAVY IONS

X. Ma[a], W. Q. Wen[a], Z. K. Huang[b], H. B. Wang[b], X. L. Zhu, S. F Zhang, J. Yang[a], L. J. Mao[a], X. H Zhou[a], J. C. Yang[a], H. S. Xu[a], Y. J. Yuan[a], J. W. Xia[a], H. W. Zhao[a], and G. Q Xiao[a]

[a] Institute of Modern Physics, CAS, Lanzhou, China; [b]UCAS, Beijing, China

A new project—High Intensity heavy ion Accelerator Facility (HIAF) was approved by the Chinese government on 31 December 2015. The project was proposed in the year of 2007, was selected as one of the 16 priority national Projects for Science and Technology for the 12th 5-Year-Plan in China. The HIAF project consists of ion-Linac (iLinac), a Booster Ring (Bring), a radioactive beam line of fragmentation type, a spectrometer ring (SRing), and several experimental terminals at low and high energy ends as well as setups for in-ring experiments. The rings will be equipped with electron cooler and stochastic cooling devices. The experimental terminals include nuclear structure spectrometer, low energy irradiation target cave, electron-ion recombination, high energy external target station, precision spectrometer ring, etc. Some parameters are summarized in table 1.

Atomic physics foresees new opportunities at HIAF. At low energy branch together with the nuclear structure terminals, a collinear laser spectrometer will be built. For in-ring experiments, a dedicated electron target for dielectronic recombination studies, an internal target for spectroscopy and relativistic collision dynamics experiment, a setup for laser cooling and laser spectroscopy studies, and a double-ToF detector for precision mass measurements will be installed. HIAF will extend our research to unstable ions far from stability.

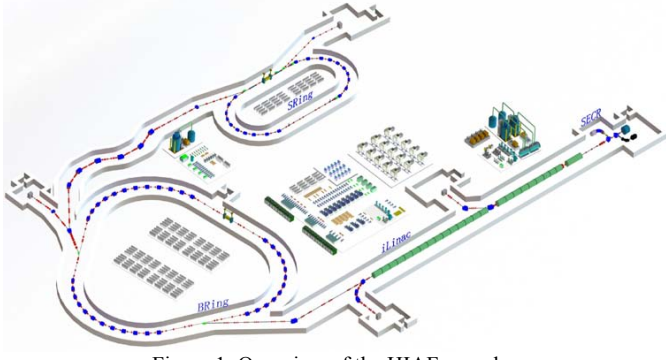

Figure 1: Overview of the HIAF complex

Table 1 Parameters of HIAF accelerators

	Ions	Energy	Intensity
SECR	U^{34+}	14 keV/u	0.05 pmA
iLinac	U^{34+}	17 MeV/u	0.028 pmA
BRing	U^{34+}	0.8 GeV/u	~1.0×10^{11}ppp

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DESIGN OF RFQ COOLER BUNCHER FOR RISP PROJECT

Ramzi Boussaid, Young-Ho Park and Sergey Kondrashev

Institute for Basic Science, 70, Yuseong-daero 1689-gil, Yuseong-gu, Daejeon, Korea, 305-811

A heavy ion accelerator facility called RAON is being designed to produce various rare isotopes under the Rare Isotope Science Project (RISP). Using the ISOL and IF beam production methods, RAON will provide wide variety of intense rare isotope ION beams. An Electron Beam Ion Source (EBIS) charge breeder has been designed and is being built to charge breed rare isotope ion beams for further acceleration. EBIS CB is preferable choice for the most ongoing projects, including RISP, because of its high breeding efficiency, short breeding time, and in particular, high purity of charge bred ion beams. The optimum operation of EBIS CB requires injection of bunched beam with small emittance and low energy spread. A buffer gas RFQ cooler buncher (RISP-RFQCB) is designed to meet these requirements.

At present RFQCB is operational at multiple rare isotope facilities like TITAN, CARIBU, ISCOOL, NSCL and others. In order to meet requirements of modern ISOL facilities, it is necessary to increase the beam intensity limit of such device from typically several tens of pico-amperes (~10^6 pps) to several tens of nano-amperes (~10^9 pps) and to accumulate the ions during time determined by the required EBIS charge breeding time (~10-1000ms). As the existing devices are not able neither to handle high beam current nor to accumulate ions for long period of time, a new RISP-RFQCB device is being developed.

In order to meet the EBIS beam requirements, the RISP-RFQCB should efficiently accept high intensity continuous beams from ISOL ion source and deliver to the EBIS charge breeder bunched ion beams with small emittance (around 3 π.mm.mrad), low energy spread (less than 10 eV) and short bunch width (~2-10 μs).

The RISP-RFQCB is designed to handle a wide range of ion masses (6-180 a.m.u), and to deliver ion beam bunches with high rep-rate (1-100 Hz). A new design concept to be implemented in the RISP RFQCB have been developed, including a novel injection/extraction electrodes geometry, the use of new RF system with frequency up to few MHz and voltage amplitude up to few kV with improved differential pumping system.

Simulations have shown the efficient handling of beam intensities which were never handled so far with improved beam quality. An overview of the RISP RFQCB design concept will be presented. Simulated performance of the device and design of different sub-systems will be presented and discussed. Input and output beam parameters will be measured using Faraday cups and emittance meter. The design of these diagnostics tools will be described as well.

APPA R&D — BMBF COLLABORATIVE RESEARCH AT FAIR

S. Schippers[a] and Th. Stöhlker [b,c] on behalf of the APPA collaborations

[a]I. Physikalisches Institut, Justus-Liebig-Universität Gießen, 35392 Giessen, Germany
[b]GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany
[c]Helmholtz-Institut Jena, 07743 Jena, Germany

The research collaboration APPA R&D [1] comprises the German university groups who have set out to perform scientific research at the future international accerlator complex FAIR (Facility for Antiproton and Ion Research) under the umbrella of APPA (Atomic, Plasma Physics and Applications). The FAIR-installations are currently under construction at the site of the GSI Helmholtz Center for Heavy Ion Research in Darmstadt, Germany. APPA is one of the four research pillars of FAIR hosting the international research collaborations BIOMAT (biophysics and material research), FLAIR (physics with low-energy antiprotons), HEDgeHOB/WDM (plasma physics), and SPARC (atomic physics) who focus on investigations of matter under extreme conditions such as strong fields, high densities, high pressures, and high temperatures [2].

The APPA R&D research collaboration pursues coordinated research projects in the area of accelerator based experiments with heavy ions at the future FAIR-installation. Central issues are i) further development of the the experimental infrastructure, in particular, research and development for enhancing the scientific capabilities of the existing installations and of the future accelerator and detector systems including the respective base technologies, and ii) set-up of the APPA experiments of the modules 0-3 of the modularized start version of FAIR. APPA R&D is funded by the German Federal Ministry for Education and Research (BMBF) within the collaborative-research frame work ('Verbundforschung').

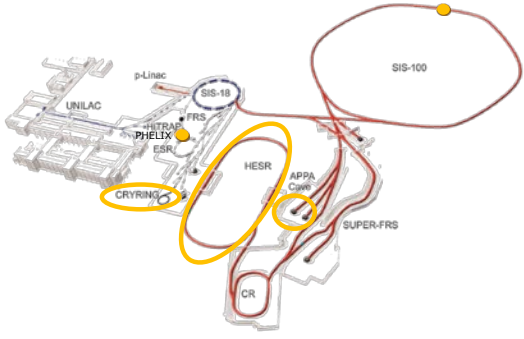

Figure 1: APPA-experiments (marked in yellow) at the future FAIR accelerator complex

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HIGH-PRECISION X-RAY SPECTROSCOPY OF HIGHLY-CHARGED IONS AT STORAGE RINGS USING SILICON MICROCALORIMETERS

Pascal Scholz[a], Victor Andrianov[a,b,c], Alexander Bleile[c,d], Artur Echler[a,c,d], Peter Egelhof[c,d], Patrick Grabitz[c,d], Caroline Kilbourne[e], Saskia Kraft-Bermuth[a], Dan McCammon[f]

[a]Institute for Atomic and Molecular Physics, Justus-Liebig-University, 35392 Giessen, Germany

[b]Institute of Nuclear Physics, Lomonosov Moscow State University, 119991, Moscow, Russia

[c]GSI Helmholtz Center, 64291 Darmstadt, Germany

[d]Institute of Physics, Johannes-Gutenberg University, 55099 Mainz, Germany

[e]NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA

[f]Department of Physics, University of Wisconsin, Madison, WI 53706, USA

The precise determination of the energy of the Lyman-α lines in hydrogen-like heavy ions provides a sensitive test of quantum electrodynamics in very strong Coulomb fields. However, one limitation of the current accuracy of such experiments is the energy resolution of available X-ray detectors [1]. To improve this accuracy, a novel detector concept, namely the concept of microcalorimeters, is now exploited for such measurements.

Microcalorimeters detect the temperature change of an absorber after an incoming particle or photon has deposited its energy as heat. This operation principle provides considerable advantage over conventional detectors with respect to energy resolution, detection efficiency, energy threshold and radiation hardness. Typical experiments on the energy determination of Lyman-a transitions require a large dynamic range and a high absorption efficiency for X-Rays, as well as sufficient detector solid angle. Therefore, the microcalorimeters used in the present experiments consist of silicon thermometers, ensuring a high dynamic range, and of absorbers made of high-Z material to provide high X-ray absorption efficiency. The desired detector solid angle is obtained by detector arrays, because the size of individual microcalorimeters is limited by constraints on their heat capacity. With this kind of detectors, a relative energy resolution of about 1 per mille is obtained in the energy regime of 1 - 100 keV.

The application of microcalorimeters for hard X-rays, based on silicon thermistors and tin absorbers, for the determination of the 1s Lamb Shift in hydrogen-like heavy ions has been pursued by our collaborating groups for more than two decades. Two detector arrays have been successfully applied in two experiments at the Experimental Storage Ring (ESR) of the GSI Helmholtz Center for Heavy Ion Research to determine the 1s Lamb Shift of hydrogen-like lead and gold [2]. An excellent agreement with theory has been obtained. Based on these experiments, a larger detector array with 6 times the active detector area in a new, cryogen-free cryostat is currently in preparation.

In this contribution, we will briefly introduce the detection principle, then we will present the ESR experiments and their results. In addition to the new detector array for experiments at the future FAIR facility, perspectives for other high-precision experiments, i.e. spectroscopy of inner-shell transitions, will be discussed.

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FLUORESCENCE AND INFRA-RED COOLING OF PAH (NAPHTALENE, ANTHRACENE) STUDIED IN AN ELECTROSTATIC STORAGE RING, THE MINI-RING.

S. Martin[1], R. Brédy[1], M. Ji[1,2], **J. Bernard**[1], C. Joblin[2] , A. Cassimi[3] and L. Chen[1]

[1]Univ Lyon, Université Claude Bernard Lyon 1, CNRS, Institut Lumière Matière, F-69622, LYON, France

[2] Université de Toulouse, UPS-OMP, IRAP, Toulouse, France

[3] CIMAP, GANIL Université de Caen, Bd. H. Becquerel, Caen, France

We report on studies about the cooling of two polycyclic aromatic hydrocarbons (PAH) cation, naphtalene$^+$ ($C_{10}H_8^+$), anthracene ($C_{14}H_{10}^+$) stored in a small electrostatic storage ring, the Mini-Ring [1]., at a kinetic energy of 12 keV. The naphtalene and anthracene cations, have been stored for 40 ms in the Mini-Ring with revolution periods of 5.5µs and 6 µs, respectively. The Figure 1 shows the evolution of the number of neutral particles emitted as a function of the storage time. LASER pulses of 532 nm were used to probe the internal energy distribution as a function of the storage time. Cooling rates in the hundred eV per second range are estimated from the measured time evolution of the internal energy distribution. The main contribution to these fast is attributed to electronic fluorescence (Poincaré fluorescence) and compared with the calculated cooling rates. The contribution of infra-red emissions to the cooling rates is also estimated.

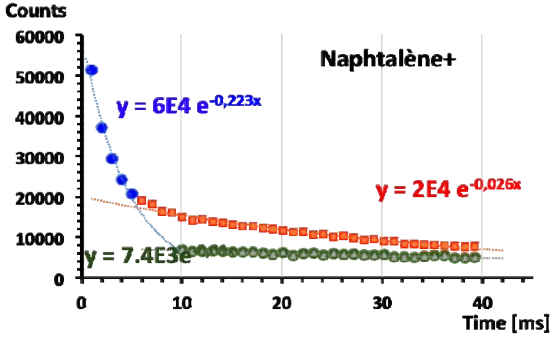

Figure 1: Fast (blue) fluorescence radiative cooling process and slow IR (red) cooling process of naphthalene. Background signal due to the collision with the residual gas (green)..

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A POWERFUL NEW ELECTRON GUN FOR ELECTRON-ION CROSSED-BEAMS EXPERIMENTS

B. Ebinger[1,2], A. Borovik Jr. [1,2], T. Molkentin [1,2], S. Schippers [1,2] and A. Müller [2]

[1]I. Physikalisches Institut, Justus-Liebig-Universität Gießen, 35392 Giessen, Germany

[2]Institut für Atom- und Molekülphysik, Justus-Liebig-Universität Gießen, 35392 Giessen, Germany

The experimental sensitivity of an electron-ion crossed-beams experiment is mainly determined by the densities of both beams in the interaction region. Aiming at the extension of the available range of accessible electron energies and densities, a new high-power electron gun has been developed and fabricated. It delivers a ribbon-shaped beam with high currents at variable energies between 10 and 3500 eV [1,2]. The design goals of the gun are being met by the utilization of a variety of electrodes, all of which are insulated from each other (Fig.1). This electrode configuration allows for a variety of possible operational modes and, thus, provides a high versatility concerning the optimization of the electron-beam properties depending on the purpose of a given experiment.

Here, we report on performance tests of our new electron gun. First experiments have demonstrated the expected high electron currents in the interaction region and good beam transmission. Meanwhile, the tests have entered the final phase as the electron gun has been integrated into the experimental crossed-beams setup in Giessen. Employing the *animated crossed-beams* technique [3], first ionization cross sections were measured. Several challenging issues associated with space-charge effects in the high-density electron beam are currently being investigated.

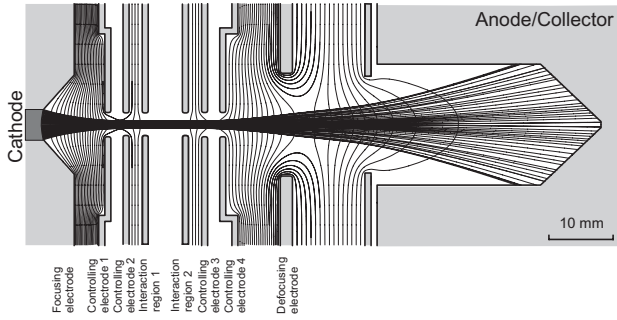

Figure 1: Geometrical sketch of the electron gun with its various electrodes as well as the trajectories of the electrons for the high-energy mode.

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IONIZATION AND EXCITATION OF TRAPPED HIGHLY CHARGED IONS USING ADVANCED PHOTON SOURCES

José R. Crespo López-Urrutia

Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg

Photon-ion interactions (photoionization and photoexcitation) are essential for energy transfer and the equilibrium state in hot plasmas. The introduction of very strong photon sources in the last decade has enabled to study such interactions in the photon energy range from 50 eV to 13 keV by using HCI in an electron beam ion trap (EBIT), FLASH-EBIT [Refs. 1-6] as target (see Fig. 1). These works have complemented three decades of systematic EBIT studies of the respective time-reversed phenomena, dielectronic and radiative recombination. Key advantages of the photon-driven experiments are both the high resolution and signal strength resulting from the excellent resolving power and strong photon fluxes of undulator-cum-monochromator systems at advanced light sources. These have made possible to reduce data acquisition times while resolving, e. g., natural line widths or Fano profiles of excitation channels.

Future experiments will aim at using sympathetically cooled HCI [7] in combination with synchrotron radiation, free-electron lasers and novel sources of high harmonics. Cooling HCI will open new possibilities for enhanced resolution, thus enabling further studies of the electronic structure of HCI including relativistic, nuclear and quantum electrodynamic contributions. Applications in x-ray metrology and frequency metrology are envisioned.

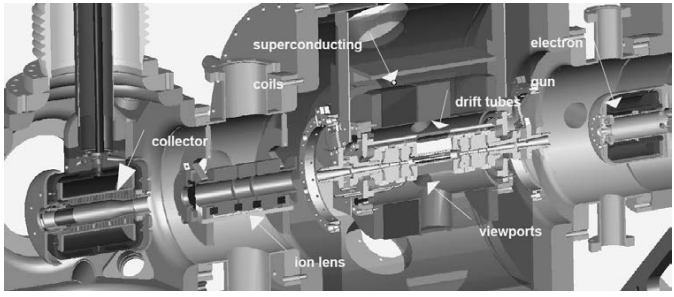

Figure 1: Section of FLASH-EBIT as used in photon-ion interaction studies.

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UNIVERSAL MAIN MAGNETIC FOCUS ION SOURCE FOR PRODUCTION OF HIGHLY CHARGED IONS

V. P. Ovsyannikov[a,*], A. V. Nefiodov[b]

[a]Hochschulstr. 13, D-01069 Dresden, Germany

[b]Petersburg Nuclear Physics Institute, 188300 Gatchina, St. Petersburg, Russia

A novel room-temperature compact ion source for the production of highly charged ions in electron beam within wide ranges of electron energy and current density is developed. Based on combination of two methods of deep ionization of atoms, the device can operate both as conventional Electron Beam Ion Source/Trap (EBIS/T) and novel Main Magnetic Focus Ion Source (MaMFIS). In EBIS/T, ions confined in the potential well are stored in the smooth electron beam going through a few (at least three) drift tubes with positive potentials applied at the edge sections. In MaMFIS, the local ion traps with extremely high electron current density are formed in crossovers of the rippled electron beam in a thick magnetic lens [1,2]. Combination of these methods in single device allows to ionize efficiently both ions in relatively low charge states with ionization energy of about a few tens of eV and highly charged ions with ionization energy of up to a few tens of keV. Towards this end, it is employed the retunable electron-optical system, which can form either smooth electron beam with current density of about a few hundreds of A/cm^2 (EBIS/T technology) or rippled electron beam with high current density in the local ions traps (MaMFIS technology). In the first experiments, the electron beam energy was varied from 8 keV to 42 keV at current of 30-50 mA (see Fig. 1). A feasibility of development of the ion source with electron energy of up to 200 keV is also discussed.

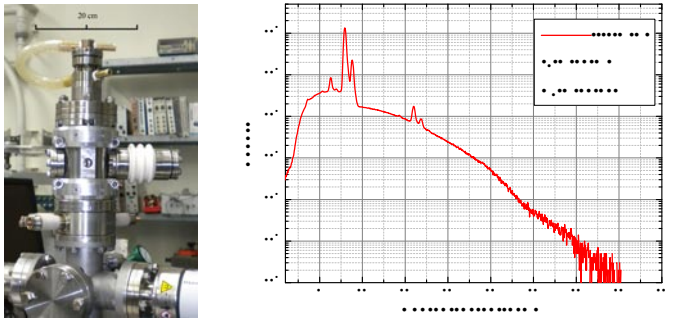

Figure 1: Pilot design of the universal MaMFIS and x-ray radiation from ions of Ir and Ce.

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TOWARDS HIGH-RESOLUTION MERGED-BEAMS ELECTRON-ION COLLISION EXPERIMENTS AT THE UPCOMING CRYRING@ESR STORAGE-RING FACILITY

C. Brandau[a,b], M. Lestinsky[b], C. Kozhuharov[b], A. Müller[c], S. Schippers[a], and Th. Stöhlker[b,d,e] for the SPARC Working Group Electron Targets

[a]I. Physikalisches Institut, Justus-Liebig-Universität Gießen, 35392 Giessen, Germany

[b]GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany

[c]Institut für Atom- und Molekülphysik, Justus-Liebig-Universität Gießen, 35392 Giessen, Germany

[d]Institut für Optik und Quantenelektronik, Friedrich-Schiller-Universität Jena, 07743 Jena, Germany

[e]Helmholtz-Institut Jena, 07743 Jena, Germany

The heavy-ion storage ring CRYRING, previously at the Manne-Siegbahn Laboratory in Stockholm, Sweden, has been recently relocated to the GSI-Helmholtzzentrum für Schwerionenforschung in Darmstadt, Germany [1]. As part of the FAIR project [2], i.e. of the upcoming large-scale facility for antiproton and heavy-ion research, CRYRING is presently being rebuilt and connected to the existing Experimental Storage Ring, ESR. At the GSI/FAIR facility, CRYRING@ESR will serve as a low-energy storage ring for highly charged ions up to bare uranium, for radioisotopes and, potentially in the future, even for antiprotons.
Among other experimental installations [1,3], CRYRING@ESR features an electron cooler with very low electron beam temperatures, both in longitudinal but particularly also in the transversal direction [4]. The electron cooler will be used as an electron target in merged-beams electron-ion collision experiments with the purpose of precision spectroscopic studies, mainly utilizing the process of dielectronic recombination [5,6,7]. Due to the exceptional quality of the electron beam, the experimental resolving power, accuracy and sensitivity will be greatly enhanced compared to previous experiments at the ESR electron cooler. The dual-ring arrangement will allow for further degrees of control of the injected species such as ions in atomic or nuclear ground or excited states [7] and will, thus, allow us to explore numerous new and fascinating topics [3].

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DEVELOPMENT OF EBIS CHARGE BREEDER FOR RARE ISOTOPE SCIENCE PROJECT

Hyock-Jun Son[a,b], Jongwon Kim[a], Young-Ho Park[a], Sergey Kondrashev[a], Moses Chung[c]

[a]Rare Isotope Science Project, Institute for Basic Science, Daejeon 305-811, Rep. of Korea
[b]Department of Advanced Green Energy and Environment, Handong Global University, Pohang 791-708, Rep. of Korea
[c]Department of Physics, Ulsan National Institute of Science and Technology, Ulsan 689-798, Rep. of Korea

In Korea, a heavy ion accelerator facility called RAON is being designed to produce various rare isotopes for the Rare Isotope Science Project (RISP). An electron beam ion source (EBIS) will be used for charge breeding of rare isotope beams in the ISOL system [1]. An electron gun with IrCe cathode for the EBIS system has been designed by the BINP. The electron beam current is set to be 3 A, and the maximum beam energy is 20 keV. The electron beam current density can reach up to 500 A/cm^2 by the maximum magnetic field of about 6 T in the ion trap region, where the electron beam radius is around 0.45 mm. In addition, an electron collector has been designed to dump the electron beam, and the electron beam power dumped on the collector surface is estimated to be less than 20 kW. We consider $^{133}Cs^{33+}$ for the initial test target ion species in the charge breeding processes. Based on this ion species, several beam simulations have been performed by using TRAK [2] and WARP codes. In particular, ion beam dynamics from injection to extraction is being investigated with the inclusion of the charge breeding processes. In this paper, the design of the collector with several test results will be presented, and the progress of the ion beam simulation will be described.

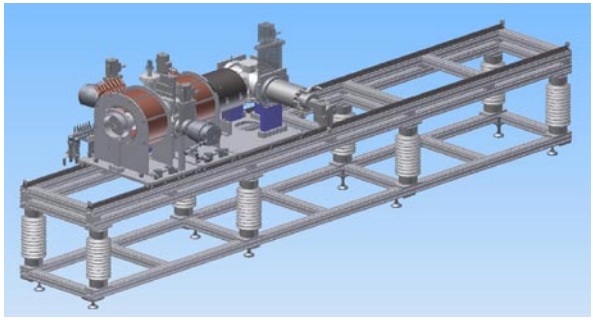

Figure 1: Design of E-gun/Collector test bench for EBIS charge breeder in RISP.

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ELECTRON LOSS STUDIES OF MANY-ELECTRON, HEAVY IONS

G. Weber[a,b], R. D. DuBois[c], S. Hagmann[b], P.-M. Hillenbrand[b], Th. Stöhlker[a,b,d]

[a]Helmholtz Institute Jena, 07743 Jena, Germany
[b]GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany
[c]Missouri University of Science and Technology, MO 65409, USA
[d]IOQ, Friedrich-Schiller-Universität, 07743 Jena, Germany

Charge-changing processes, i. e. loss or capture of electrons, occurring in ion-atom and ion-ion collisions belong to the most basic interactions in all types of plasmas. Moreover, in accelerators interactions between projectile ions and the residual gas can lead to a change of the projectile charge state. In the presence of dispersive ion optical elements, the trajectories of up- or down-charged ions do not match the one of the reference charge state, resulting in a successive defocussing and, as a consequence, loss of beam intensity.

Studies of electron loss of many-electron, heavy ions that were performed at the Experimental Storage Ring of GSI, Darmstadt [1,2,3] will be presented together with recent theoretical works. Particular emphasis will be given to the cross sections of U^{28+}, as this ion species was chosen as a reference ion for the planning of the future FAIR facility [4] currently being built at the GSI campus.

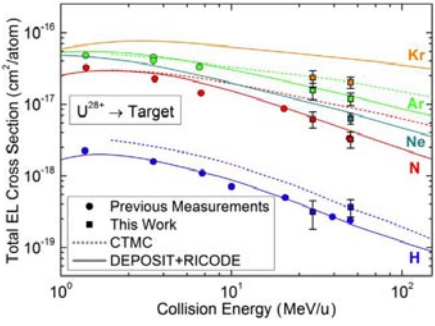

Figure 1: Compilation of total electron loss cross sections for U^{28+}, reproduced from [2].

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COMPACT 0.86 T ROOM-TEMPERATURE ELECTRON BEAM ION TRAPS

Peter Micke[a,b], Sven Bernitt[a,c], Klaus Blaum[a], Lisa F. Buchauer[a], Thore M. Bücking[a], André Cieluch[a], Alexander Egl[a], James Harries[d], Daniel Hollain[a], Steven A. King[b], Sandro Kraemer[a], Steffen Kühn[a], Tobias Leopold[b], Thomas Pfeifer[a], Thomas Stöhlker[c], Sven Sturm[a], Joachim Ullrich[b], Robert Wolf[a], Piet O. Schmidt[b,e], José R. Crespo López-Urrutia[a]

[a]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69115, Heidelberg, Germany
[b]Physikalisch-Technische Bundesanstalt, Bundesallee 100, D-38116, Braunschweig, Germany
[c]Friedrich-Schiller-Universität Jena, D-07737, Germany
[d]SPring-8, Hyogo, Japan
[e]Leibniz Universität Hannover, D-30167, Germany

Research on multiply and highly charged ions (HCIs) is of great interest not only for atomic physics but also for fundamental studies. Electron beam ion traps (EBITs) have proven to be versatile and indispensable tools for HCI production and study. In an EBIT, an electron beam is compressed by a strong, inhomogeneous magnetic field to breed and trap these ions efficiently. Usually, the magnetic field is generated by superconducting coils, but room-temperature models also exist.

To ease operation we have built a novel room-temperature EBIT based on permanent magnets whereby their magnetic field is guided and focused at the trap center, reaching a value of 0.86 T. Our prototype EBIT can provide a continuous beam of Xe ions up to charge state 29+, and a total ion current of 100 pA, with a 4 mA 2 keV electron beam. Charge states of Xe as high as 36+ were also produced. Pulsed extraction of Ar ions up to charge state 16+ was demonstrated. Following this design we recently started to construct a second generation of four new EBITs. While the protoype currently serves as a HCI source for the Penning trap ALPHATRAP, dedicated to high-precision g-factor determinations, the new-generation EBITs will serve as HCI sources for Paul or Penning traps, where precision measurements are performed at low HCI temperatures. In particular, at PTB in Braunschweig we are currently setting up an experiment aiming at quantum logic spectroscopy in a cryogenic Paul trap based on CryPTEx [1, 2] to probe a possible variation of the fine-structure constant and with the ultimate goal to create a novel optical atomic clock based on HCIs. A fourth EBIT will be constructed to provide HCIs for X-ray laser spectroscopy at synchrotron and free-electron laser light sources. This EBIT features a novel off-axis electron gun, which will enable the trap to be used for energy calibration at such facilities. The photon beam then can pass through the EBIT and remains available for beamline users downstream.

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A NEW ELECTRON BEAM ION SOURCE AS CHARGE BREEDER FOR RARE ISOTOPE BEAMS

Michael A. Blessenohl[a], Stepan Dobrodey[a], Zachary Hockenbery[a], Renate Hubele[a], Thomas Baumann[a], Jens Dilling[b], José R. Crespo López-Urrutia[a]

[a]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
[b]TRIUMF, 4004 Wesbrook Mall, Vancouver, BC V6T 2A3, Canada

TRIUMF as Canadian national research facility operates the largest cyclotron in the world, which accelerates protons to 500 MeV. These high-energy protons are sent to a target composed of heavy elements which on impact produces heavy isotopes to be studied in the two post-accelerators ISAC (Isotope Separator and Accelerator) I and ISAC II.

The new ARIEL (Advanced Rare IsotopE Laboratory) at TRIUMF will include a new electron beam ion source (EBIS) for charge breeding [1] these rare isotope beams. Highly charged heavy elements are used to keep the charge to mass ratio $^{\mathrm{A}}/_{\mathrm{Q}}$ low, which is required by the post-accelerators ISAC I and II. Aiming at the studies of isotopes with half-lives down to 65 milli-seconds and low abundances of down to 10^6 per bunch, the whole process of injection, charge breeding and extraction has to be very efficient. The repetition rate of the isotope bunches is 100 Hz, which requires fast high-voltage control and switching. The goal is to have a charge breeding efficiency of at least $20\,\%$.

Here the latest design is presented, including finite-element and Monte-Carlo simulation results, concepts for the on-line diagnostics and a fast control system.

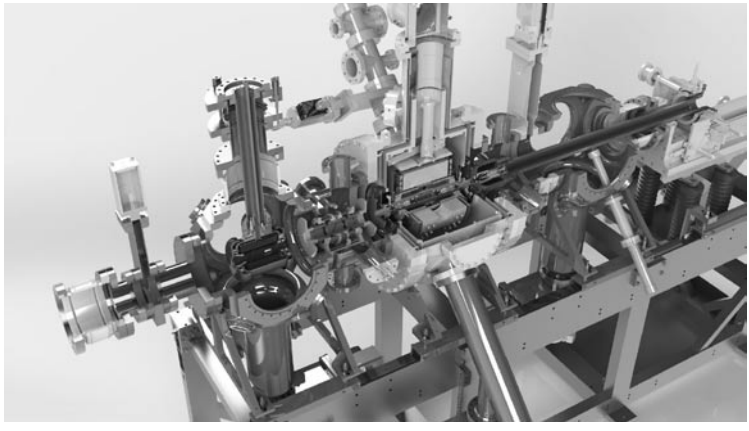

Figure 1: Sectional view of the new EBIS assembly.

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EXPERIMENTAL SETUP FOR STUDYING COLLISIONS OF HIGHLY CHARGED IONS WITH GRAHPENE AND OTHER 2D MATERIALS

J. Schwestka, R.A. Wilhelm, D. Melinc, L. Leonhartsberger and F. Aumayr

Institute of Applied Physics, TU Wien, Wiedner Hauptstr. 8-10/E134, 1040 Vienna, Austria

Collision studies between ions and 2D materials, like the ultimately thin single layer graphene (SLG), are of fundamental interest, because they bridge the gap between atomic collisions in gaseous and those in solid targets [1]. To learn more about the microscopic interaction mechanism we built a new experimental setup (figure 1) based on the time-of-flight (TOF) technique, which allows us to study electron emission, energy loss and charge exchange associated with highly charged ion (HCI) impact on SLG simultaneously.

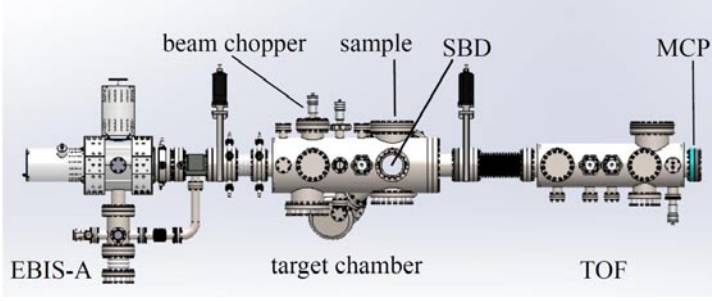

Figure 1: New experimental setup based on the time-of-flight technique

A room-temperature electron beam ion source (Dreebit EBIS-A) provides HCI of different charge states q (Xe^{1+} to Xe^{46+}) at kinetic energies ranging from 100eVxq to 12keVxq. To generate a start signal in our TOF setup the beam is blanked by a pulsed voltage applied to electric field plates. A set of collimators with an acceptance of <0.5° allows us to use blanking voltages of <50V with a rise/fall time of less than 1ns (GBS Spezialelektronik) [2]. Ions traversing through a SLG sample are recorded by an imaging multi channel plate (MCP) located at the end of the 1.7m long flight path. The MCP signal serves as a stop for the TOF measurement and an electrostatic beam deflector in front of the MCP allows a charge state separation. We plan to achieve an energy resolution of $\Delta E/E<2\%$, which will be sufficient to measure charge state enhanced kinetic energy loss [1]. In parallel to the TOF a Vienna electron statistics detector is mounted [3]. Electrons emitted from the SLG are attracted by a weak electric field applied to a highly transparent grid, which shields a surface barrier detector (SBD) biased at 25-30 kV. The quantity of emitted electrons per impact is obtained from the pulse height of the SBD. We aim on measure not only energy loss for charged and neutral transmitted ions/atoms, but also on coincidence measurements of charge exchange and electron emission.

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RADIATIVE LIFETIME MEASUREMENT OF THE $^1S_0$ METASTABLE STATE OF Ar^{2+} USING AN ELECTROSTATIC ION BEAM TRAP

N. Ojima[b], **M. Saito**[a], T. Majima[ac], M. Imai[a], H. Tsuchida[ac], Y. Haruyama[b],

[a]Department of Nuclear Engineering, Kyoto University, Kyoto 615-8540, Japan
[b] Laboratory of Applied Physics, Kyoto Prefectural University, Kyoto 606-8522, Japan
[c]Quantum Science and Engineering Center, Kyoto University, Uji 611-0011, Japan

The radiative lifetime of the $^1S_0$ metastable level in Ar^{2+} has been studied experimentally and theoretically by several groups [1]. The experiments have been done using ion traps or storage rings. The reported experimental lifetimes are scattered within ±20% of the average, and their experimental errors are somewhat large (±20%) except for the value measured using a storage ring [2]. The uncertainties in the measurements stemmed largely from the correction of the destruction of the trapped ions by collisions with background gases. On the other hand, the theoretical values reported until now are in agreement with each other.

The radiative lifetimes of the $^1S_0$ metastable state in Xe^{2+} [3] and Kr^{2+} [4] have been measured recently using an electrostatic ion trap of the ion-beam storage type (electrostatic ion beam trap). Using such traps, the variation in the number of stored ions over time can be monitored readily, which enables correction for the collisional losses of the stored ions. In this work, we measured the radiative lifetime ($^1S_0 \rightarrow {}^3P_1$) of the metastable Ar^{2+} using the electrostatic ion beam trap, and was compared with the previous experimental and theoretical data.

Figure 1 shows a schematic of the experimental apparatus. A 2.4-keV Ar^{2+} pulse ion beam was mass analyzed magnetically, and was accumulated in the trap. The photons emitted in the transition from $^1S_0$ to $^3P_1$ (311 nm) were selected by a band-pass filter, and were detected by a photomultiplier. The photon counts were recorded by a MCS, which provides the photon spectrum as a function of time. In order to estimate the lifetime of the trapped ions due to collisions with background gases, the number of neutral particles escaping from the trap was measured by a MCP. Preliminary measurements were performed using a wide band-pass filter (330±35 nm) to check the optical system, and time decay was observed in the photon spectrum. The results using a narrower band-pass filter and the derived lifetime will be presented.

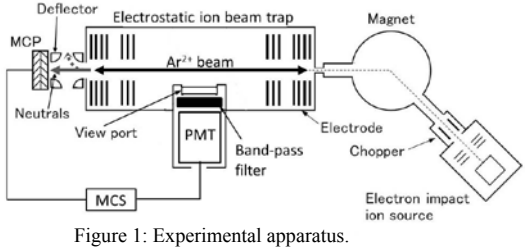

Figure 1: Experimental apparatus.

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LIST OF AUTHORS

Zhao D.M.	ST16, PA51, PA72
Zhao H.W.	PA72, PB70
Zhao Q.S.	ST16
Zhao Y.	ST20, PA22
Zhao Z.Z.	PB07
Zhou X.	ST20, PA22
Zhou X.H.	PB70
Zhu L.F.	PA31
Zhu X.L.	ST16, PA31, PA51, PA72, PB70
Zou Y.	PR1, ST21, PA80, PB07, PB15, PB29
Zouros T.J.M.	PA41, PA43, PB12
Zubova N.A.	PB17

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HEADQUARTERS GROSSROEHRSDORF

Dr. Guenter Zschornack, CTO
Southwallstr. 5
01900 Grossroehrsdorf, Germany

Phone: +49-35952-420-201
Cell: +49-174-3281-681
Email: guenter.zschornack@dreebit.com

www.dreebit-ibt.com

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Conference Programme

Time	Monday September 12	Tuesday September 13	Wednesday September 14	Thursday September 15	Friday September 16
09:00 / 09:00 09:20 / 09:45 10:05 / 10:15	Opening P. Beiersdorfer T. Brage	S. Schippers A. Wolf S.W. Epp	G. O'Sullivan L. Schmöger Y. Ralchenko	P.O. Schmidt A.S. Kadyrov D.A. Glazov	H. Zettergren E. Gruber M. Trassinelli
10:35 – 11:05	Coffee	Coffee	Coffee	Coffee	Coffee
11:05 11:15 11:55	D. Kato A. Gumberidze Y.S. Kozhedub	J. Bernard F. Herfurth A. Borovik, Jr	O.A. Fojon M. Łabuda X.L. Zhu	E. Giglio D. Misra C.C. Montanari	N. Stolterfoht HQ. Zhang Closing
12:15 – 14:00	Lunch	Lunch	Lunch	Lunch	Lunch
14:00 14:30 14:50 15:10	Y. Wang S. Bernit J. Ulmann J. Machado	P. Boduch J.N. Tan S. Ali E. Sokell	Outing 14:00 – 18:00	M. Chabot R. Cheng W. Li Ch. Shah	Transportation to Cracow
15:30 – 16:00	Coffee	Coffee		Coffee	
16:00 16:20 16:40	J. Hoszowska A. Surzhykov D. Banaś	Poster Session A 16:00 – 18:00		Poster Session B 16:00 – 18:00	
	Lab Visit 17:00 – 19:00	G. Gierliński Public Lecture 18:00 – 19:00	Ligth dinner 18:00 – 20:00	Conference dinner 19:00 – 22:00	

RL: Review Lectures | PR: Progress Report | ST: Special Topics | LR: Local Report | PL: Public Lecture