

ELECTRON IMPACT IONIZATION OF GROUND-STATE AND METASTABLE Li^+ IONS

A. Borovik, Jr., I. Bray*, D. V. Fursa*, S. Schippers and A. Müller

Institut für Atom- und Molekülphysik, Universität Giessen, D-35392 Giessen, Germany

(*) ARC Centre for Antimatter-Matter Studies, Curtin University of Technology, Australia

He-like systems are next in simplicity to H-like atoms and ions. Understanding their behavior in collisions is among the most fundamental problems in atomic physics. Although the first measurements on electron-impact ionization of He-like lithium ions have been performed a long time ago [1], satisfying theoretical treatment has become possible only recently. Benchmark-quality calculation have been published for ground state $\text{Li}^+(1s^2)$ [2] and metastable $\text{Li}^+(1s2s)$ ions [3]. The present investigation aimed primarily at providing high-quality experimental data on the electron impact ionization of ground state and metastable Li^+ ions and was accompanied by new calculations employing the converged coupled channel (CCC) method.

The crossed-beams technique was used to measure absolute cross sections in the energy range from near threshold to 1000 eV for electron impact ionization of Li^+ ions. By evaporating different parent materials into the ion source plasma, pure beams of ground-state or mixed beams of metastable and ground-state ions could be prepared. Fig. 1 shows experimental and theoretical data for ionization of ground-state Li^+ . Almost perfect agreement is found between our experiments and the most recent theoretical calculations.

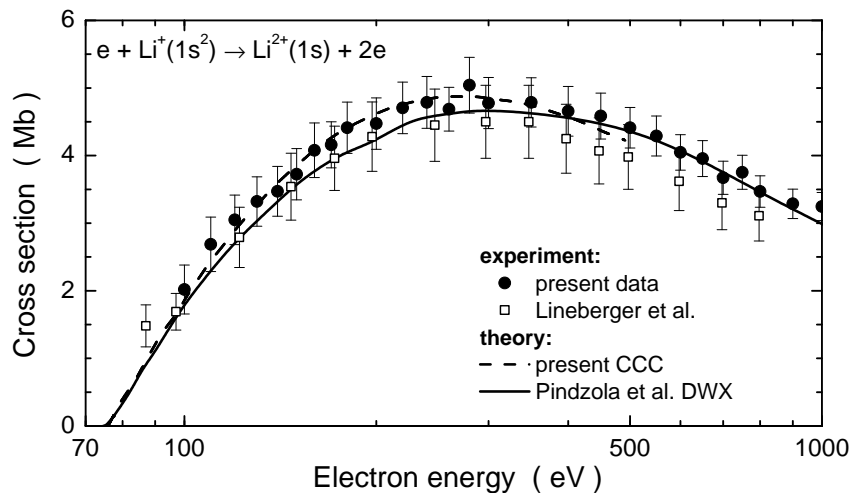


Figure 1: Electron impact ionization of $\text{Li}^+(1s^2)$: solid points and solid line represent the present experimental and theoretical results. Open squares are previous experimental data [1], the dashed curve shows distorted-wave with exchange (DWX) results from reference [2].

References

- [1] W.C. Lineberger, J.W. Hooper, and E.W. McDaniel, *Phys. Rev.* **141**, 151-7 (1966)
- [2] M. Pindzola et al., *Phys. Rev. A* **61**, 052712 (2000).
- [3] J.C. Berengut et al., *J. Phys. B: At. Mol. Opt. Phys.* **40**, 1331-1336 (2007).

OBSERVATION OF HIGHER ORDER RESONANT ELECTRON RECOMBINATION PROCESSES BY HIGHLY CHARGED KRYPTON IONS

C. Beilmann, Z. Harman, **J. R. Crespo López-Urrutia**, V. Mäckel, H. Tawara, and J. Ullrich

Max Planck Institute for Nuclear Physics, Saupfercheckweg 1, 69117 Heidelberg, Germany

By measuring resonant electron capture processes by highly charged ions, where the kinetic energy of the captured electron is transferred to bound electrons, atomic structure calculations can be tested stringently. These data are also relevant for plasma diagnostics applications. Many measurements of dielectronic recombination (DR) have been reported in recent years, see e. g. [1,2]. More detailed benchmarking of theory would results from the measurement of higher order resonant electron capture processes In the so called “trielelectronic recombination” (TR) or “quadreelectronic recombination” (QR) resonances, two respectively three bound electrons are excited by the captured electron. Among the few reported related experiments, there exists an upper limit determination of the cross section for the TR-process in krypton [3] and also an observation of TR resonances in outer shells of Be-like chlorine at the Test Storage Ring [4]. We present the first observation of TR resonances including the K shell (*KL-LLL* TR) in highly charged krypton ions. Signatures of QR resonances

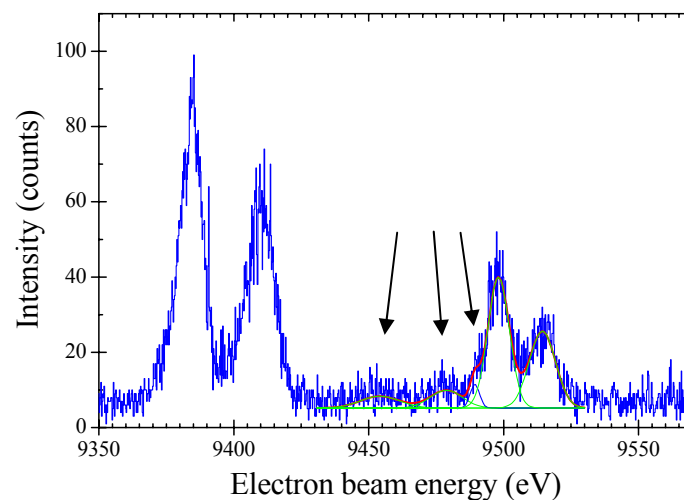


Fig. 1. Recombination of Kr HCI as a function of the electron beam energy. Mean peaks are due to C-like and N-like Kr. The weak features indicated by the two leftmost arrows were reproduced in several measurements and can be identified as the predicted TR of C-like krypton. The rightmost arrow appears at the position predicted for Be-like QR. The energy scale is preliminary.

have also been found for the first time (*KLL-LLL* QR). The excellent resolution achieved, has yielded more accurate data also for the DR resonances. These results have brought a further reduction of the uncertainty in the determination of the absolute resonance energies, and show good agreement with newest predictions of their values.

References

- [1] A.J. González-Martínez *et al.*, Phys. Rev. Lett. **94** (2006) 203201
- [2] Y. Zou, J. R. Crespo López-Urrutia and J. Ullrich, Phys. Rev. A **67** (2003), 043703
- [3] M. Chevallier *et al.*, Phys. Rev. A **61** (2000), 022724
- [4] M. Schnell *et al.*, Phys. Rev. Lett. **91** (2003) 043001

HIGH RESOLUTION LOW-ENERGY DIELECTRONIC RECOMBINATION RATE COEFFICIENTS OF BERYLLIUM-LIKE GERMANIUM: QED TEST BENCH FOR TWO-VALENCE-ELECTRON SYSTEMS

D. A. Orlov, C. Krantz, D. Bernhardt*, C. Brandau**, J. Hoffmann, A. Müller*, T. Ricsóka*, S. Schippers*, A. Shornikov, and A. Wolf

Max-Planck-Institut für Kernphysik, D-69117 Heidelberg, Germany

(*) Institut für Atom- und Molekülphysik, Universität Giessen, D-35392 Giessen, Germany

(**) Gesellschaft für Schwerionenforschung, D-64291 Darmstadt, Germany

High resolution measurements of low-energy dielectronic resonances of lithiumlike Sc^{18+} , performed at the Heidelberg TSR with a cold photoelectron target, allowed us to determine the $2s_{1/2}$ - $2p_{3/2}$ transition energy in these systems with an accuracy of 4.6 ppm, less than 1% of the few-body effects on radiative corrections [1]. Following these studies we have investigated beryllium-like heavy ions with low-energy dielectronic resonances where QED corrections in atomic energy levels for a system with two valence electrons are promising for high accuracy tests. The dielectronic recombination (DR) of Ge^{28+} with a resonant capture of a free electron to the $9l$ Rydberg state accompanied by excitation of inner valence electrons from the $2s^2$ to the $2s2p(^1P_1)$ state was expected to show low-energy DR resonances below 0.2 eV.

The experiment at the TSR were carried out with different isotopes $A=70, 73, 74$ of beryllium-like Ge^{28+} . The MPIK tandem accelerator was used to inject ions of about 340 MeV kinetic energies into the storage ring with a typical ion current of few μA . The TSR's twin-beam electron facility was used for these measurements. Phase space cooling of ions was provided by an electron beam of high density ($1.6 \times 10^7 \text{ cm}^{-3}$) from the electron cooler. The cathode voltage of the cooler was kept constant, while the probe electron beam of low density ($5.2 \times 10^5 \text{ cm}^{-3}$) from the cryogenic photoelectron target [2] was used to measure DR spectra by scanning the electron energy. For these measurements the electron temperatures of the target beam were about 1.5 meV and 0.03 meV in the transverse and longitudinal direction, respectively. The details of the cryogenic photocathode target of the Heidelberg TSR are described elsewhere [2,3].

The DR measurements of beryllium-like Ge indeed revealed a series of sharp low-energy resonances in the range from about 100 meV up to 1.8 eV. The resonances can be assigned to capture of a free electron to the $9l$ Rydberg state accompanied by transition of a valence electron from the $2s^2$ to the $2s2p$ orbital forming a 1P_1 singlet state. Preliminary analysis shows that positions of low-energy resonances around 100 meV can be obtained with an accuracy of about 0.2 meV. The accurate calculations of Rydberg binding energies for these resonances is still required to derive a precise value of the 1S_0 - 1P_1 transition energy, which may give the opportunity to test QED corrections with high accuracy for atomic energy levels for two valence electron systems.

References

- [1] M. Lestinsky, et. al., Phys. Rev. Let. **100**, 033001 (2008)
- [2] D.A. Orlov, et. al., J.Phys.: Conf. Series **4**, 290 (2005)
- [3] F. Sprenger, et. al., NIM A, **532**, 298 (2004)

LOW-LYING DIELECTRONIC RESONANCES OF FE XXII AND FE XVIII FOR ACCURATE ENERGY DETERMINATION OF AUTOIONISING RYDBERG LEVELS FOR BORON- AND FLUORINELIKE CORES

C. Krantz, D. A. Orlov, J. Hoffmann, T. Ricsóka[†], S. Ricz[†], S. Schippers[†], and A. Wolf

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

[†]Institut für Atom- und Molekülphysik, Justus-Liebig-Universität, Leihgesterner Weg 217, 35392 Gießen, Germany

We present high-resolution low-energy dielectronic recombination (DR) measurements of Fe²¹⁺ and Fe¹⁷⁺ performed at the Heidelberg Test Storage Ring (TSR) using the merged-beam technique.

Electron-ion recombination of *L*-shell ions has been studied at the TSR in the past as the dominant recombination process in interstellar plasmas [1, 2]. Besides their astrophysical relevance, such recombination processes provide an opportunity of testing atomic structure calculations of few-electron systems with multiple valence electrons.

The energy resolution of older datasets is limited by the former experimental setup at the TSR which involved only one electron cooler. This is especially true for the spectroscopically interesting low-energy part of the DR spectrum, at electron-ion collision energies below 1 eV. The setup has been improved by addition of an electron target, separate from the existing electron cooler, which produces an ultra-cold electron probe beam employing a cryogenic photocathode [3, 4]. We were thus able to significantly improve the energy resolution of the DR measurements in the low-energy part of the spectra. In the case of Fe²¹⁺ the amount of individually resolved resonances is at least doubled compared to the previous measurement published in [2].

While former DR measurements on *L*-shell ions were focused on the absolute magnitude of the electron-ion recombination rate coefficient, our data provides a precise energy determination of low-energetic autoionising Rydberg levels with boron- and fluorinelike ionic cores, that could be used as a test bench in the process of extending existing precise atomic structure calculations for helium- and lithiumlike ions to systems with higher numbers of valence electrons.

References

- [1] D. W. Savin *et al.*, *Astrophys. J. Lett.*, **489**, 115 (1997)
- [2] D. W. Savin *et al.*, *Astrophys. J. Suppl. Ser.*, **147**, 421 (2003)
- [3] F. Sprenger *et al.*, *NIM A*, **532**, 298 (2004)
- [4] D. A. Orlov *et al.*, *NIM A*, **532**, 418 (2004)

DIELECTRONIC RECOMBINATION OF LI- AND BE-LIKE XENON IONS

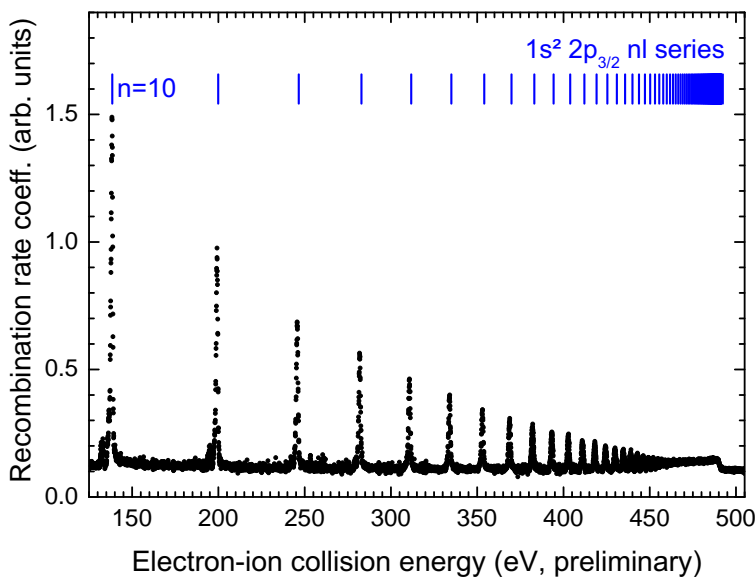
D. Bernhardt, S. Böhm, H. Knopp, J. Jacobi, S. Kieslich, P. H. Mokler, A. Müller, **S. Schippers**,
W. Shi, P. Beller*, F. Bosch*, C. Brandau*, C. Kozhuharov*, F. Nolden*, M. Steck*

Institut für Atom- und Molekülphysik, Justus-Liebig-Universität, 35392 Giessen, Germany

(*) Gesellschaft für Schwerionenforschung (GSI), 64291 Darmstadt, Germany

Dielectronic recombination (DR) of few-electron ions has evolved into a sensitive spectroscopic tool for highly charged ions. Recent experiments with Li-like ions clearly demonstrate that this collision spectroscopy is sensitive to 2nd order QED and to nuclear effects [1,2]. These studies exploit the fact that state-of-the-art theoretical methods treat few-electron systems with very high precision (see e.g. [3,4]).

With our present measurements of DR of Li-like $^{136}\text{Xe}^{51+}$ and Be-like $^{136}\text{Xe}^{50+}$ we aim at bridging the gap between low-charged systems such as F^{6+} [4] and highly charged ions such as U^{89+} [5]. At the same time xenon ions offer a broad distribution of naturally occurring isotopes with atomic mass numbers ranging from 124 to 136. This may be exploited in the future for studying isotope shifts of DR resonances and the extraction of nuclear charge radii [2]. The experiments were carried out by employing the electron-ion-merged-beam technique at GSI's heavy-ion storage ring ESR. The experimental collision energies ranged from 0 to ~ 500 eV in the electron-ion center-of-mass frame. For both ions DR resonance spectra were obtained with high experimental resolving power (Fig. 1). Data analysis is in progress.



Dielectronic recombination of Li-like Xe^{51+} : In the displayed electron-ion collision energy range the DR spectrum exhibits a Rydberg series of $2p_{3/2}nl$ DR resonances associated with $2s_{1/2} - 2p_{3/2}$ core excitations. Individual nl resonance groups are resolved up to $n = 33$.

References

- [1] M. Lestinsky et al., Phys. Rev. Lett. **100**, 033001 (2008)
- [2] C. Brandau et al., Phys. Rev. Lett. **100**, 073201 (2008)
- [3] Z. Harman et al., Phys. Rev. A **73**, 052711 (2006)
- [4] M. Tokman et al., Phys. Rev. A **66**, 012703 (2002)
- [5] C. Brandau et al., Phys. Rev. Lett. **91**, 073202 (2003)

EFFECTIVE COLLISION STRENGTHS FOR THE ELECTRON IMPACT EXCITATION OF Ni XVII

C.E. Hudson, P.H. Norrington, C.A. Ramsbottom

Department of Applied Mathematics and Theoretical Physics, The Queen's University of Belfast,
Belfast BT7 1NN, Northern Ireland, UK

Ni XVII has recently been detected by the EIS instrument onboard Hinode [1]. The 249.18 Å line corresponding to the $3s^2\ ^1S_0-3s3p\ ^1P_1^o$ transition is analogous to the 284.16 Å transition of the iso-electronic Fe XV ion. Since this line is unblended, Young et al [1] indicate that it will be a useful probe of the hot cores of active regions.

Currently for this ion, there are no effective collision strength values available. Christensen et al [2] provide collision strengths at three incident electron energies using a Distorted Wave evaluation, and involving 16 fine structure levels. This method however does not include contributions from resonances, the presence of which can significantly enhance the maxwellian averaged effective collision strengths and in turn greatly affect any diagnostics based on the data.

Therefore to provide a more accurate set of data, we have carried out a scattering calculation using the Dirac atomic R -matrix code (DARC), a method which does include contributions from resonances. The lowest 35 fine structure levels have been included, having configurations $3s^2$, $3s3p$, $3p^2$, $3s3d$, $3p3d$, $3d^2$ and the current evaluation considers partial waves up to $2J \leq 45$. Up to 52,000 energy points have been used to determine the detail in the collision strengths.

We mostly find good agreement in the background level of our collision strengths with the values from the Distorted Wave calculation of Christensen et al [2]. Collision strengths and effective collision strengths will be presented at the conference.

References

- [1] P.R. Young, G. Del Zanna, H.E. Mason, et al, Publ. Astron. Soc. Japan **59**, S857-S864 (2007).
- [2] R.B. Christensen, D.W. Norcross and A.K. Pradhan, Phys. Rev. A **34**, 4704-4715 (1986).

DIELECTRONIC RECOMBINATION INTO Mg-LIKE IONS

Izumi Murakami, Ulyana I. Safronova*, Takako Kato

National Institute for Fusion Science, Toki, Gifu 509-5292, Japan

(*) Department of Physics, University of Nevada, Reno, NV 89557, USA

Dielectronic recombination (DR) is important process governing ionization state of ions in various plasmas. Many theoretical and experimental studies on DR have been done for K-shell and L-shell ions, but not many for M-shell ions. Recently Netzer [1] and Kraemer et al. [2] suggested importance of M-shell Fe ions and the data needs for astrophysical plasmas such as photoionized plasma of active galactic nuclei. The solar observational satellite HINODE was launched in 2006 and has EUV Imaging Spectrometer (EIS) to observe the sun with EUV spectral lines of Fe M-shell ions [3]. Reliable data of total DR rate coefficient and state-selective DR rate coefficients are needed for determining ionization state of ions and level populations to estimate spectral line intensities.

Here we focus on DR process forming Mg-like ions. We have calculated energy levels, radiative transition probabilities, and autoionization rates for $1s^2 2s^2 2p^6 3l' nl$ ($n=3-12, l < n$) and $1s^2 2s^2 2p^6 4l' nl$ ($n=4-7, l < n$) states in Ti^{10+} , Fe^{14+} [4], Zn^{18+} , Se^{22+} , Kr^{24+} , and Mo^{30+} ions by using the Hartree-Fock-Relativistic method (Cowan code [5]). Autoionizing levels above three thresholds $1s^2 2s^2 2p^6 3s$, $1s^2 2s^2 2p^6 3p$, and $1s^2 2s^2 2p^6 3d$ are considered. Contributions from the excited states $1s^2 2s^2 2p^6 3l' nl$ with $n > 12$ and $1s^2 2s^2 2p^6 4l' nl$ with $n > 7$ to DR rate coefficients are estimated by extrapolation of all atomic characteristics. The state-selective and total DR rate coefficients are derived as a function of electron temperature. Figures 1 and 2 show the total DR rate coefficients of Kr and Zn ions. Contributions of high n states become important at $T_e > 10eV$.

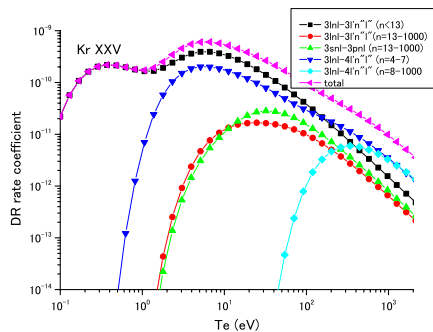


Fig.1 DR rate coefficient for Kr^{25+} .

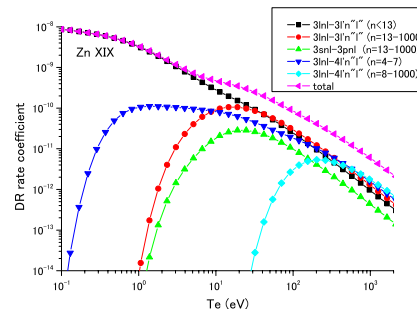


Fig.2 DR rate coefficient for Zn^{19+} .

This work is supported by Matsuo Foundation.

References

- [1] H. Netzer, *ApJ* **604**, 551 (2004)
- [2] S. B. Kraemer, G. L. Ferland, and J. R. Gabel, *ApJ* **604**, 556 (2004)
- [3] J. L. Culhane, *Solar Phys.*, **243**, 19 (2007)
- [4] I. Murakami et al., NIFS-DATA-96 (2006); *J. Phys. B*, **39**, 2917 (2006)
- [5] R. D. Cowan, *The Theory of Atomic Structure and Spectra* (Univ. of California Press, Berkeley, 1981)

CORRELATED STRONG-FIELD DYNAMICS AND NUCLEAR PROPERTIES EXPLORED BY RESONANT ELECTRON RECOMBINATION WITH HIGHLY CHARGED IONS

Z. Harman, O. Postavaru, U.D. Jentschura, C.H. Keitel, W. Scheid*, V. Mäckel, C. Beilmann, J.R. Crespo López-Urrutia, H. Tawara, J. Ullrich, C. Brandau**, C. Kozhuharov**, Th. Stöhlker**

Max-Planck Institut für Kernphysik, 69117 Heidelberg, Germany

(*) Justus-Liebig-Universität, 35392 Giessen, Germany

(**) Gesellschaft für Schwerionenforschung (GSI), 64291 Darmstadt, Germany

In dielectronic recombination (DR), a free electron is recombined into an ion by resonantly exciting a bound electron. Dynamical and structural properties of highly charged ions have successfully be investigated by means of DR during the last decade. Also, it is one of the dominant atomic processes occurring in astrophysical and nuclear fusion plasmas, thus DR cross sections and spectra of x-rays emitted during the process yield indispensable information on a range of plasma properties.

We study the role of relativistic electron interaction and quantum electrodynamic effects in the strong binding fields of heavy nuclei in connection with experiments at the Heidelberg Electron Beam Ion Trap (EBIT) [1] and the Experimental Storage Ring of the GSI Darmstadt [2]. Current studies focus on DR resonance strengths and transition energies associated with the K-LL, K-LM and K-LN recombination channels in few-electron ions as heavy as W, Hg [1] and U [2]. Agreement between our calculations and the experiment is found only if the Breit contribution to the interaction of actively involved electrons is included in the theoretical model. The contribution of this relativistic correction to the total resonance strength amounts to 44% in the case of U [2]. Our investigations confirm the role of relativistic corrections to the electron interaction in a dynamical setting.

Furthermore, we investigate the higher-order resonant recombination process of trielectronic recombination (TR) in which two ionic electrons are simultaneously excited by nonlinear electron interaction. Our theoretical predictions for few-electron Kr ions have recently been confirmed by the first observation of KL-LLL TR using the Heidelberg EBIT [3].

Isotope shift measurements of low-lying dielectronic resonances, combined with atomic structure calculations, allow one to extract information on the nuclear charge distribution of the isotopes involved. We analyze the dependence of the electron interaction and QED contributions on the nuclear size and calculate mass shift terms to determine the change of the nuclear radius corresponding to the isotope shift in Li-like Nd measured with the ESR storage ring of the GSI [4]. This approach constitutes a new technique to determine nuclear radii.

References

- [1] Z. Harman, I.I. Tupitsyn, A.N. Artemyev, *et al.*, Phys. Rev. A **73**, 052711 (2006); A.J. González Martínez, J.R. Crespo López-Urrutia, J. Braun, *et al.*, Phys. Rev. A **73**, 052710 (2006); V. Mäckel, Master's Thesis, Ruprecht-Karls-Universität Heidelberg, Germany (2006)
- [2] C. Brandau, C. Kozhuharov, A. Müller, *et al.*, Rad. Phys. Chem. **75**, 1763 (2006)
- [3] C. Beilmann, Z. Harman, J.R. Crespo López-Urrutia, *et al.*, this volume
- [4] C. Brandau, C. Kozhuharov, Z. Harman, *et al.*, Phys. Rev. Lett. **100**, 073201 (2008)

HIGH PRECISION MEASUREMENT OF THE SPECTRAL WIDTH OF THE NICKEL-LIKE MOLYBDENUM X-RAY LASER

N. Hasegawa, T. Kawachi, A. Sasaki, H. Yamatani, M. Kishimoto, M. Tanaka, Y. Ochi, M. Nishikino, Y. Kunieda, and H. Yoneda*

Quantum Beam Science Directorate, Japan Atomic Energy Research Agency (JAEA)
8-1 Umemidai, Kizugawa, Kyoto, 619-0215, Japan.

(*) Institute for Laser Science, University of Electro-Communications
1-5-1, Chofugaoka, Chofushi, Tokyo 182, Japan.

In recent years, the advent of high-performance ultra short pulse lasers has made it possible to generate the high-brightness compact x-ray lasers [1-3] based on laser-produced plasmas. The gain media of the x-ray lasers are highly charged ions in high density plasmas. The precise knowledge about the wavelength and the spectral width of the lasing line is important for the applications of x-ray lasers, and especially for the spectral width, it is good benchmark of the atomic code because it depends on the electron collisional excitation and de-excitation rate coefficient. Only a few measurements of the spectral width of the laser line have been reported [4, 5], because the spectral width of the x-ray laser is so narrow that the required spectral resolution is quite high, *e.g.* $\Delta\lambda/\lambda \sim 10^{-4}$.

In this study, we took the nickel-like molybdenum x-ray laser ($4d\ ^1S_0 - 4p\ ^1P_1$) as an example, and measure the spectral width by use of the high resolution spectrometer in order to compare it with a theoretical one. We obtained the spectral width of 20 mÅ at the wavelength of 18.9 nm ($\Delta\lambda/\lambda = 10^{-4}$). The details of the result of comparison the experiment result with the theoretical one are described in this conference.

References

- [1] M. P. Kalachnikov *et al.*, Phys. Rev. A **57**, 4778 (1998).
- [2] B. M. Luther *et al.*, Opt. Lett. **30**, 165 (2005).
- [3] R. Keenan *et al.*, Proc. SPIE Vol. 5197, 213 (2003).
- [4] J. A. Koch *et al.*, Phy. Rev. A **50**, 1877 (1994).
- [5] N. Hasegawa *et al.*, Jpn. J. Appl. Phys. Vol. 43, 2519 (2004).

ELECTRON ION COLLISION STUDIES AT THE STOCKHOLM ELECTRON BEAM ION TRAP

S. Böhm, I. Orban, R. Schuch

Atomic Physics, Fysikum, Stockholm University, Alba Nova S-106 91 Stockholm, Sweden

A new laboratory for highly charged ions (HCI) has been build up at Stockholm University. An electron beam ion trap (S-EBIT) (3T magnet, <30keV electron beam) was installed and presently upgraded to a Super-EBIT version with 250 keV. It is used for in-trap spectroscopic and electron ion collision studies. In cooperation with Uppsala University an EUV-spectrometer has been mounted recently at the S-EBIT. S-EBIT is also used as an electron beam ion source. At one beam line an ion trapping system has been built up to cool HCI. These ions will be extracted into the ion trap SMILETRAP used for precision mass measurements[1]. Another beam line has been built up for measurements with nanocapillaries [2].

S-EBIT was used first in recombination studies of highly charged silicon and sulphur ions. X rays emitted from radiative recombination (RR) and dielectronic recombination (DR) and recorded in list mode as the electron beam energy was scanned. The recombination resonances can also be detected by counting the extracted ions of a certain charge state. This can be done using a photomultiplier detector after the charge state analyzing magnet. Another novel method is a time of flight detector mounted under zero degree which enables us to monitor several charge states simultaneously [3].

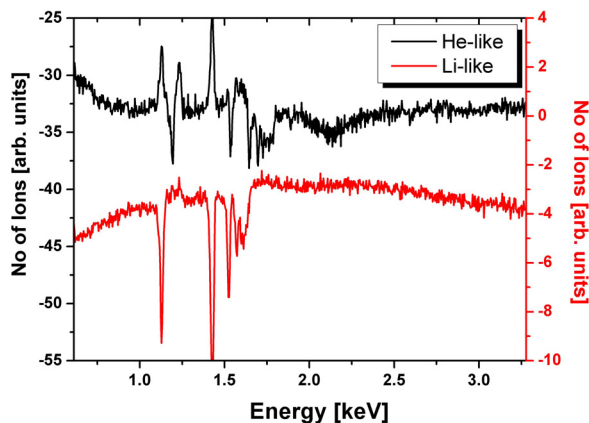


Figure 1. The recombination rate coefficients for He- and Li-like silicon ions measured with the TOF detector.

After the probing time during which the photons are measured the charge state distribution of the ions is recorded. As the electron energy is scanned and the electron ion collision energy matches a DR resonance the peak height of the charge state recombining decreases while the peak height of the adjacent next lower charge state increases. Figure 1 shows the integral over the peak of He- and Li-like silicon ions plotted against the collision energy. This technique can be combined with the one described in the paragraph above where the photons of the recombination process are measured. This will provide a more complete picture of the recombination processes. Silicon and sulphur are astrophysical abundant elements and accurate knowledge of the recombination process will help to improve theoretical methods used to model astrophysical plasmas.

References

[1] see contribution by M. Hobein et al.

[2] see contribution by P. Skog et al.

[3] S. Böhm, A. Enulescu, T. Fritioff, I. Orban, S. Tashenov, R. Schuch, *Journ. Phys.* **58**, 303, 2007

INVESTIGATING CORRELATED HIGH-FIELD FEW-ELECTRON QED BY MEANS OF DIELECTRIC RECOMBINATION IN $W^{69+...72+}$ IONS

V. Mäckel, J. R. Crespo López-Urrutia, A. J. González Martínez, Z. Harman, H. Tawara, J. Ullrich
Max-Planck Institut für Kernphysik, 69117 Heidelberg, Germany

The study of dielectronic recombination (DR) in highly charged ions provides unique possibilities to explore relativistic correlation, quantum electrodynamic (QED) and nuclear size effects. Since deeply bound electrons experience extremely strong electromagnetic fields close to the nucleus, the the QED contributions to their binding energies become experimentally seizable. For tungsten ions ($Z=74$), QED contributions amount to roughly 100 eV. These effects can be estimated by accurately measuring the energies at which DR resonances occur.

In the present work, the KLL-DR resonances, where a free electron is captured by an ion into the L-shell while resonantly exciting a bound electron from the K-shell to the L-shell, were measured using the Heidelberg electron beam ion trap (EBIT). By slowly scanning the electron beam energy over the KLL-DR region between 39 keV and 44 keV and simultaneously monitoring the emitted x-rays, the DR resonance energies (see Fig. 1) of different charge states were determined relatively to the He-like resonances with a relative error as small as 3 eV at excitation energies of 40 keV. This high experimental accuracy allows one to test electron screening contributions to the QED corrections of self-energy and vacuum polarisation. A comparison with different predictions shows strong discrepancies for certain Li- and Be-like ion states while general agreement with other charge states is found. These results confirm earlier findings for mercury ($Hg^{75+...78+}$) DR measurements [1,2], highlighting the need for further investigations.

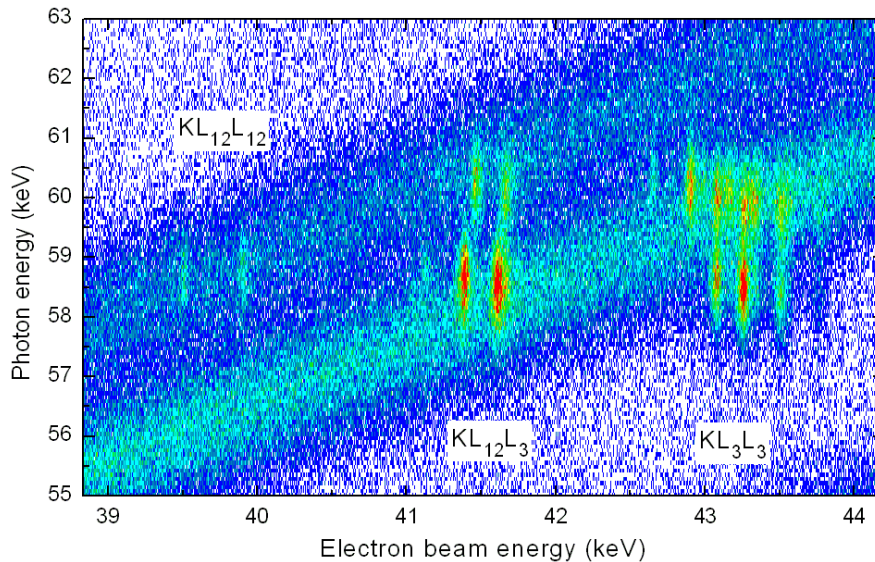


Figure 1: Scatter plot (photon counts as a function of electron beam energy and photon energy) showing the KLL DR resonances of $W^{69+...72+}$ ions which appear as distinct bright spots on top of the diffuse radiative recombination lines.

References

- [1] A.J. González Martínez et al., Phys.Rev. A 73 (2006) 052710
- [2] Z. Harman et al., Phys.Rev. A 73 (2006) 052711

DIELECTRONIC RECOMBINATION OF Na-LIKE S AND Na-LIKE Ar IN THE PRESENCE OF EXTERNAL FIELDS

I. Orban^a, S. Böhm^a, S. Trotsenko^b, and R. Schuch^a

^a Department of Atomic Physics, S - 10691 Stockholm , Stockholm University, Sweden

^b Gesellschaft für Schwerionenforschung, D - 64291 Darmstadt, Germany

Dielectronic recombination (DR) is a resonant channel, in which recombination of a free electron and an ion takes place through an intermediate doubly excited state. DR is an important process governing charge-state distributions in astrophysical and laboratory plasma. External fields can enhance DR and can have important effects on various parameters of the plasma, e.g., can increase significantly the radiative cooling of magnetically confined fusion plasma.

Enhancements of DR by external fields were first suggested by LaGattuta et al. [1] and were experimentally verified by Muller et al. [2] in a crossed-beam experiment. DR in presence of external fields (DRF) was later studied at storage rings for Li-like ions [3, 4].

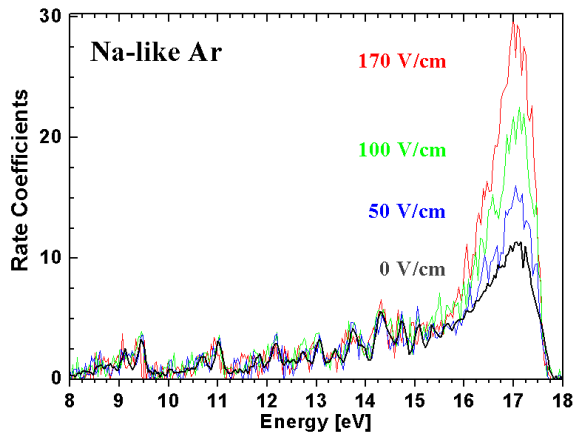


Fig. 1. Recombination spectra of Na-like Ar.

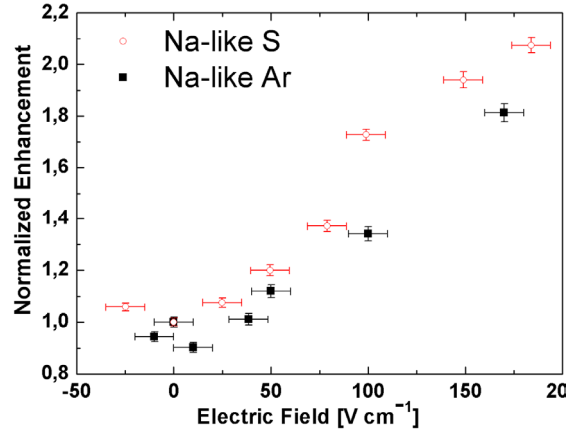


Fig. 2. Normalized enhancement coefficients.

We present preliminary results from the first storage-ring investigations of DRF, in spectra of astrophysically abundant Na-like ions. Recombination spectra of Na-like S⁵⁺ and Na-like Ar⁷⁺, in the presence of motional electric fields ranging between 0 and 185 Vcm⁻¹, were measured at the CRYRING storage ring. In the electron cooler section of the storage ring, an electron beam was merged with the circulating ions over a distance of 80 cm. A motional electric field was created in the interaction region by inducing an angle between the 30 mT magnetic field guiding the electrons and the ion trajectory. Recombined ions were separated from the circulating beam in the first dipole magnet after the electron cooler. Field ionization at this dipole magnet hindered detection of ions recombined into high Rydberg states.

The recorded spectra (fig. 1) were integrated over the range affected by the external electric fields and the results were normalized to the 0 field case. An enhancement increasing with the electric field was observed for both ions, with enhancement factors of over 2 and 1.8, in case of Na-like S and Na-like Ar, respectively. Saturation was not reached yet, and as seen from the trend of enhancement vs. electric field (see figure 2), even higher enhancements are to be expected at stronger fields.

References

- [1] K. LaGattuta *et al.* Phys. Rev. Lett. **51**, 558 (1983)
- [2] A. Müller *et al.* Phys. Rev. Lett. **56**, 127 (1986)
- [3] T. Bartsch *et al.* Phys. Rev. Lett. **79**, 2233 (1997)
- [4] S. Böhm *et al.* Phys. Rev. A **65**, 052728 (2002)

POSSIBILITY OF RESONANT CAPTURE OF ANTIPROTONS BY ELECTRON EXCITATION IN HYDROGENLIKE IONS

M. Genkin and E. Lindroth

Stockholm University, Atomic Physics, AlbaNova University Center, S-10691 Stockholm, Sweden

Exotic atoms are fascinating systems where the parameters determining the properties of ordinary matter can be tuned and investigated in completely new regimes. Since the early nineties the $\text{He}^+\bar{p}$ system has been studied intensively and has e.g. recently led to a significant improvement of the value for the electron-antiproton mass ratio. With the future facility FLAIR at GSI, cooled antiprotonic beams with an intensity much higher than available today will be provided which might open new possibilities for the production of antiprotonic exotic systems, as for example highly charged antiprotonic ions. Here we study the feasibility of resonant antiprotonic capture by highly charged hydrogenlike ions, a process that can be seen as the antiprotonic analogon of dielectronic recombination.

If, in an electron-ion collision, the energy of the antiproton is tuned such that the resonant condition is fulfilled, it can be captured into a bound orbit by simultaneous excitation of a target electron and thus form a doubly excited electron-antiproton state. This presents an additional channel to non-resonant capture of antiprotons by ions [1-3] where the energy is transmitted to an ejected target electron. The doubly excited state can subsequently decay by electron-, antiproton- or photon emission, and the rates for these processes will essentially determine the cross section for antiprotonic capture.

We have calculated the positions of the resonances and the rates for antiproton- and electron emission for a test case; Ca^{19+} . The full Hamiltonian is diagonalized on a B-spline basis, and complex scaling is used to handle the coupling to the continuum [4]. The numerical accuracy of the of the antiprotonic capture rates was tested through comparison between a second order complex rotation calculation and a Fermi Golden Rule calculation. Radiative decay rates were estimated in the dipole approximation with a first order perturbation theory approach.

Several groups of resonances were found in the region close to the $\text{Ca}^{19+}(1s)$ ionization threshold, arising from the configurations $(n_e, n_{\bar{p}}) = (2, 48), (2, 49), (3, 45)$ and $(4, 44)$. Electronic radiative transitions provide the dominant decay channel, and the antiproton ejection rate is found to be very sensitive to the total angular momentum of the resonances.

References

- [1] J. S. Cohen, Phys. Rev. A **69**, 022501 (2004)
- [2] K. Sakimoto, Phys. Rev. A **74**, 022709 (2006)
- [3] K. Sakimoto, Phys. Rev. A **76**, 042513 (2007)
- [4] J. L. Sanz-Vicario, E. Lindroth, N. Brandefelt, Phys. Rev. A **66**, 052713 (2002)

THE ENHANCEMENT EFFECT IN RADIATIVE RECOMBINATION OF BARE URANIUM IONS WITH COOLING ELECTRONS

D. Banaś¹, M. Pajek¹, Th. Stöhlker², H. F. Beyer², F. Bosch², C. Brandau²,
S. Chatterjee², M. Czarnota¹, A. Gumberidze², S. Hagmann², C. Kozhuharov², D. Liesen²,
P. H. Mokler², R. Reuschl², U. Spillmann², S. Tachenov², S. Trotsenko², P. Verma², D. Sierpowski³,
A. Warczak³, S. Böhm⁴, A. Müller⁴, E. W. Schmidt⁴, J.-Cl. Dousse⁵, J. Szlachetko^{1,5}

(¹) Jan Kochanowski University, Kielce, Poland

(²) GSI, Darmstadt, Germany

(³) Jagiellonian University, Cracow, Poland

(⁴) Justus-Liebig Universität, Giessen, Germany

(⁵) University of Fribourg, Switzerland

The "enhancement" effect, which was observed in radiative recombination (RR) of heavy bare ions with cooling electrons in storage ring experiments by observing recombined ions (see Ref. [1]), needs detailed experimental studies to be fully explained. Guided by this motivation, the radiative recombination of U^{92+} ions (23 MeV/u) with electrons was studied in a state-selective way by observing the emitted x-rays for relative electron energies in the range $E_{rel} = 0 - 1000$ meV. The x-rays emitted from the recombination process were measured by two germanium detectors placed close to 0° and 180° with respect to the ion beam direction. In this experiment the radiative recombination into low n-states was probed by observing the K-RR and L-RR x-rays, while the emitted Lyman and Balmer x-ray transitions, populated by the radiative cascades following decay of high Rydberg states, yielded information on the RR into high n-states.

From the the measured K-RR recombination rate for relative electron energies $E_{rel} = 0 - 1000$ meV the transverse electron beam temperature was derived allowing thus a determination of the recombination enhancement for the cooling condition ($\langle E_{rel} \rangle = 0$ meV). The measured RR rates for the K-shell were compared with the relativistic calculations of the RR process. In this comparison a correction for a contribution from the two-step RR+RD process [2], namely the RR into high n-state followed by the radiative decay (RD) via the transition $np-1s$, was estimated. We demonstrate that in the present experiment an enhancement of the recombination of U^{92+} ions with cooling electrons for $n=1$ state was observed by comparing the K-RR data with the theoretical predictions. This is the first experimental observation of the recombination enhancement for the low n-state, which is important for explanation of the origin of the enhancement effect.

References

[1] W. Shi *et al.*, Eur. Phys. J. D15, 145 (2001).

[2] M. Pajek *et al.*, presented at the ICPEAC-2007 Conference.

THEORETICAL INVESTIGATION ON QUANTUM INTERFERENCE EFFECTS BETWEEN DIELECTRONIC RECOMBINATION AND RADIATIVE RECOMBINATION FOR HIGHLY CHARGED IONS

Y. L. Shi¹, J. J. Wan¹, C. Z. Dong^{1,2}

¹ College of Physics and Electronic Engineering, Northwest Normal University, Lanzhou 730070, China

² Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator of Lanzhou, Lanzhou 730000, China

The photorecombination (PR) process of a multiply charged ion with a free electron is traditionally described in terms of two distinct recombination mechanisms. The first is nonresonant or direct radiative recombination (RR), which is the inverse of the ordinary photoionization process, and the second corresponds to the two-step, resonant dielectronic recombination (DR) process. These two recombination mechanisms are usually treated as independent processes. It has been recognized, however, that the traditional description of RR and DR, as two independent, noninterfering processes, is not strictly permissible within the framework of a rigorous quantum-mechanical theory [1].

Indeed, more than 40 years ago, Fano [2] predicted the interference between transition amplitudes leading directly into the ionization continuum and those indirectly proceeding via a discrete intermediate resonant state. Several theoretical investigations have been carried out in pursuit of prominent manifestations of the quantum-mechanical interference between RR and DR. Asymmetrical PR cross-section profiles, which are characteristic spectral signatures of a prominent quantum-interference effect, have been observed firstly by Knapp *et al.* [3] for the PR of very highly charged uranium ions, and also have been detected for highly charged mercury ions by González Martínez *et al.* [4] recently.

Using a projection-operator and resolvent-operator approach [1], total cross section of electron-ion photorecombination processes are calculated for highly charged Hg^{75+} ion. This approach provides a unified quantum-mechanical description of the combined electron-ion PR process, including radiative and dielectronic recombination as coherent, interfering components. The related energy levels, wavefunctions and transition data for B-like Hg ion have been obtained using GRASP92 package [5], component program REOSS99 [6] and AUGER [7], which is based on multiconfiguration Dirac-Fock method. The RR cross section calculated using our recent developed program RERR06 [8]. The present theoretical results show evident asymmetrical profile in the $KL_{12}L_3$ DR resonant region.

References

- [1] M. Zimmermann, N. Grün, W. Scheid, *J. Phys. B* **30**, 5259 (1997)
- [2] U. Fano, *Phys. Rev.* **124**, 1866 (1961)
- [3] D. A. Knapp, P. Beiersdorfer, M. H. Chen *et al.*, *Phys. Rev. Lett.* **74**, 54 (1995)
- [4] A. J. González Martínez, J. R. Crespo López-Urrutia, J. Braun *et al.*, *Phys. Rev. Lett.* **94**, 203201 (2005)
- [5] F. A. Parpia, C. Froese Fischer, I. P. Grant, *Comput. Phys. Commun.* **94**, 249 (1996)
- [6] S. Fritzsche, C. Froese Fischer, C. Z. Dong, *Comput. Phys. Commun.* **124**, 340 (2000)
- [7] S. Fritzsche, H. Aksela, C. Z. Dong *et al.*, *Nucl. Instrum. Methods B* **205**, 93 (2003)
- [8] J. J. Wan, C. Z. Dong, C. C. Sang *et al.*, *J. Phys: Confer. Ser.* **58**, 367 (2007)

RESONANCE ELECTRON IMPACT EXCITATION AND POLARIZATION OF MAGNETIC QUADRUPOLE LINE OF NEONLIKE Ba^{46+} IONS

J. Jiang, C. Z. Dong, L. Y. Xie, J. G. Wang*

College of Physics and Electronics Engineering, Northwest Normal University,
Lanzhou 730070 China

(*) Institute of Applied Physics and Computational Mathematic, Beijing 100088, China

When the highly charged ions are excited by electron beam or more generally by electrons with an anisotropic velocity distribution, the excited state populations for the magnetic sublevels may be in a nonstatistical way. Then, the radiation emitted from these unequally populated sublevels to a lower level may be strongly polarized. The degree of polarization depends on the extent of deviation from the statistical populations of excited magnetic sublevels. In the present work, a new rapid and accurate fully relativistic Distorted program has been developed, based on the Zhang's method[1] and the Grasp92[2], Ratip [3] and REIE [4] packages, for calculating the specific magnetic sublevel excitations including both the direct and resonance excitation contributions. As an example, the electron impact excitation processes of neonlike Ba^{46+} ions were studied systematically, and the polarization degree of the magnetic quadrupole line is obtained and compared with the experimental measurements[5]. Our results shown that the $4l5l'$ resonant series have larger contributions on the electron impact excitation cross sections which were enhanced more than two times compared with the direct excitation when the impact energy in the range of 5keV to 5.2keV, and the polarization changes from -22% to 4% in this energy range. However, the $4l6l'$ and $5l5l'$ resonant series have small contributions to the excitation cross sections, but they make the polarization of the M2 line changes evidently. Our results are found to be in excellent agreement with the experimental results[5].

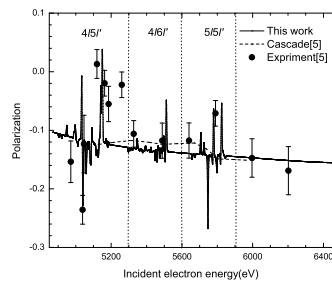


Figure 1: Linear polarization degree of neonlike Ba^{46+} M2 line $(2p_{3/2}^{-1}3s_{1/2})_2 \rightarrow 2p^6 J = 0$ as a function of the incident electron energy.

References

- [1] H. L. Zhang, *et. al.* Phys. Rev. A **41**, 198 (1990), Phys. Rev. A **66**, 042704 (2002)
- [2] F. A.Parpia, C. F. Fischer and I. P. Grant, Comput. Phys. Commun **94**, 249 (1996)
- [3] S. Fritzsche *et al.*, Nucl. Instr. and Meth. in Phys. Res. B **205**, 93 (2003)
- [4] J. Jiang, C. Z. Dong, L. Y. Xie, *et. al.* Chin. Phys. Lett. **24**, 691 (2007)
- [5] E. Takács, E.S. Meyer, J.D. Gillaspay, J.R. Roberts, *et. al.* Phys. Rev. A **54**, 1342 (1996).

ISOMER EFFECT ON IONIZATION PROCESSES IN COLLISIONS OF 6-MEV/AMU BARE-IONS WITH C₃H₆ MOLECULES

T. Nakazato¹, **T. Matsuo**², T. Kohno³, Y. Ohno⁴, S. Watanabe² and T. Murakami⁴

1. Institute of Laser Engineering, Osaka Univ., Suita-shi, 565-0871 Osaka, Japan
2. Kanagawa Institute of Technology, Atsugi-shi, 243-0292 Kanagawa, Japan
3. Tokyo Institute of Technology, Yokohama-shi, 226-8502 Kanagawa, Japan
4. National Inst. of Radiological Sciences, Inage-ku, 263-8555 Chiba, Japan

We have been studying ionization of hydrocarbon molecules in 6-MeV/amu fully stripped-ion impact through measurements of gross ionization cross sections and relative intensities of individual secondary ions. In the present study, the target was chosen to be hydrocarbon isomers, C₃H₆ propylene and (CH₂)₃ cyclopropane to study the effect of molecular structure on the ionization and subsequent fragmentation processes. The experiment was carried out using the 6-MeV/amu-H⁺, He²⁺, -C⁶⁺, -Ne¹⁰⁺, and -Ar¹⁸⁺ projectiles provided by the Heavy Ion Medical Accelerator in Chiba (HIMAC) of the National Institute of Radiological Sciences.

The gross ionization cross sections were measured with the parallel-plate-condenser method [1]. The reproducibility of the cross sections was within 2%. The cross sections of cyclopropane were found to be 2-3% larger than those of propylene for all projectiles studied here. On the contrary, the electron impact experiments for isomer hydrocarbons showed quite different features; the cross sections for propylene were reported to be larger than those for cyclopropane (roughly 2-3%) [2]. Unfortunately, no comparable data exists in the ion impact, and the cause of such discrepancies is not clear at present.

Figure 1 shows the secondary ion spectra measured for propylene and cyclopropane. It should be noted that the most prominent peak is the parent molecular (CH₂)₃⁺ ion in cyclopropane, whereas the C₃H₅⁺ ion predominates the C₃H₆⁺ ion in propylene, indicating an isomer effect in fragmentation. Doubly charged molecular ions, such as C₃H₆²⁺, C₃H₅²⁺, C₃H₄²⁺ and C₃H₃²⁺, were apparently produced in these molecules.

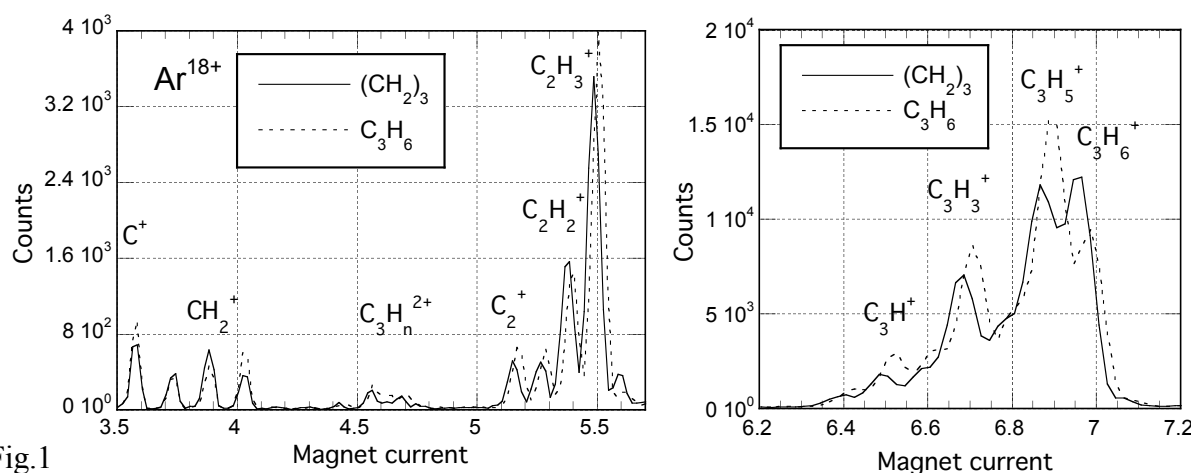


Fig.1

References

- [1]T. Matsuo, T. Kohno, et al., Phys. Rev. A, 60, 3000-3007, 1999.
- [3]H. Nishimura and H.Tawara, J. Phys. B: At. Mol. Opt. Phys. 27, 2063-2074, 1994.

STATE-SELECTIVE DIFFERENTIAL CROSS SECTIONS FOR SINGLE, DOUBLE ELECTRON CAPTURE IN LOW ENERGY He^{2+} -HE COLLISIONS

Xiaolong Zhu¹, **Xinwen Ma**^{1,2}, Li Bin^{1,2}, Shaofeng Zhang^{1,2}, Wentian Feng^{1,2}, Huiping Liu¹, Lanfang Chen^{1,2}, Shiping Cao^{1,2}, Dongbin Qian^{1,2}, Dacheng Zhang^{1,2}

1 Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000

2 Graduate University of Chinese Academy of Sciences, Beijing 100049

For 20-40 keV He^{2+} on He collisions, we have measured state-selective single and double electron capture cross sections and differential cross sections in projectile scattering angle by the Cold Target Recoil Ion Momentum. Absolute state-selective angular differential cross sections are obtained for electron capture into ground state and excited states of projectiles. It is found that the single electron capture into the L shell is a dominant reaction channel, and double electron capture into ground state is by far dominant in the incident energy range. The single electron capture into the excited states occur at a smaller distances than the ground state capture. Figure 1 shows the energy dependence of state-selective capture cross sections, where results are compared with Fritsch's calculation [1] and other experimental results [2]. Figure 2 shows the state-selective angular differential cross sections. More results for double electron capture will be presented at the conference.

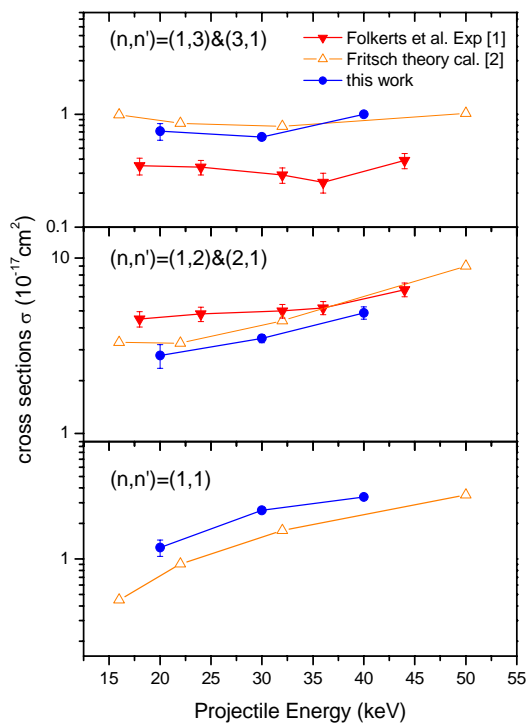


Fig. 1 State-selective cross sections for 20, 30 and 40 keV He^{2+} on He single electron capture.

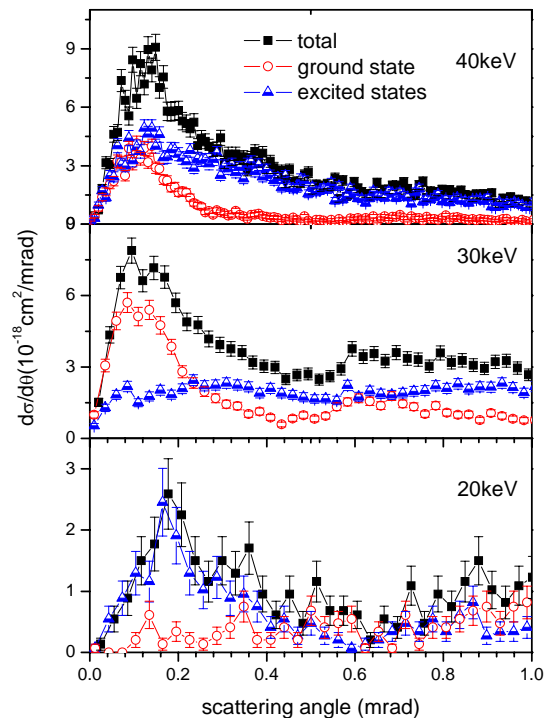


Fig. 2 Scattering angle distribution for 20, 30 and 40 keV He^{2+} on He single electron capture.

References

- [1] Folkerts H O , Blik F W, Meng L et al. J. Phys. B: At. Mol. Opt. Phys. **27**,3475(1994)
 [2] Fritsch W, J. Phys. B: At. Mol. Opt. Phys. **27**, 3461(1994)

ASYMPTOTIC THEORY FOR SINGLE AND DOUBLE ELECTRON CAPTURE IN LOW – ENERGY COLLISIONS OF HIGHLY CHARGED IONS WITH MOLECULES

M. V. Khoma, V. Yu. Lazur, R. K. Janev*,†

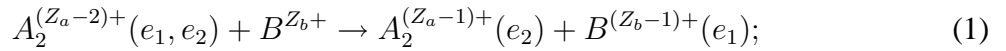
Department of Theoretical Physics, Uzhgorod National University, Uzhgorod 88000, Ukraine

(*) Macedonian Academy of Sciences and Arts, MK-1000 Skopje, Macedonia

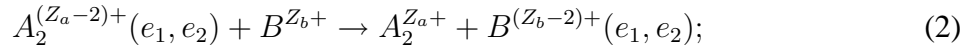
† Institut für Plasmaphysik, Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany

The collision processes of highly charged ions B^{Z_b+} with molecules $A_2^{(Z_a-2)+}$ have recently attracted considerable interest in view of their observed role in generation the X–ray and EUV radiation in the cometary atmospheres interacting with the solar wind [1a] and in certain astrophysical environments [1b], and in the cooling of divertor plasmas of magnetic fusion devices [1c]. In the present work we shall employ the asymptotic method [2] to study the electron–exchange interactions and the dynamics of corresponding inelastic low–energy collision processes in the $A_2^{(Z_a-2)+} + B^{Z_b+}$ collision system, where Z_a and Z_b are the effective charges of the molecular core $A_2^{Z_a+}$ and of the ion B^{Z_b+} . We study the most important one- and two–electron exchange processes in this collision system:

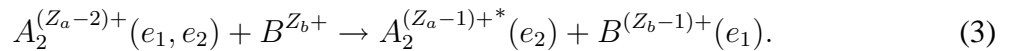
- nondissociative single electron captures (NDSEC):



- two–electron capture (TEC):



- single electron capture with simultaneous target excitation:



The method of deriving the asymptotic form of one–electron three–centre wave function of the quasi-molecules $A_2^{Z_a+} + B^{(Z_b-2)+}$ and $A_2^{(Z_a-2)+} + B^{Z_b+}$ in different regions of configuration space is described. Obtained results are used to calculate the asymptotically exact one– and two–electron exchange interactions (nonadiabatic couplings) responsible for one–electron capture (1) and two–electron processes (2) and (3), respectively. The obtained analytical results on electronic couplings are used for close–coupling calculations of the total and state-selective n –, ℓ –resolved cross sections of one- and two–electron capture processes in the $\text{He}^{2+} + \text{H}_2$ collision system in energy range 0.1 – 50 keV/amu.

References

- [1] (a) T. E. Cravens, *Science* **296**, 1042 (2002); (b) R. Lallement, *Astron. and Astrophys.* **422**, 391 (2004); (c) R. K. Janev, *Contemporary Phys.* **46**, 121 (2005)
- [2] M.I. Chibisov, R.K. Janev, *Phys. Rep.* **166**, 1 (1988); V.Yu. Lazur, M.V. Khoma, R.K. Janev, *Phys. Rev. A.* **73**, 032723 (2006)

ENERGY GAIN MEASUREMENTS OF HIGHLY CHARGED Xe IONS IN COLLISIONS WITH RARE GAS TARGETS AT 200 eV

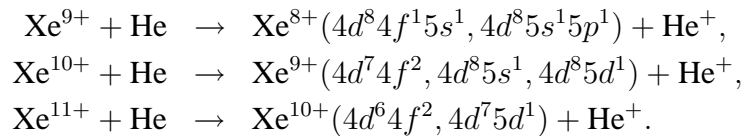
K. Ishii, Y. Inoue and H. Ogawa

Dept. of Physics, Nara Women's University, Nara, 630-8506, Japan
Graduate school of Humanities and Science, Nara Women's University, Nara, 630-8506, Japan

Experimental study of collision dynamics of multiply charged Xe and Sn ions with atoms and molecules at low energies below 1 a.u. is important not only in atomic physics but also in various applied fields. Especially, charge transfer processes involving Xe and Sn ions in their plasmas have attracted attention for the developments of strong EUV light sources for new lithography techniques. In the Xe or Sn plasmas, these ions always capture electron(s) and de-excite with emitting photons (sometimes EUV) or electrons. Therefore knowledge of charge transfer and decay scheme of these ions in plasma is needed for the development of strong EUV source. However it is difficult to understand not only those energy levels including their excited states but also charge transfer process, since multiply charged heavy ions such as Xe^{q+} and Sn^{q+} (q around 10) still have many electrons.

In this work, we have measured energy gain spectra of Xe^{q+} with rare gas targets for the charge state around ten at 200 q eV. The experiment was performed using Mini-EBIS ion source at Nara Women's University [1]. Multiply charged Xe ions extracted from the Mini-EBIS were mass-analyzed by electro-magnetic analyzer and collided with the effusive target gas at the collision cell. Then projectile ions after the collision were analyzed by a parallel plate energy analyzer, detected by Position sensitive detector and recorded into PC.

We have compared the measured energy gain spectra with theoretical energy levels of projectile ion after the charge transfer. Here we have used calculated energy levels of excited Xe ions by Kagawa et al [2]. The dominant charge transfer processes are predicted as following,



For $q = 9-11$, Xe^{q+} ions dominantly capture electron into $\text{Xe}^{(q-1)+}$ ($n = 4, 5$), although predicted energy levels of projectile after charge transfer by using classical over barrier model are much higher [3]. Detailed results and discussions including results for another target species and calculation by classical over barrier model will be presented at the conference.

References

- [1] K. Ishii, Y. Inoue, H. Ogawa, A. Itoh and N. Sakamoto, J. Phys. Conf. Ser. **58**, 275 (2007).
- [2] T. Kagawa, private communication
- [3] A. Niehaus, J. Phys. B: At. Mol. Phys. **19**, 2925 (1986).

DIFFERENTIAL CROSS SECTIONS FOR SINGLE-ELECTRON CAPTURE BY LOW-ENERGY O_2^{2+} IONS FROM Ne and O_2

E. Y. Kamber

Physics Department, Western Michigan University, Kalamazoo, MI 49008-5252, USA

Electron capture processes by multiply charged molecules are of importance not only in hot astrophysical and terrestrial plasmas but also in low-temperature plasmas. The O_2^{2+} ions are of particular interest due to their potential influence on the properties of the ionosphere and their involvement in many atmospheric and astrophysical phenomena. In the present work, state-selective differential cross sections for non-dissociative single-electron capture processes in low-energy collisions of O_2^{2+} recoil ions with Ne and O_2 at an impact energy of 100 eV and scattering angles between 0° and 6° have been studied using a differential energy-gain spectrometer [1], capable of measuring simultaneously the energy-gain and the scattering angle of projectile products in ion-atom/molecule collisions. Our results show clear evidence of the presence of metastable states in the incident O_2^{2+} ion beam.

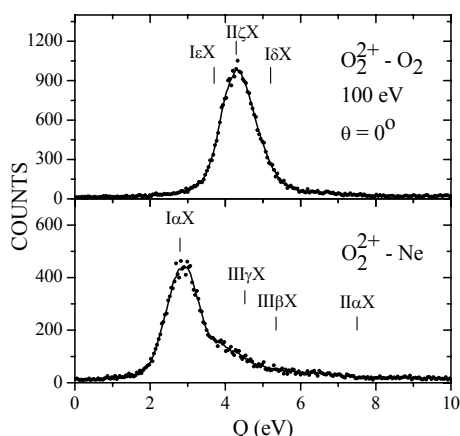


Figure 1: Translational energy-gain spectra for single-electron capture by 100 eV O_2^{2+} ions from O_2 and Ne at 0° scattering angle. The designations I, II, and III represent, respectively, the ground, first, and second electronically excited states of O_2^{2+} ; α , β , γ , represent the ground and subsequent electronically excited states of O_2^+ ion; X, represents the ground state of the target product.

In $O_2^{2+} - O_2$ system, the observed spectrum shows that the dominant exit channel (peak II ζ X) is due to capture by low-lying metastable state ($A^3\Sigma_u^-$) of the O_2^{2+} ions into the ($c^4\Sigma_u^+$) state of O_2^+ . In $O_2^{2+} - Ne$ collision, the dominant peak correlates with single-electron capture from ground state ($1^1\Sigma_g^+$) of O_2^{2+} ions into X $^2\Pi_g$ (peak I α X) state of O_2^+ , while the unresolved structure on the higher-energy side of the dominant peak is due to capture from the metastable state O_2^{2+} ($W^3\Delta_u$) ions into a $^4\pi_u$ and $A^4\pi_u$ excited states of the O_2^+ product ions, in agreement with the other measurements at 6 keV [2]. The energy-gain spectra are interpreted qualitatively in terms of the reaction windows, which are calculated using the Landau-Zener model and the extended version of the classical over-the-barrier model. Additional measurements of differential cross sections will be presented.

References

- [1] S. Yaltkaya, E. Y. Kamber and S. M. Ferguson, Phys Rev A **48**, 382 (1993).
- [2] M. Hamdan and A.G. Brenton, Chem. Phys. Lett. **164**, 413 (1989).

NON-PERTURBATIVE INVESTIGATION OF THE INTERFERENCE EFFECTS IN THE IONIZATION OF H₂ BY CHARGED PARTICLE IMPACT

L. Nagy, S. Borbély and K. Póra

Faculty of Physics, Babeş-Bolyai University, Kogălniceanu Street No. 1, 400084 Cluj-Napoca, Romania

The interference effects in the double differential ionization cross section of H₂ was studied both theoretically [1] and experimentally [2]. It is shown by Rodríguez et. al. [3], that theoretical models developed for the ionization of the atomic systems by intense ultrashort laser pulses can be applied with success to study the ionization by charged particle impact in the case of distant collisions. Based on these results in this work the Volkov and MSSFA (momentum space strong-field approximation) models [4], developed for the over the barrier ionization, are applied to study the ionization of the hydrogen molecule by charge particle impact. By employing the Volkov and MSSFA we are able to study separately the influence of the two-center initial wave function and of the two-center Coulomb potential on the interference effects. Beside these non-perturbative approaches, calculations are also performed using a perturbative, impact parameter method [1]. The interference effects are analyzed in the angular distribution of the ejected electrons in the collisional plane for fixed impact parameter at different molecular axis orientations. The sharp minima in the Volkov angular distributions presented on Figure 1 are clear evidence of the destructive interference, which appears due to the two-center initial state wave function. The electron ejection angle integrated spectra are also analyzed and the influence of the interference is discussed.

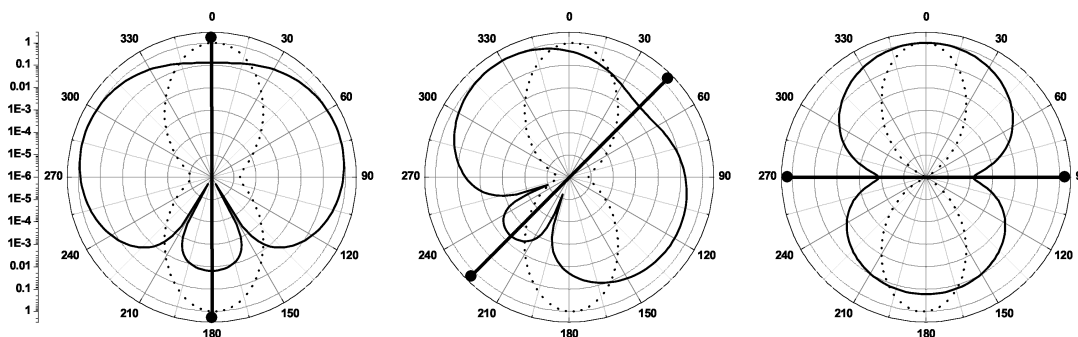


Figure 1: The angular distribution of the electrons ejected in the collisional plane with 65 eV ejection energy, for fixed impact parameter (4 a.u.) of the 68 MeV/u Kr³³⁺ projectile, for different molecular axis orientations. Solid line - Volkov results, Dotted line - impact parameter method. The presented distributions are normalized to maximum value.

References

- [1] L. Nagy, L. Kocbach, K. Póra, J. P. Hansen, *J. Phys. B: At. Mol. Opt. Phys.* **35**, L453 (2002).
- [2] N. Stolterfoht et. al., *Phys. Rev. Lett.* **87**, 023201 (2001).
- [3] V. D. Rodríguez, P. Macri, R. Gayet, *J. Phys. B: At. Mol. Opt. Phys.* **38**, 2775 (2005).
- [4] S. Borbély, K. Tókési, L. Nagy, *Phys. Rev. A* **77**, 033412 (2008).

A DISTORTED WAVE MODEL FOR ELECTRON IONIZATION IN COLLISIONS BETWEEN CLOTHED-IONS AND ATOMIC TARGETS

J. M. Monti^(*), R. D. Rivarola^(*), P. D. Fainstein⁽⁺⁾

(*) Instituto de Física Rosario, CONICET and Universidad Nacional de Rosario,
Av. Pellegrini 250, 2000 Rosario, Argentina

(+) Centro Atómico Bariloche, 8400 Bariloche, Río Negro, Argentina

The Continuum Distorted Wave - Eikonal Initial State (CDW-EIS) model has been used with success to describe electron ionization of atomic targets by bare ions [1]. The interest of the present work is to extend the CDW-EIS model to the case of dressed projectiles, where some electrons are initially bound to the ion. A three-body approximation is proposed [2], where in the entry channel the initial target state is distorted by an eikonal phase corresponding to the long distance interaction between the screened projectile and the active target electron. The projectile electrons are assumed to remain as frozen during the collision, so that model potentials are used [3-4] in order to describe the short range interaction between the projectile and the active electron. In the exit channel a product of a plane wave and two wave functions (corresponding to the continua of the active electron in the asymptotic projectile and residual targets fields) is proposed. Double differential spectra are analyzed as a function of the final energy and angle of the emitted electron. In particular two different effects previously observed in the binary encounter region: i) an increasing of its height at forward emission angles as the number of the projectile electrons increases [5] and, ii) a double structure appearing in a narrow band, at larger emission angles, which was attributed to a rainbow effect [6-7], are investigated.

References

- [1] N. Stolterfoht, R. D. DuBois and R. D. Rivarola, *Electron Emission in Heavy Ion-Atom Collisions*, Springer, Berlin (1997) and references therein.
- [2] P. D. Fainstein, V. H. Ponce, R. D. Rivarola, *J. Phys. B* **21**, 287 (1988).
- [3] A. E. S. Green, D. L. Sellin and A. S. Zachor, *Phys. Rev.* **184**, 1 (1969).
- [4] R. H. Garvey, C. H. Jackman and A. E. S. Green, *Phys. Rev. A* **12**, 1144 (1975).
- [5] P. Richard, D. H. Lee, T. J. M. Zouros, J. M. Sanders and J. L. Shinpaugh, *J. Phys. B* **23**, L213 (1990).
- [6] C. O. Reinhold, D. R. Schultz and R. E. Olson, *J. Phys. B* **23**, L591 (1990).
- [7] C. O. Reinhold *et al.*, *Phys. Rev. Lett.* **66**, 1842 (1991).

A FULL FOUR-BODY CONTINUUM DISTORTED WAVE - EIKONAL INITIAL STATE MODEL FOR IONIZATION OF He BY ION IMPACT

J. M. Monti^(*), O. A. Fojón^(*), J. Hanssen⁽⁺⁾, **R. D. Rivarola**^(*)

(*) Instituto de Física Rosario, CONICET and Universidad Nacional de Rosario,
Av. Pellegrini 250, 2000 Rosario, Argentina

(+) Institut de Physique, Laboratoire de Physique Moléculaire et des Collisions, Université de Metz,
Technopôle 2000, 1 Bv. Arago, 57078 Metz Cedex 3, France

Electron ionization of atomic targets produced in collisions with bare ions is usually studied using three-body distorted wave approximations. The three considered bodies are the incident projectile, the residual target and the *active* electron (the electron to be ionized as a consequence of the collision). The other electrons, the *passive* ones, are assumed to remain as frozen in their initial orbitals during the reaction (see for example Ref. [1]). Four-body distorted wave models were also introduced to investigate ionization of dielectronic targets ([2-3]). Correct boundary conditions were preserved in both the entry and exit channels but only the *active* electron was considered to be distorted by the projectile.

In order to avoid any asymmetric description of the target electrons we consider both of them as *active* electrons in a four-body Continuum Distorted Wave - Eikonal Initial State (CDW-EIS) approximation. Thus, the initial bound state is distorted in the entry channel by two eikonal phases associated with the interaction of the projectile with each one of the target electrons. These phases correspond to an approximated description of the projectile-target electrons continuum states for large enough collision velocities. As we are here interested in ionization-excitation processes the residual bound wave function is distorted by a projectile-residual target electron eikonal phase as in the single-electron excitation Symmetric Eikonal (SE) approximation [4] and the emitted electron is considered to move in the combined fields of the projectile and residual target as in the single-electron ionization CDW-EIS model [5]. The use of four-body representations where the two electrons are considered as *active* ones, allows the study of the influence of *static* and *dynamical* electron correlation on multiple differential and total cross sections. The case of a bare ion impacting on a He target will be presented in the conference.

References

- [1] P. D. Fainstein, V. H. Ponce, R. D. Rivarola, J. Phys. B **21**, 287 (1988).
- [2] D. Belkic, J. Phys. B **30**, 1731 (1997).
- [3] D. Belkic, Nucl. Instr. Meth. B **124**, 365 (1997).
- [4] G. R. Deco, P. D. Fainstein and R. D. Rivarola, J. Phys. B **11**, 213 (1986).
- [5] D. S. F. Crothers and J. F. McCann, J. Phys. B **16**, 3229 (1983).

NEW CLASSICAL CTMC APPROACHES TO $A^{q+} + He$ PROCESSES

F. Guzmán¹, L. F. Errea¹, L. Méndez¹, B. Pons² and A. Riera¹

¹ Departamento de Química, Universidad Autónoma de Madrid, 28049 Madrid (Spain)

² CELIA, UMR 5107 du CNRS, Université de Bordeaux-1, 351 Cours de la Libération, 33405 Talence (France)

Any small perturbation in the classical stable Helium atom produce unphysical autoionization that prevents any classical dynamical study. Previous attempts [1,2,3] have required barrier potentials to limit the electron energy.

In a first approach we consider two sets of N classical electron trajectories, whose evolution obey the Hamilton equations in the full Hamiltonian. Each classical electron of one set feels the average repulsion due to the classical electrons of the other set. This is combined with the smoothing of the evaluation of the classical electronic repulsion by assuming that each electron can be described by gaussian functions centred on the position of the corresponding electrons [4].

The initial electronic densities, have been obtained from a microcanonical distribution that takes into account the electrostatic field created by the other set of electrons, that is also a microcanonical distribution. Initial distribution can evolve, before the projectile starts the collisions, under the influence of the actual He atom to describe more accurately the exact ones. A second approach employs N couples of electrons that evolve under model potentials exerted by the other electron both in the target and projectile, through a time-dependent parameter that represent the number of core electrons.

Results will be presented at the conference.

References

- [1] C.L. Kirschbau and L. Wilets, Phys. Rev. A **21**, 834, (1980)
- [2] J.S. Cohen, Phys. Rev. A **54**, 573, (1996)
- [3] V.J. Montemayor and G.S. Schiwietz, Phys. Rev. A **40**, 6223, (1989).
- [4] A. Donoso and C. C. Martens, J. Chem. Phys **116**, 10598 (2002)..

A NEW MOTRIMS APPARATUS FOR HIGH RESOLUTION MEASUREMENTS IN ION-ATOM COLLISIONS AND TRAPPED ATOMS STUDIES

J. Blicck, X.Fléchard, A. Cassimi*, H. Gilles[#], S. Girard[#], and D. Hennecart[#]

LPC Caen, ENSICAEN, Université de Caen, CNRS/IN2P3, Caen, France

(*) CIMAP-GANIL, avenue H. Becquerel, 14070 Caen Cedex 5, France

([#]) CIMAP-ENSICAEN, 6 Boulevard du Maréchal Juin, 14050 Caen Cedex, France

MOTs (magneto-optical traps) and COLTRIMS (cold target recoil ion momentum spectroscopy) are two of the most fruitful experimental techniques developed these last decades in atomic, molecular, and optical (AMO) physics. Laser cooling and trapping of atomic samples in a MOT is now a first step for many exciting and innovating experiments: among well known examples, one can find Bose-Einstein condensate formation and superfluidity studies, electromagnetically induced transparency, photoassociation, quantum information, etc. On the other hand, the COLTRIMS technique has proven to be very powerful for mapping the dynamic of ion-atom/molecule and photon-atom/molecule collisions. Based on the measurement of the full momentum vector of the charged target fragments, the COLTRIMS technique gives access to the dynamic of the projectile-target interaction. Quite recently, several groups merged both MOTs and COLTRIMS techniques by using trapped atoms as a cold target for the COLTRIMS methodology [1]. This new development, called MOTRIMS, added several advantages to the standard technique: the very low temperature of the target (on the order of 100 μ K) does not limit the resolution in recoil momentum, and the MOT provides an additional set of atomic species such as alkali atoms. These atoms can be easily optically pumped with lasers and allow measurements with different initial states of the target (including aligned or oriented states).

A new MOTRIMS apparatus has been built at the LPC-CAEN, and recently tested with a beam of 2 keV Na^+ projectiles colliding a trapped Rb target. In this work, we demonstrate the capability of the setup to provide, with a very high signal over background ratio, fully differential cross sections in scattering angle, initial state, and final state of the system. We also detail features that had not been described previously in the literature: an extraction of the recoil ions transverse to the ion beam axis, and a fast switch for the MOT magnetic field. Future possibilities for the setup, including the target orientation and the electron detection will be presented at the conference.

References

[1] B.D. DePaola, R. Morgenstern, and N. Andersen, in *Advances in Atomic, Molecular and Optical Physics*, Vol. 55, p. 139, edited by E. Arimondo, P. Berman, C. Lin (Academic Press, 2007)

VACANCY DISTRIBUTION OF THE X-RAY SATELLITE SPECTRA OF SiO₂ AEROGEL BOMBARDED WITH CALCIUM IONS

Aneta Gójska¹, Jacek Rzadkiewicz¹, Olga Rosmej², Marek Polasik³, Katarzyna Slabkowska³

¹The Andrzej Soltan Institute for Nuclear Studies, 05-400 Świerk, Poland

²GSI, Darmstadt, Germany

³Faculty of Chemistry, Nicholas Copernicus University, 87-100 Toruń, Poland

The Si x-ray spectra of the low-density SiO₂ aerogel target indicated with Ca⁶⁺ ions with initial energy of 11.4 MeV/u were measured with a high spectral and spatial resolution along 80% of the ion beam stopping path [1]. The K α L⁰ diagram and K α Lⁿ (n=1-5) satellite lines (appearing in these spectra as a result of the radiative deexcitation of multiply ionized atomic states) were observed. The K α Lⁿ x-ray satellite lines were resolved from the parent diagram lines and the energy shifts were determined [2]. From the relative intensities of satellites, the population of the primary KLⁿ vacancy configurations (at the moment of collision) were deduced by taking into account the intra-atomic rearrangement processes occurring before the K x-ray emission. Assuming that the L-shell vacancy can be produced in near-central collisions by two uncorrelated processes: direct ionization and electron capture of the target L-shell electron into the K-shell of the projectile, the L-shell ionization probabilities were deduced by means of statistical considerations. The experimental values were compared with the results of theoretical semi-classical (SCA) and geometrical model (GM) calculations. It was found that both theoretical models overestimate the experimental L-shell ionization probabilities. Moreover, for each projectile energy the significant enhancement of the KL⁰ vacancy configuration was observed in measured spectra. The possible influence of the delta electrons appearing in stopping processes as well as chemical environment of the stopping media on the shape of the K x-ray spectra will be discussed.

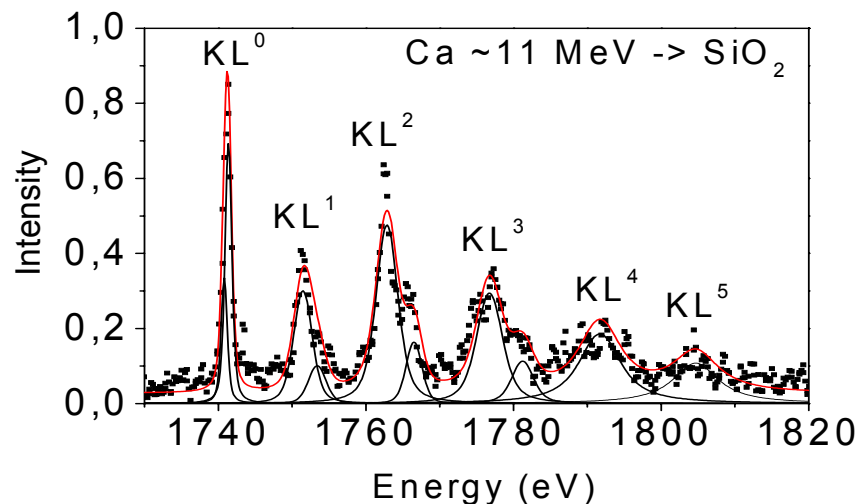


Fig. 1. High resolution spectrum of low-density SiO₂ aerogel induced by Ca projectiles for 0.5 mm (11.4 MeV/u). Results of the simplified fitting procedure is also shown (solid lines).

References

[1] O. N. Rosmej et al., PRA **72**, 052901 (2005)

[2] J. Rzadkiewicz et al., High Energy Density Physics **3**, 233 (2007)

COMPLEMENTARY SPECTROSCOPY OF TIN IONS BY USING ION BEAMS AND ELECTRON BEAMS

H. Ohashi, S. Suda, H. Tanuma, S. Fujioka*, H. Nishimura*, K. Nishihara*, T. Kai**, A. Sasaki**,
H. A. Sakaue†, N. Nakamura††, and S. Ohtani††

Department of Physics, Tokyo Metropolitan University, Hachioji, Tokyo 192-0397, Japan

(*) Institute of Laser Engineering, Osaka University, Suita, Osaka 565-0871, Japan

(**) Japan Atomic Energy Agency, Kizu, Kyoto 619-0215, Japan

(†) National Institute for Fusion Science, Toki, Gifu 509-5292, Japan

(††) Institute for Laser Science, The University of Electro-Communications,
Chofu, Tokyo 182-8585, Japan

Sn plasmas have been studied for the EUV (extreme ultraviolet) lithography using the light of the wavelength around 13.5 nm. Theoretical calculations suggested that not only the resonance lines but also the satellite lines, corresponding to the transitions between the excited states, of Sn ions contributed to the 13.5 nm emission.

To provide the spectroscopic data on the multiply charged Sn ions, we have measured EUV spectra of the emission following the charge transfer collisions of the Sn ions with rare gas targets in the charge exchange spectroscopy (CXs). In this method, we can select the charge states of the emitting ions, because the single-electron capture is dominant in collisions of highly charged ions. We, however, can not distinguish between the resonance lines and the satellite lines in the observed spectra. On the other hand, in the electron beam ion trap (EBIT), the ions are excited by the electron impact, and most of the emission from the ions are resonance lines. In this apparatus, the ionic charge can be controlled by the electron energy. But, generally speaking, a couple of charge states exist in the trap at the same time. In this study, we have measured the emission spectra of multiply charged Sn ions in the EUV region both with the CXs and the EBIT, and discussed those complementary results.

The CXs experiments have been performed with a 14.25 GHz electron cyclotron resonance (ECR) ion source in Tokyo Metropolitan University. The EBIT in the University of Electro-Communication has been operated with extremely low electron energies as this device to produced moderately charged ion. The emission spectra were measured by using the same grazing-incident spectrometer equipped with a liquid nitrogen cooled CCD camera.

The spectrum observed in collisions of Sn^{15+} -He and that observed in the EBIT with the electron beam energy of 312 eV are shown in Figure 1. Both of the spectra have a common strong emission line at 13.3 nm, and we considered it to be a resonance line of Sn^{14+} . We also suggest that the emissions between 13.5 and 14.3 nm are satellite lines corresponding to the 4d-4f transitions by the comparison with the theoretical calculations. The complementary research using the different experimental methods is significantly effective to study the spectroscopic properties of multiply charged ions.

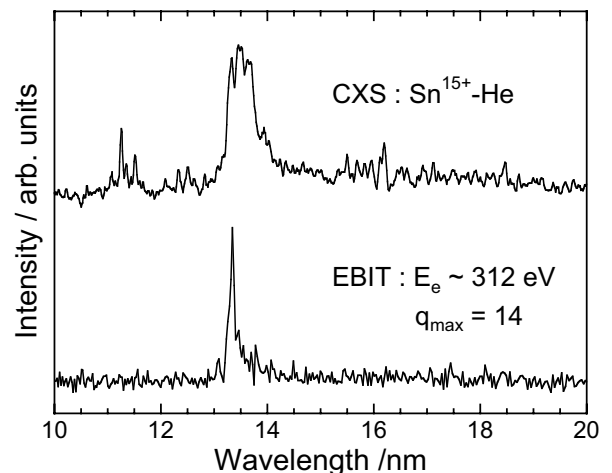


Figure 1: EUV emission spectra in collisions of Sn^{15+} -He and in EBIT.

LINEAR POLARISATION STUDIES FOR RADIATIVE ELECTRON CAPTURE TRANSITIONS INTO HIGHLY CHARGED URANIUM

S. Hess*, H. Bräuning*, C. Brandau*, S. Geyer*, M. Hegewald, C. Kozhuharov*,
T. Krings**, A. Kumar*, R. Märtin*, B. O'Rourke*, D. Protić**, R. Reuschl*,
U. Spillmann*, M. Trassinelli*, S. Trotsenko*, G. Weber*, Th. Stöhlker*

*Gesellschaft für Schwerionenforschung mbH, Planckstr. 1, 64291 Darmstadt, Germany

**Forschungszentrum Jülich GmbH, Wilhelm-Johnen-Straße, 52428, Germany

The recent advances in the development of energy, time and position sensitive 2D microstrip detectors [1] opens up new possibilities for the investigation of physical processes producing linearly polarized X-rays. We present new measurements of Radiative Electron Capture (REC) into the K- and L- shells of highly charged Uranium ions at the Experimental Storage Ring of the GSI facility in Darmstadt, Germany.

For the experiment, a stored beam of cooled bare Uranium ions with 96.6 MeV/u beam energy was crossed with a hydrogen gas target. The preliminary data analysis shows a strong linear polarization for the KREC transition into bare Uranium at an angle of 90 degrees with respect to the ion beam. In contrast to this, at 35 degrees, a strong depolarization has been observed. This is in agreement with theoretical descriptions and measurements [2, 3], predicting an increased importance of higher order multipole processes leading to a strong depolarization of the emitted light.

References

- [1] D. Protić, T. Krings, IEEE Transactions on Nuclear Science **50**, (2003)
- [2] S. Tashenov, Th. Stöhlker, et al., Physical Review Letters **97**, (2006)
- [3] A. Surzhykov, S. Fritzsche, Th. Stöhlker et al., Radiation Physics and Chemistry **75**, (2006)

ONE- AND TWO- ELECTRON TRANSFER TO CONTINUUM IN NEAR-RELATIVISTIC ION-ATOM COLLISIONS

S. Hagmann^{1,2}, M. Nofal^{2,3}, Th. Stöhlker^{2,4}, A. Surzhykov^{3,4}, S. Fritzsche^{2,4},
D. Jakubassa-Amundsen⁵, B. Najjari³, A. Voitkiv³, C. Kozhuharov², J. Ullrich³,
R. Moshhammer³, A. Gumberidze², U. Spillmann², R. Reuschl², S. Heß², S. Trotsenko²,
F. Bosch², D. Liesen², R. Dörner¹, H. Rothard⁶, G. Lanzano⁷, E. De Filippo⁷
¹Institut für Kernphysik, Univ. Frankfurt, ²GSI, Darmstadt, ³Max Planck Institut für Kernphysik,
Heidelberg, ⁴Physik. Institut, Univ. Heidelberg, ⁵Mathemat. Inst., LMU-München, ⁶CIRIL-Ganil,
Caen, France, ⁷INFN, Sezione di Catania, Catania, Italy

Observing the different electron transfer to continuum channels in fast ion-atom collisions permits to study the dynamics of ionization as well as of radiative and non-radiative capture very close to threshold; it is therefore a test of unparalleled sensitivity for first order theories.

Theories for electron transfer to the continuum, however, have encountered considerable difficulties to take into account the intrinsic many-electron processes in the capture channel which have been seen in slow collisions, but which persist surprisingly also in very fast collisions. This may partially be attributed to large momentum transfers involved and thus collision systems are mostly not in the realm of first order perturbation theories. For this reason we have studied simultaneously competing electron transfer processes, like radiative (RECC) and non-radiative electron capture to continuum (ECC) in the relativistic domain where one or two active electrons are involved; additionally, the projectile electron loss to continuum (ELC) channel permits to comparatively study in the same collision the dynamics of ionization very close to threshold.

We have studied these electron transfer processes in forward electron emission in two systems of different projectile Compton profile, $U^{88+} + N_2$ and $Sn^{47+} + N_2$ collisions using the forward electron spectrometer at the supersonic jet-target of the ESR storage ring. We report first results for differential cross sections and compare with available theories.

STRONG FORWARD-BACKWARD ASYMMETRY OF H₂O IONIC FRAGMENTS BY SLOW HIGHLY CHARGED IONS IMPACT

Z.D. Pešić^{1,2}, R. Hellhammer², B. Sulik³ and N. Stolterfoht²

¹Institute of Ion Beam Physics and Materials Research, Forschungszentrum Dresden-Rossendorf, 01314 Dresden, Germany

²Hahn-Meitner Institut, Glienickerstr. 100, D-14109 Berlin, Germany

³Institute of Nuclear Research - ATOMKI, H-4001 Debrecen, Hungary

Fragmentation of molecules subsequent to the interaction with ions has been studied intensively in the last decade [1]. If the projectile is fast that the interaction time is orders of magnitude smaller than the dissociation time, the collision can be considered as a two-step process [2]. On the other hand, for slow ($v < 1$ a.u.), highly charged projectiles the energy and angular distribution of fragments is determined by the energy and momentum transferred from the projectile, in addition to the energy gained by the repulsive dissociation of the molecule [3].

We present the results of the fragment ion spectroscopy studies of water molecules subsequent to impact of highly charged 1-220 keV Xe^{q+} ions ($q=10, 15$ and 22). We observed a strong forward-backward asymmetry in the emission of the ionic fragments. For example, the ion yield in the forward direction is almost completely suppressed for the impact of below 10 keV Xe²²⁺ ions. These results are compared with our previous studies of water fragmentation induced by He^{1,2+} and Ne⁽³⁻⁹⁾⁺ ions [1, 4, 5]. For projectiles with low charge state, the final kinetic energy is apparently determined by the related Franck-Condon transition. In order to guide the interpretation of the experimental data, we performed a classical trajectory simulation within the framework of a Coulomb Explosion model wherein a satisfactory agreement is achieved. Finally, the integrated cross sections over all fragmentation channels are compared with results of the semiempirical scaling law deduced from a multi-electron capture model [6].

References

- [1] N. Stolterfoht *et al.*, *Advanc. in Quantum Chem.* **52**, 149 (2007) and references therein
- [2] B. Siegmann *et al.*, *J. Phys. B: At. Mol. Opt. Phys.* **34**, L587 (2001)
- [3] C.R. Feeler *et al.*, *Phys. Rev. A* **60**, 2112 (1999)
- [4] P Sobocinski *et al.*, *J. Phys. B: At. Mol. Opt. Phys.* **39**, 927 (2006)
- [5] Z. D. Pešić *et al.*, *J. Phys. B: At. Mol. Opt. Phys.* **37**, 1405 (2004)
- [6] N Selberg *et al.*, *Phys. Rev. A* **54**, 4127 (1996)

INVESTIGATION OF THE MULTIPLE ELECTRON SCATTERING SEQUENCES IN $C^{N+} + AR$ COLLISIONS

K. Tőkési and B. Sulik

Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI),
H-4001, Debrecen, Hungary, EU

Multiple electron scattering in low and intermediate energy ion-atom and ion-molecule collisions may contribute to the emission of fast, high energy electrons. It manifests itself in the structures of the double differential electron spectra [1,6]. In such processes, an electron is repeatedly scattered by the ionic cores of the projectile and the target, and it gains energy in every encounter with the projectile. This mechanism is often referred to as Fermi-shuttle acceleration [4]. Fast electrons have been identified from double, triple and quadruple scattering by the projectile and target cores [4]. The effect is the most pronounced in collisions of dressed heavy projectiles and heavy target atoms. These systems are particularly challenging theoretically to describe at a level of the double differential electron emission cross sections. So far, no quantum calculations were carried out at such a complexity. For modeling these collisions, classical trajectory Monte-Carlo (CTMC) calculations have been performed for many collision systems. Surprisingly, a general quantitative agreement has been found compared with the experimental data [5,6] in intermediate energy collisions. This fact allows us to identify multiple scattering events in a classical sense, by analyzing the calculated individual particle trajectories. Moreover, it has been found that the cross section of multiple scattering sequences is dramatically increases towards lower projectile velocities.

In this work, we present a systematic theoretical study of the electron emission from collisions of carbon ions at 60 keV energies with argon atoms. In the Monte Carlo simulation the electron emission yield is calculated separately for the contribution from the target and projectile ionization. On the basis of the present calculations we suggest some experiments to be performed in this energy region, to separate and identify target and projectile multiple scattering contributions to the fast electron spectrum. Moreover, we present the principles of a random sampling analysis of the individual CTMC trajectories to identify and determine the contribution of multiple scattering sequences.

References

- [1] S. Suarez et al., Phys. Rev. Lett. 77 (1996) 474.
- [2] U. Bechtold et al., Phys. Rev. Lett. **79** (1997) 2034
- [3] G. Lanzano et al., Phys. Rev. Lett. **83** (1999) 4518.
- [4] B. Sulik et al., Phys. Rev. Lett. **88** (2002) 073201.
- [5] T. Ricsóka et al., Nucl. Instr. Meth. B **235** (2005) 397
- [6] B. Sulik and K. Tőkési, Adv. Quant. Chem. **52** (2007) 253.

YOUNG TYPE INTERFERENCE IN ELECTRON EMISSION FROM H₂ AND FORWARD-BACKWARD ASYMMETRY: A NEW APPROACH

D. Misra, S. Chatterjee and Lokesh C. Tribedi

Tata Institute of Fundamental Research, Colaba, Mumbai 400005, India

The coherent electron emission from the inversion-symmetric homonuclear diatomic molecule H₂, carry the signature of the Young type interference effect under fast ion and photonic collisions. Although it was predicted about forty years back it was first observed in fast ion-molecule collisions a few years back by Stolterfoht et al. [2]. Since the double differential cross section (DDCS) varies over several orders of magnitudes in an energy range of few hundred eV, it is difficult to observe a small variation in the DDCS spectrum owing its steep variation. Therefore, to observe the oscillatory structure, the ratio of H₂-to-2H cross sections, are used which are either obtained theoretically [2] or in an experiment with atomic H [3]. We have recently reported [4] an independent way of obtaining the interference structure by using the forward backward asymmetry parameter of electron DDCS. This method does not need any input from the theoretical model calculations and neither requires a complementary experiment with atomic H. Bare C (6MeV/u) and F (4 MeV/u) ions were available from the BARC-TIFR Pelletron accelerator at TIFR. The experiments were carried using low pressure H₂ gas. Energy and angle resolved electrons were detected, using a hemi-spherical electrostatic analyzer, at several forward and backward angles between 20⁰ and 160⁰. The difference in the oscillation frequency for the forward and backward angles causes the oscillation in the forward backward asymmetry parameter which is also reproduced by the molecular CDW-EIS calculation[4,5]. A model calculation based on Cohen-Fano model joined together with the frequency difference in forward-backward angles, fits the spectrum well. The ratio of frequency in 160⁰ and 20⁰ was about 1.8. Since this study does not need any atomic target, can be applied for other diatomic molecular targets: a step forward towards the study of Young type interference in ionizations of molecule. Besides first order interference the re-scattering of the electron from the second atom can give rise additional oscillatory structure in the electron spectrum. Such second order effect was first predicted by Stolterfoht et al.[6] for GeV energy collision. We provide here the evidence of frequency doubling of the oscillations in ionization of H₂ in collisions with 4 MeV/u bare F ions. We believe the present experimental data provides strong support for the evidence of a higher frequency component in interference oscillations as predicted in [6].

References:

1. H. D. Cohen and U. Fano, Phys. Rev 150, 30 (1966).
2. N. Stolterfoht et al., Phys. Rev. Lett., 87, 023201 (2001).
3. D. Misra, U. Kadhane, Y.P. Singh, L. C. Tribedi, P.D. Fainstein and P. Richard, Phys. Rev. Lett. 92, 153201 (2004).
4. D. Misra, A. Kelkar, U. Kadhane, Ajay Kumar, L. C. Tribedi, and P.D. Fainstein, Phys. Rev. A-Rapd comm.. 74, 060701(R) (2006).
5. M.E. Gallasi, R.D. Rivarola, P.D. Fainstein and N. Stolterfoht, Phys. Rev A 66, 052705 (2002).
6. N. Stolterfoht et al., Phys. Rev. A. 69, 012701 (2004).

INTERFERENCE PATTERNS IN SPECTRA OF ELECTRON IONIZATION OF HETERONUCLEAR HeH⁺ TARGETS IN INTERACTION WITH FAST ION BEAMS

C. A. Tachino^(*), M. E. Galassi^(*), F. Martín⁽⁺⁾ and R. D. Rivarola^(*)

(*) Instituto de Física Rosario, CONICET and Universidad Nacional de Rosario,
Av. Pellegrini 250, 2000 Rosario, Argentina

(+) Departamento de Química, C-9, Universidad Autónoma de Madrid, 28049 Madrid, Spain

Coherent electron emission from diatomic molecular targets provokes the presence of interference patterns in the corresponding spectra of electron ionization. This effect was theoretically predicted more than forty years ago for the case of photoionization [1]. At the beginning of the present century, oscillations appearing in double differential cross sections were measured by the first time for impact of fast multiply charged heavy ions on H₂ targets [2], confirming the existence of the physical effect. This was an incentive for further active experimental and theoretical research, not only for photon and ion beams but also for electron beams (for a brief review, see Ref. [3]), in all cases considering homonuclear targets.

In the present work, we investigate the possible existence of the effect when a *heteronuclear* HeH⁺ molecule is ionized by a fast ion beam. It could be associated with the interference two-slit Young experiment, but where the two orifices have different dimensions. Vibration and rotation of the molecule are considered to be produced in times much larger than the collision time, so that their influences on the studied reaction are neglected. In particular, the internuclear axis is assumed to remain as *frozen* during the ionization reaction. The orbital of each one of the target electrons in the fundamental state of HeH⁺ is described by a linear combination of Gaussian functions centred on the positions of the nuclei of the molecule. It allows us to investigate the ionization process within a two-effective centre approximation (TEC; see Ref. [4]), where two effective coulombic continuum functions (associated with each one of the molecular centres) are chosen to describe the interaction of the ejected electron with the residual target in the exit channel. The dynamics of the reaction is analyzed using the Continuum Distorted Wave – Eikonal Initial State model (CDW-EIS), so that the influence of the projectile on the emitted electron is also taken into account. Moreover, into the straight line version of the impact parameter approximation, the interaction of the projectile with the nuclei of the molecule can be easily included [4] when differential cross sections are studied as a function of the momentum transfer.

The initial bound electron wavefunction presents a strong monocentric character. The electrons are placed mostly around the alpha particle but however they have a smaller probability to remain at the proximities of the proton center. This relatively weak two-centre behaviour is the origin of the presence of interference patterns in differential cross sections. Results corresponding to different collision systems will be presented at the conference.

References

- [1] H. D. Cohen, U. Fano, Phys. Rev. **150** (1966) 30.
- [2] N. Stolterfoht *et al.*, Phys. Rev. Lett. **87** (2001) 023201.
- [3] R. D. Rivarola, Nucl. Instr. Meth. B **261** (2007) 161.
- [4] M. E. Galassi, R. D. Rivarola, P. D. Fainstein, Phys. Rev. A **70** (2004) 032721.

THEORETICAL ANALYSIS OF MULTIPLE IONIZATION OF AR-IONS IN GAS TARGETS

G. Schenk, T. Kirchner, V.P. Shevelko*

Institut für Theoretische Physik, TU Clausthal, D-38678 Clausthal-Zellerfeld, Germany

(*) P.N. Lebedev Physical Institute, 119991 Moscow, Russia

Current activities at accelerator facilities, e.g., in the framework of the FAIR project at GSI require precise knowledge of electron stripping cross sections for fast highly-charged ions in gas targets. As a first step toward the goal of providing cross section data for lowly-charged uranium ions from the MeV/amu to the GeV/amu regime we have considered electron loss from sixfold and eightfold argon ions in helium and argon gases at around 10 MeV/amu. Our calculations are based on a mean-field description of the electron dynamics and the nonperturbative basis generator method [1] for orbital propagation.

In the case of Ar^{6+} ions we find that a considerable fraction of electron loss is due to ionization from the L-shell (see figure). Consequently, Auger processes can contribute to multiple electron loss. We have taken them into account on the basis of a statistical model introduced recently [2] and find that they indeed have a major influence on the final charge-state distributions of the ions. Furthermore, we argue that antiscreening, i.e., the ionization of a projectile electron due to a direct interaction with one of the target electrons does play a role. It is not unlikely that both processes are also important for the uranium ions of interest at GSI [3].

Work supported in part by the BMBF.

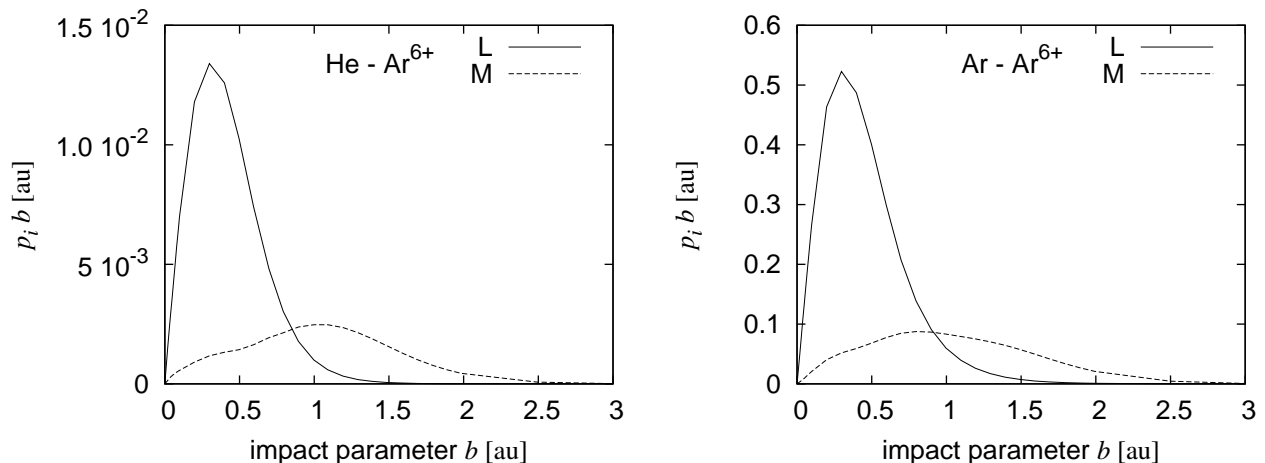


Figure 1: Ionization probabilities $p_i(b)$, weighted with the impact parameter b and number of electrons of the respective shell.

References

- [1] O.J. Kroneisen *et al.*, J. Phys. A **32**, 2141 (1999)
- [2] T. Spranger and T. Kirchner, J. Phys. B **37**, 4159 (2004)
- [3] R.E. Olson *et al.*, J. Phys. B **37**, 4539 (2004)

HIGH-RESOLUTION X-RAY STUDY OF MULTIPLE IONIZATION OF Pd ATOMS BY FAST OXYGEN IONS

M. Czarnota¹, D. Banaś¹, M. Pajek¹, J.-Cl. Dousse², J. Hoszowska², Y.-P. Maillard²,
O. Mauron², M. Berset², P. A. Raboud², D. Chmielewska³, J. Rządkiwicz³, Z. Sujkowski³,
M. Polasik⁴, K. Słabkowska⁴,

¹Institute of Physics, Jan Kochanowski University, 25-406 Kielce, Poland

²Physics Department, University of Fribourg, CH-1700 Fribourg, Switzerland

³Sołtan Institute for Nuclear Studies, 05-400 Otwock-Świerk, Poland

⁴Faculty of Chemistry, Nicholas Copernicus University, 87-100 Toruń, Poland

In high-resolution measurements of the x-rays excited in collisions of heavy ions with atoms the complex x-ray satellites, corresponding to the multi-vacancy configurations present in the moment of X-ray emission, are observed. In this way a high resolution measurements of the X-ray satellites give thus access to study the dynamics of multiple ionizations. In particular, the ionization probabilities for the L- and M-shells can be derived from the measured x-ray spectra of multiply ionized atoms.

In the present paper a high-resolution x-ray spectra of Pd $L\alpha_{1,2}$ x-ray transitions excited by O^{6+} ions of energy 279 MeV [1] is discussed, which were measured by a high resolution von Hamos crystal spectrometer having energy resolution of about 0.6 eV. The measured x-ray spectra, showing both the M-shell satellite and L-shell hypersatellite x-ray transitions, were interpreted in terms of the multi-configuration Dirac-Fock (MCDF) calculations. In this way the ionization probabilities for L- and M-shell were obtained for the moment of x-ray emission, which were further compared with the semiclassical (SCA) calculations of the ionization probabilities. Since the ionization probabilities are calculated for the moment of collision, they were corrected for the vacancy rearrangement processes taking place between the moments of collision and x-ray emission. The SCA calculations, which were performed using relativistic hydrogenic (SCA-HYD) and self-consistent Dirac-Hartree-Fock (SCA-DHF) wave functions, indicate strong effect of the realistic description of the electronic wave function for the L- and M-shell. A systematic comparison of the SCA-DHF/SCA-HYD calculations will be discussed in details.

References

- [1] M. Czarnota *et al.*, Nucl. Instr. and Methods B 205, 133 (2003)

RADIATIVE ELECTRON CAPTURE AND SUBSEQUENT RADIATIVE DECAY IN COLLISIONS OF U^{89+} IONS WITH N_2

J. J. Wan, Y. J. Wang, X. B. Ding, **C. Z. Dong**, X. W. Ma^{*},
J. Rzadkiewicz^{**†}, Th. Stöhlker[†] and S. Fritzsche^{†,‡}

College of Physics and Electronic Engineering, Northwest Normal University, 730070, Lanzhou, China

(^{*})Institute of Modern Physics, 730000, Lanzhou, China

(^{**})The Soltan Institute for Nuclear Studies, 05-400 Świerk, Poland

([†])Gesellschaft für Schwerionenforschung (GSI), D-64291 Darmstadt, Germany

([‡])Max-Planck-Institut für Kernphysik, D-69029 Heidelberg, Germany

The radiative electron capture (REC) in collisions of U^{89+} ions with N_2 target molecules [1-4] has been studied theoretically, along with the subsequent radiative deexcitation (RD) spectra. In this study, the REC cross sections and photon energies for the capture into the levels of the $1s^2 2snl$ ($2 \leq n \leq 9$, $0 \leq l \leq 6$) configurations, starting from the $1s^2 2s$ ground configuration of the U^{89+} ions, have been calculated for the first time by applying the newly-developed program RERR06. This program is based on the RATIP package [5] and includes the contributions of all required multipole transitions. The REC spectra were generated by using the cross sections and the Compton profile of the N_2 molecule. When compared with new experiments at GSI [4], the calculated REC spectra are in good agreement with the observations. Furthermore, by combining the cross sections from above together with the computation of the transition probabilities among the lowest 147 levels of Be-like U^{88+} ions in the $1s^2 2snl$ configurations ($2 \leq n \leq 9$, $0 \leq l \leq 6$), the RD spectra from the subsequent decay has been simulated using both the multi-step model and coupled rate equations. The results were found in good agreement with the experimental spectra.

References

- [1] Th. Stöhlker, H. Geissel, H. Irnich *et al.*, Phys. Rev. Lett. **73**, 3520 (1994)
- [2] Th. Stöhlker, C. Kozhuharov, P. H. Mokler *et al.*, Phys. Rev. A **51**, 2098 (1995)
- [3] X. W. Ma, Th. Stöhlker, H. F. Beyer *et al.*, Nuclear Physics Review **19**, 131 (2002)
- [4] J. Rzadkiewicz, Th. Stöhlker, D. Banaś *et al.*, Phys. Rev. A **74**, 012511 (2006)
- [5] S. Fritzsche, J. Electron Spectroscopy and Related Phenomena **114-116**, 1155 (2001)

LOSS MECHANISM AND LIFETIME OF IONS BEAM IN HIRFL-CSRE

Y. L. Xue, X. Cai*, D. Yu, C. J. Shao, F. F. Ruan, D. J. Qi, M. W. Zhang, W. Wang

Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, 730000 China

Ion	Energy (MeV/u)	τ_{rr}/s	τ_r/s	τ_t/s	τ_{total}/s
C ⁶⁺	50	3.77×10 ³	1.91×10 ⁵	1.79×10 ²	1.71×10 ²
	100	4.17×10 ³	8.73×10 ⁵	7.68×10 ²	6.48×10 ²
	200	5.02×10 ³	3.66×10 ⁶	3.03×10 ³	1.89×10 ³
	300	5.94×10 ³	7.55×10 ⁶	6.28×10 ³	3.05×10 ³
	400	6.95×10 ³	1.16×10 ⁷	1.00×10 ⁴	4.10×10 ³
Ar ¹⁸⁺	50	3.54×10 ²	5.62×10 ⁴	5.52×10 ²	2.15×10 ²
	100	3.90×10 ²	1.39×10 ⁵	1.41×10 ²	1.04×10 ²
	200	4.70×10 ²	8.00×10 ⁵	7.98×10 ²	2.96×10 ²
	300	5.57×10 ²	2.24×10 ⁶	2.22×10 ³	4.45×10 ²
	400	6.51×10 ²	4.42×10 ⁶	4.48×10 ³	5.68×10 ²
Xe ⁵⁴⁺	50	33.8	1.39×10 ⁵	1.40×10 ²	27.2
	100	37.3	2.99×10 ⁵	3.05×10 ²	33.2
	200	44.9	7.12×10 ⁵	7.43×10 ²	42.3
	300	53.2	1.24×10 ⁶	1.33×10 ³	51.1
	400	62.2	1.87×10 ⁶	2.07×10 ³	60.4
U ⁹²⁺	50	10.9	3.38×10 ⁴	35.3	8.3
	100	12.0	6.45×10 ⁴	67.7	10.2
	200	14.5	1.34×10 ⁵	1.42×10 ²	13.1
	300	17.1	2.18×10 ⁵	2.32×10 ²	16.0
	400	20.0	3.17×10 ⁵	3.40×10 ²	18.9
500	23.2	4.30×10 ⁵	4.65×10 ²	22.1	

Table 1. $\tau_{rr}(s)$, $\tau_r(s)$, $\tau_t(s)$ and $\tau_{total}(s)$ are the partial and total lifetimes resulting from interaction with electrons in e-cooler, residual gas, internal nitrogen gas jet target, respectively.

internal target, and radiative recombination with the electrons in e-cooler restricted the beam lifetime considerably. For heavy beams such as ¹³²Xe⁵⁴⁺ and ²³⁸U⁹²⁺, the radiative recombination with the electrons in e-cooler is the main loss mechanism.

References

- [1] J. W. Xia, W. L. Zhan, B. W. Wei, et al. Nucl. Instr. and Meth. A**488**, 11 (2002).

HIRFL-CSRe is the experimental ring of the Cooler-Storage-Ring system HIRFL-CSR [1] in Lanzhou. The lifetime of highly charged ions (HCIs) beam in HIRFL-CSRe mainly depends on the interaction between HCIs and residual gas molecules, electron in e-cooler and internal target atoms/molecules. The main processes include the single, multiple Coulomb scattering and charge exchanges between HCIs and residual gas molecules; radiative recombination, which occurs in the interaction of HCIs beam with cooling electrons; and Coulomb scattering and charge exchange in the collision between HCIs and internal target atoms/molecules.

The loss mechanism and lifetime of ions beam in collisions with residual gas (3.0×10^{-11} mbar, 85% H₂, 15% N₂), internal target ($N_2: 5.0 \times 10^{12}$ atoms/cm²) and electrons in e-cooler (5×10^7 electrons/cm³) in HIRFL-CSRe were studied, and the partial beam lifetimes resulting from various loss mechanisms and the total beam lifetimes of 50-500MeV/u ¹²C⁶⁺, ³⁶Ar¹⁸⁺, ¹³²Xe⁵⁴⁺ and ²³⁸U⁹²⁺ stored in HIRFL-CSRe were calculated (see table 1).

The calculations indicate that the charge exchanges between HCIs and the

electrons in e-cooler restricted the beam

lifetime considerably. For heavy beams such as ¹³²Xe⁵⁴⁺ and ²³⁸U⁹²⁺, the radiative recombination

with the electrons in e-cooler is the main loss mechanism.

INVESTIGATION OF MULTIPLE ELECTRON TRANSFER IN ION ATOM COLLISIONS

I. Blank¹, V.G. Hasan², S. Götz¹, T. Mullins¹, W. Salzmann¹, R. Morgenstern², M. Weidemüller¹,
and R. Hoekstra²

¹Physikalisches-Institut, Universität Freiburg, D-79104 Freiburg, Germany

²KVI Atomic Physics, University of Groningen, 9747 AA Groningen, the Netherlands

Double-electron transfer in collisions of highly charged ions on atoms leads to the creation of doubly excited ($nln'l'$) projectile states. In most studies noble gases, in particular He, or H_2 have been used as electron donors, which implies the capture of two equivalent electrons. As a general finding two distinct population processes, namely mono-electronic and dielectronic processes are found to be responsible for the population of either near symmetric ($n'\sim n$) or asymmetric ($n'\gg n$) configurations.

In mono-electronic transitions the electrons are transferred independently one at a time. This process is called uncorrelated or sequential double capture (SDC). In dielectronic transitions the two electrons are captured simultaneously. For two-electron capture from He it has been shown that the population of asymmetric ($n'\gg n$) final states cannot be described when assuming independent electron transfer, i.e. a mono-electronic transition. Hence this dielectronic transition process is called correlated double capture (CDC). Near symmetric configurations ($n'\sim n$) on the other hand can be populated by uncorrelated double capture.

In contrast to transfer of two equivalent electrons studies on two-electron capture of nonequivalent electrons are rather scarce. Alkali atoms are ideal target systems to study capture of two nonequivalent electrons. The main double capture process is the transfer of the valence electron and one of the inner-shell electrons. The question is whether here symmetric and asymmetric $nln'l'$ configurations are also populated via distinct mechanisms.

We have performed the experiments using a magneto-optically trapped Na target and recoil ion momentum spectroscopy (MOTRIMS). Figure 1 shows an example of the recoil momentum spectra obtained. One clearly sees that different configurations can be resolved. But most remarkably one sees that in particular the $3l3l'$ states and the $3ln'l'$ states with $n'\gg 5$ get populated, while the $3l4l'$ configurations seems to be not populated at all. As for Na one starts with an asymmetric initial state ($\dots 2p3s$) the $3l3l'$ configurations in O^{4+} are expected to be populated by CDC while the $3ln'l'$ states with $n'\gg 5$ are populated via SDC.

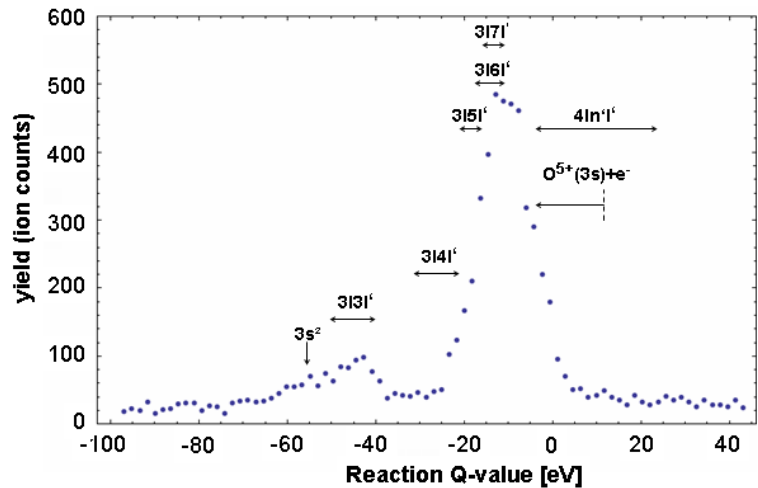


Figure 1: Q-value spectrum of Na^{2+} recoils resulting from $O^{6+} + Na(3s)$ collisions at an energy of 8.625 keV/amu. Double capture states of O^{4+} are indicated as well as the onset for transfer ionization.

Electron-impact excitation of $2p^53l \rightarrow 2p^53l'$ line emission of Fe XVII

D. Kato, H.A. Sakaue, I. Murakami, T. Kato,
N. Nakamura*, S. Ohtani*, N. Yamamoto**, and T. Watanabe***

National Institute for Fusion Science, Toki, Gifu 509-5292, Japan

(*) ILS, Univ. Electro-Commun., Chofu, Tokyo 182-8585, Japan

(**) Osaka University, Suita, Osaka 565-0871, Japan

(***) National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan

We present theoretical investigations on $2p^53l \rightarrow 2p^53l'$ line intensities of Fe XVII excited by electron-impact. These lines of the extreme ultraviolet wavelengths appeared in solar flares [1] and beam-foil spectra [2]. Most of the lines were identified with good confidence [2-4]. Among them, Fe XVII 204.6 Å and 254.8 Å lines, $2p^53p (^1S_0) \rightarrow 2p^53s (3/2, 1/2)_1$ and $\rightarrow 2p^53s (1/2, 1/2)_1$, respectively, have the electric-dipole branching ratio close to unity. The two lines have therefore been predicted to have almost the same intensities [5].

Recently, solar coronal emission lines were observed by means of the Extreme Ultraviolet Imaging Spectrometer on *Hinode* satellite. It was reported [4] that measured intensities of the two lines differed by a factor of 2.5. Even though the unexpectedly large difference in the two intensities can be ascribed to blending of other ion lines and some calibration issues, the measured intensities can not be reconciled with atomic data of the CHIANTI code. Thus, we undertook careful studies on atomic processes relevant to those line emissions for a better understanding.

In the present studies, besides electron-impact excitation from the ground state of Fe XVII, i.e. $2p^6 (^1S_0)$, other atomic processes to make population of the upper level are also examined, e.g. the inner-shell ionization excitation of Fe XVI: $2p^63s \rightarrow 2p^53l + e$, the dielectronic recombination of Fe XVIII: $e + 2p^5 \rightarrow 2p^43s3l \rightarrow 2p^53l + hv$. We evaluate published data for electron-impact cross sections of the processes concerned, and also conduct calculations of the distorted-wave Born and the isolated-resonance approximations. Based upon the cross sections, we analyze population kinetics of the $2p^53l$ levels.

The present work is supported by the NIFS/NINS project of Formation of International Network for Scientific Collaborations.

References

- [1] K.P. Dere, *Astrophys. J.* **221**, 1062 (1978)
- [2] J.P. Buchet et al., *Phys. Scr.* **31**, 364 (1985)
- [3] C. Jupén, *Mon. Not. R. Astr. Soc.* **208**, short communication 1 (1984)
- [4] U. Feldman, G.A. Doschek, and J.F. Seely, *Mon. Not. R. Astr. Soc.* **212**, 41 (1985)
- [5] G.A. Doschek, U. Feldman, and A.K. Bhatia, *Phys. Rev. A* **43**, 2565 (1991)
- [6] H.P. Warren, U. Feldman, and C.M. Brown (private communications)