

Structure and dynamics of atoms, ions molecules and surfaces: Atomic physics with ion- and electron beams

*S. Hagmann, Physics Dept. J. R. Macdonald Lab., KSU, Manhattan, Kansas 66506 and
Inst. für Kernphysik, Universität Frankfurt, Frankfurt, Germany*

The projects presented in this section cover advances in spectroscopy of few electron very heavy ions, a new access to (e,3e) spectroscopy of atoms, and delta electron spectroscopy for heavy ions traversing condensed matter.

Recent progress and future plans :

1. Electron spectroscopy of relativistic ions in the ESR storage ring

S. Hagmann(KSU and IKF, Frankfurt), Th. Stöhlker(IKF, Frankfurt), J. Ullrich, R. Moshhammer(MPI, Heidelberg , Ch. Kozhuharov(GSI, Darmstadt)

We have designed a new electron spectrometer to be used in the ESR storage ring; its purpose is twofold: a) investigate the role of strong ($E \geq 10^{16}$ V/cm) and rapidly varying ($\tau \leq 10^{-18}$ sec) electromagnetic fields active in the fragmentation of ions and atoms during relativistic collisions using high resolution projectile electron spectroscopy; b) investigate (e,2e) spectroscopy of ions in inverse kinematics using a combination of the electron spectrometer with the reaction microscope.

The instrument is designed as a forward electron spectrometer for electrons emitted near 0° around the beam direction with $v_e \cong v_{\text{Proj}}$. The spectrometer consists of a 60° dipole magnet followed by a quadrupole triplet and second 60° dipole. After momentum analysis, electrons will be detected by a 2D position sensitive detector. We will make use of the advantages offered by relativistic kinematics, which allows for $\beta \cong c$ very high resolution spectroscopy of high lying autoionizing Rydberg states (e.g. with $n \geq 100$ in few electron U ions) in such collisions. We can thus study coherent states via anisotropies of Rydberg states and the corresponding asymmetry¹ of ELC and ECC Cusp peaks. For kinematically complete experiments, i.e. when jointly operated with the reaction microscope, the optical design D-QT-D allows us to reconstruct the scattering plane for (e,2e) experiments on ions performed in inverse kinematics. This latter type of experiment will be feasible after implementation of a new reaction microscope in the ESR, until then we will use the forward electron spectrometer to study ELC and ECC Cusps.

In relativistic collisions a large flood of secondary products is generated besides electrons ionized from the collision partners; as the current 2D position sensitive detector in the electron spectrometer is not measuring the energy of the detected particles, it is imperative to show first that the spectrometer is suppressing the intense beam-induced background and is only transmitting electrons of selected momenta onto the detector.

In the commissioning phase of the instrument we have for this reason temporarily replaced the 2D position sensitive detector with an energy analyzing Si(Li) and studied the reaction $392 \text{ MeV/u } U^{89+} + N_2 \rightarrow U^{90+} + \text{fragments} + \text{electrons}$. We could verify that the spectrometer very efficiently suppresses the flood of secondary products generated in the collision; the spectrometer was operated at a current for which, according to optics calculations, it only transmits electrons with a momentum of a Cusp electron, i.e. with a velocity $v_e \cong v_{\text{Proj}}$. Virtually all electrons detected with the Si(Li) appeared in coincidence with the charge exchanged projectile U^{90+} ; the energy loss measured for these electrons is

in accordance with that calculated for Cusp electrons traversing the Fe exit window of the spectrometer.

An interesting first application after completion of this phase of commissioning will be a combined study of the shape of the ECC Cusp in coincidence with the Radiative Electron Capture into Continuum, RECC, photons- a process which is closely related to the elementary process of bremsstrahlung.

At least one new Ph.D student will be joining our group in fall 2002 to work on this topic.

1. J. Burgdörfer, Phys. Rev. A33(1986) 1578

2. Two-electron Lambshift in high-Z He-like Ions

A. Gumberidze, Th. Stöhlker, F. Bosch, Ch. Kozhuharov(GSI, Darmstadt) X. Ma(IMP Lanzhou), S. Hagmann(KSU and IKF, Frankfurt), Y. Zou(Fudan Univ, Shanghai)

We are using radiative recombination (RR) into the 1s state of bare and H-like U to investigate 2-electron contributions to the ground state of He-like U and thus gain access to 2-electron QED effects. In RR electrons undergo direct transitions to bound states of ions via emission of photons carrying $\Delta E = E_{\text{kin}} + E_{\text{bind}}$. The difference in the energies for RR transitions into a vacant shell of a bare or H-like ion is equal to the difference in the associated ionization potentials of the respective H- and He-like ions created in the collision. This directly provides the two-electron contribution to the ground state energy of He-like ions. The different energies of these photon transitions will be measured for bare and H-like $U^{92+,91+}$ beams in the ESR cooler region with an intended accuracy of below 5 eV. Since 2-electron QED effects are calculated to contribute 7eV such an experiment would provide the first test of higher order QED corrections for high-Z ions.

The experiment will be conducted in the electron cooler region of the ESR storage ring and is taking advantage of the deceleration technique where the beam energy of the bare and H-like U ion is taken from 400 MeV/u - where bare and H-like ions can be produced very efficiently - to 43.5 MeV/u. At such low collision energies bremsstrahlung intensity is much attenuated and Doppler corrections are strongly reduced. A preliminary analysis for a test run determined the splitting with an accuracy of 9 eV; this is to be compared with a QED contribution of 7 eV to a total 2-electron contribution of 2.2 keV. As a next step we plan a production run with the same collision system to achieve an experimental accuracy of below 5 eV

3. He-double ionization via electron impact: (e,3e) spectroscopy

A. Knapp, L. Schmidt, R. Dörner, O. Jagutzki, H. Schmidt-Böcking(IKF, Frankfurt), S. Hagmann(KSU and IKF, Frankfurt)

The COLTRIMS technique has established itself as an immensely powerful technique to study the dynamics of atomic and molecular collision processes, as it provides in a natural way reconstruction of vector momenta of all collision partners involved in a collision. We have undertaken to construct a COLTRIMS type spectrometer which will allow us to measure kinematically complete 5-fold differential ionization cross sections for double ionization of He under electron impact. Scattered electrons which have ionized the target are energy analyzed following the target zone using a 127° electrostatic analyzer equipped with a 2D position sensitive electron detector while the direct beam not having suffered an energy loss will leave the spectrometer through a slit in the outer

section of the 127^0 spectrometer. An electric extraction field in the target zone perpendicular to the primary electron beam guides slow ionized electrons with an energy of up to 10 eV with a 4π solid angle onto a large 2D position sensitive delay line detector. The same electric field will guide recoiling He ions from the target zone onto another 2D position sensitive detector with a momentum resolution of 0.53 a.u./mm. Flight-time and detection location on the respective detectors provides the charge state and the momentum of the particles. For double ionization of He the momentum of the fast ionized electron- if not detected - can be reconstructed via momentum and energy conservation. At present the ion- and electro-optical properties of the entire spectrometer are mapped. First experiments will focus on single ionization of He, followed by studies of double ionization for low collision energies, where the projectile electron's energy loss is significant. Here discrepancies with theory are large. The coincidence rates are estimated to be a factor of 100 higher than in traditional configurations. This is the Ph.D. project of A. Knapp

4. An electrostatic toroidal electron energy analyzer for delta electrons excited in collisions of heavy ions up to relativistic collision velocities

S. Dreuil, G. Kraft(GSI, Darmstadt) S. Hagmann(KSU and IKF, Frankfurt), H. Rothard(CIRIL, Caen)

In radiotherapy with relativistic heavy ions the success in cell deactivation and thus an effective treatment is largely based on understanding the details of the mechanism of energy deposition in the intracellular medium leading to double strand breaks of DNA. For relativistic ion beams the energy deposition in a cellular environment is dominated by creating free electrons from the ionization of molecules; these electrons in turn will ionize other molecules and thus produce a high concentration of chemically active radicals.

The biological effective dose optimization, at the core of inverse treatment planning¹ codes, thus depends – as a key part of it – on the electron emission pattern observed for swift heavy ions passing through dense matter. Such electron emission cross sections differ depending on the proximity to the primary track. For regions more distant from the primary projectile track model calculations appear to be in sufficient agreement with experiment. However, a serious lack of precise data is found to exist for electron emission for the inner track ($< 10^{-7}$ cm). Here a large number of biologically active electrons with energies $E < 100$ eV is created but important details are not known. The extrapolation of data from gas targets is not adequate because density effects on production and transport are not of any importance as in solids. Our goal is a systematic measurement of doubly differential cross sections DDCS for electron emission and of electron transport for a variety of condensed matter targets, emphasizing variations in solid state density and electron density to assess their respective influence on creation and transport of continuum electrons. Two additional Ph.D. students are expected to join this project later this fall.

1. W. K. Weyrather *et al.*, Int. J. of Radiation Biology 75(1999) 1357

5. Laser Spectroscopy of Hyperfine Transitions in very heavy H- and Li-like ions in the ESR

Th. Kühl, W. Nörtershäuser, A. Dax, M. Tomaselli, R. Sanchez , (GSI-Darmstadt), S. Hagmann(KSU and IKF, Univ. Frankfurt), Th. Stöhlker(IKF, Univ. Frankfurt)

The simplest and most basic magnetic interaction in atomic physics is the hyperfine splitting of the 1s ground state of a one-electron ion or atom. For very heavy ions, around Pb and Bi, QED effects - which amount to just 10^{-6} for protons - rise to several percent; theory thus can be subject to very sensitive tests in this region. Recently discrepancies have been found¹ between high-resolution optical spectroscopy of hyperfine transitions and calculated wavelengths, for $^{207}\text{Pb}^{81+}$ and $^{209}\text{Bi}^{82+}$. In the case of lead, optical spectroscopy in the infrared range on 200 MeV/u $^{207}\text{Pb}^{81+}$ was performed. Of two rotating bunches of ions in the ESR ring the ions in one bunch were excited by a frequency doubled Nd:YAG laser. While ions were excited in one of the straight sections, fluorescence light detection occurred in the other in an array of mirrors equipped with 3 photomultipliers. Fluorescence detection was synchronized with the bunches: light from one bunch was beam related background, while light from the other also contained the signal. Wavelength tuning was affected by changing the electron coolers acceleration voltage, thus changing the beam velocity. The resulting wavelength for the M1 hyperfine transition was found to be 1019.7 nm, i.e. a disagreement of 4.5 nm with respect to theory. In order to address questions with respect to a possible nuclear origin of the observed discrepancy we plan to improve the experimental setup by increasing the light detection efficiency in a new design of the fluorescence detection assembly and then measure Li-like 2s and H-like 1s hyperfine transitions for $^{209}\text{Bi}^{82+}$.

1. P. Seelig *et al.*, Phys. Rev. Lett **81**, 4824 (1998).