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The dynamcis of target ionization by fast highly charged projectiles

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Abstract
We report on the first kinematically complete investigation of single target ionization by fast heavy ions, on the measurement of all low energy electrons down to zero emission velocities and on the determination of the projectile energy loss on the level of $\Delta E_p/E_p \approx 10^{-7}$. *This has been achieved by combining a high-resolution recoil-ion momentum spectrometer with a novel* 4π *electron analyzer. The complete momentum balance between electron, recoil-ion and projectile for single ionization of helium by 3.6MeV/u* Ni^{24+} *was explored. Low energy electrons are found to be ejected mainly into the forward direction with a most likely longitudinal energy of only 2 eV. The electron momentum is not balanced, as might be expected, by the projectile momentum but is nearly completely compensated by the recoil ion. Surprisingly, the momenta of the helium-atom "fragments", the electron and the* He^{1+} *recoil ion, are considerably larger than the total momentum loss of the projectile: the target atom seems to dissociate in the strong, longranging projectile potential. The collision has to be considered as a real three body interaction.*

In spite of the importance of target ionization concerning energy loss and straggling of fast heavy ions in matter our understanding of the full dynamics of an ionizing ion atom encounter is still not yet complete. The momentum transfer between the projectile and all participating particles, namely the recoiling target-ion and the emitted electrons, reveals important information about the dynamics of the ionization process. The detailed understanding of the macroscopic effects resulting from ion-matter interactions like ion-tracks in solids, demage of biological tissue, heating of plasmas, requires the reliable and quantitative knowledge on the facets of energy and momentum transfer in one single collision. The measurement of the full kinematics yields highly-differential cross-sections and is therefore a stringent test of available theoretical models.

Theoretically, considerable progress has been achieved within the last decade in the description of the ionization collision dynamics of both simple and complicated systems. In multiple ionization events induced by fast heavy-ion impact electrons were predicted to be ejected collectively [1], opposite to the recoil-ion into forward direction and onto the side of the incoming projectile [2]. The recoil-ion was found to compensate the electron (sum) momentum in distant collisions, being scattered backwards with a transverse momentum exceeding that of the projectile. According to the calculations the projectile is deflected to the recoil-ion side (negative deflection angle) for a major part of the ionizing collisions.

Experimental studies of target ionization by energetic heavy-ion impact have been mainly restricted to total cross section measurements and to studies differential in the momentum of only one of the outgoing particles. Only few coincidence studies have been reported so far [3,4] and therefore most of the above stated theoretical predictions could not yet be proven in detail. Experimentally this is an extremely challenging task since a

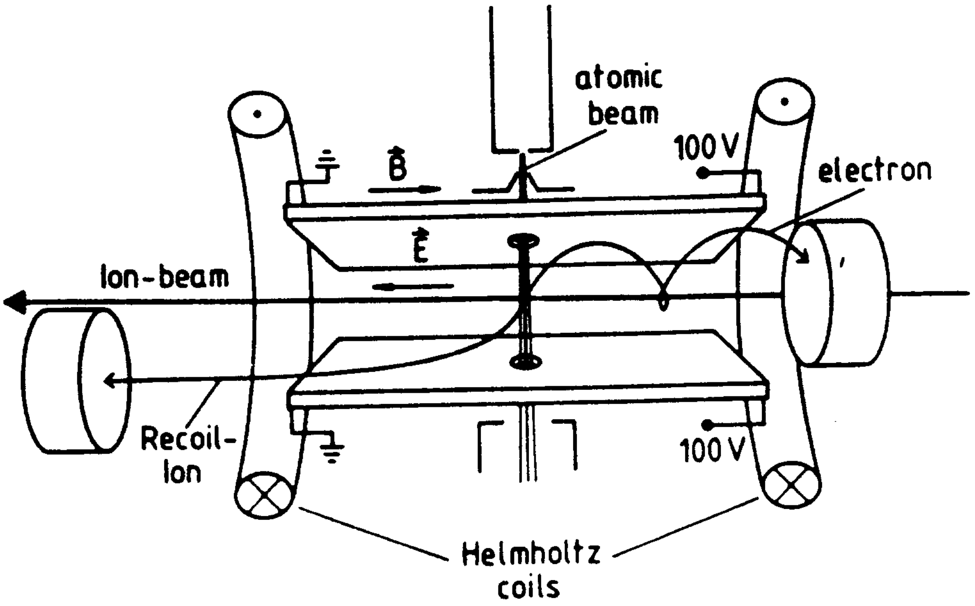

Figure 1: *Schematic drawing of the combined recoil-ion electron spectrometer*

considerable fraction of the electrons are emitted with energies below 50 eV and the recoiling target-ions of interest have energies in the sub-meV regime. Only recently efficient recoil-ion detection techniques, based on ultra-cold supersonic jet-targets (COLTRIMS), have been developed which are sensitive on such small energy transfers [5,8]. Efficient methods for the detection of low-energy electrons have been missing for electron energies below 5 eV. Thus the coincident high-resolution spectroscopy of the electron and the recoiling target-ion, which is the only way to prove in detail the theoretical predictions, was beyond the experimental capabilities.

In this contribution we report on the first kinematically complete experimental investigation of single target ionization by fast heavy-ion impact [7], on the measurement of low-energy electrons including those with zero emission velocities and on the determination of the projectile energy loss on the level of $\Delta E_P/E_P \approx 10^{-7}$. Furthermore, projectile scattering angles with an uncertainty of less than $\Delta\vartheta_P < 5 \cdot 10^{-7}$ rad became accessible. This has been achieved by combining a high resolution recoil-ion momentum spectrometer with a novel 4π electron analyzer (fig.1). Using a ultracold supersonic jet-target of sub-Kelvin temperature the momentum transfer to the recoiling target-ion and to the emitted electron can be determined simultaneously with a solid angle of 4π and a momentum resolution of $\Delta p \approx \pm 0.1$ a.u. (atomic units). This corresponds to an uncertainty of a recoil-ion energy measurement of $\Delta E_R \approx \pm 15\mu$eV (see Refs. 1-3). The atomic beam from the gas jet is crossed with a well collimated beam of 3.6 MeV/u Ni^{24+} ions. The projectiles were charge state analyzed after the collision and Ni^{24+} ions (no charge exchange) were recorded by a fast scintillation counter.

The recoiling target-ions and the electrons are extracted into opposite directions from the point like reaction zone by a uniform electric field of 4.55 V/cm. An additional parallel magnetic field of 12 Gauss generated by two Helmholtz coils forces the electrons on cyclotron trajectories and guaranties a high efficiency for the electron detection. Electrons emerging from the collision with $E_e < 50$ eV are all ($\Delta\Omega_e = 4\pi$) collected by the electron

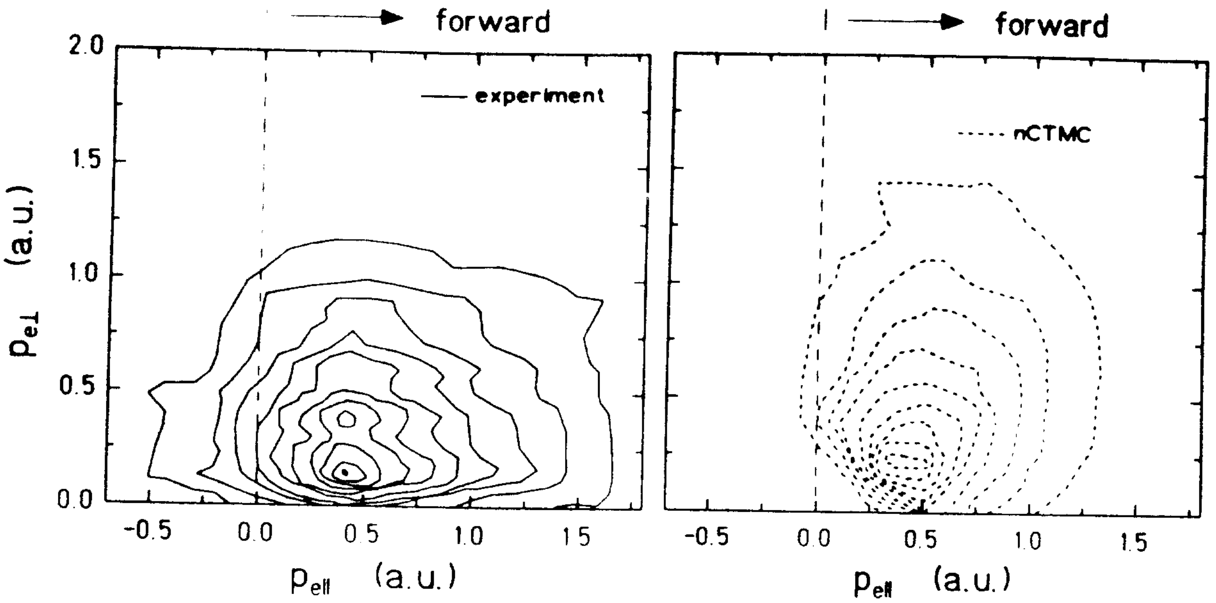

Figure 2: *Doubly differential cross section $d\sigma/dp_{\parallel}dp_{\perp}$ for the emission of soft electrons in helium single ionization by 3.6 MeV/u Ni^{24+}*

detector. By means of time of flight and position measurements using two dimensional position sensitive (2D PS) detectors the complete initial momentum of the recoiling target-ion and of the emitted electron can be deduced in coincidence (for details see [12]).

Our new technique for low energy electron detection removes many of the tremendeous experimental difficulties of conventional spectrometers. First, the target extension is well defined by the supersonic jet [6]. Second, electrons from the restgas are completely suppressed in the triple coincidence spectra. Third, as for the recoil-ions, the influence of electric fringe fields and magnetic distortions is drastically reduced by extracting the electrons. The energy resolution is good and the complete emission characteristics is measured with the full solid angle of 4π (fig.2). Furthermore, due to the simultaneous recoil-ion detection, the final target charge state is defined. We emphasize, that the energy acceptance and the resolution can be significantly and easily enhanced in the future by elongation of the electron drift path, the use of time-focussing geometry in the direction of extraction and implementation of large active-diameter 2D PS electron detectors. For the investigation of multiple ionization, multihit 2D PS counters will be implemented.

The longitudinal sum-momentum resolution of the recoil-ion and the electron is controlled experimentally. For singly ionizing collisions with small momentum and energy transfers (both are perfectly fulfilled in this experiment) it follows from momentum and energy conservation for the longitudinal momentum balance (all in atomic units):

$$-\Delta p_{p\parallel} = p_{R\parallel} + p_{e\parallel} = (Q + E_e)/v_p = \Delta E_p/v_p \tag{1}$$

or

$$p_{R\parallel} + p_{e\parallel} - E_e/v_p = Q/v_p \tag{2}$$

where ΔE_P is the total energy loss of the projectile. It is the sum of the He(1s) binding energy (Q=0.903 a.u.) and the continuum energy E_e of the emitted electron (typically

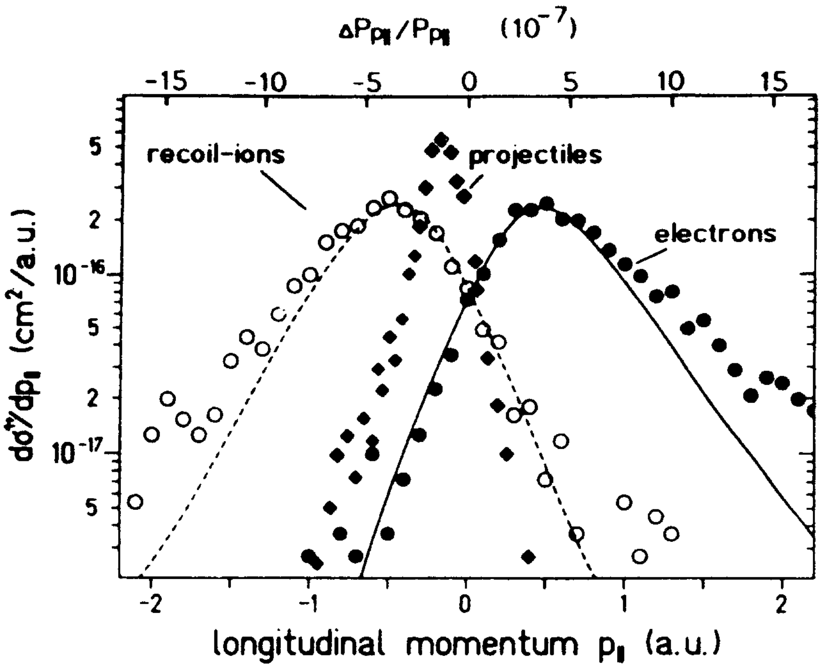

Figure 3: *Longitudinal momentum distributions of low-energy electrons (full circles) and recoil-ions (open circles) for single ionization of helium in collisions with 3.6 MeV/u* Ni^{24+}. *Full diamonds: longitudinal momentum change of the projectile* $\Delta p_{P\parallel}$ *(relative to its initial momentum on the upper scale). Full and dashed lines: results of nCTMC calculations multiplied by a factor of 1.6.*

about 1 a.u.). v_P is the incoming projectile velocity of 12 a.u. Since the longitudinal momenta of the recoil-ion and the electron as well as the electron continuum energy is measured in each single event the left hand side of eq. 2 is determined experimentally and should result in a sharp peak with its position defined by the He(1s) binding energy and the projectile velocity. A combined resolution of $(\Delta p_{R\parallel}^2 + \Delta p_{e\parallel}^2)^{1/2} = \pm 0.11$ a.u. was reached, which corresponds to a sensitivity in the projectile momentum change of $\Delta p_{P\parallel}/p_{P\parallel} = \pm 1.7 \cdot 10^{-7}$. Estimating for the electrons $\Delta p_{e\parallel} = \pm 0.1 a.u.$ (equivalent to $\Delta E_{e\parallel} = \pm 130$ meV) due to the finite time resolution and the target extension a resolution of $\Delta p_{R\parallel} = \pm 0.08$ a.u. was obtained for the recoil-ions, the best value ever reported. The transverse resolution is $\Delta p_{R\perp} < \pm 0.25$ a.u. and is caused by the size of the ion-beam - target-beam overlap of $1 \times 1 \mathrm{mm}^2$ defined by the collimation of the ion-beam. The electron energy uncertainty in transverse direction is $\Delta E_{e\perp} \leq 400$ meV for energies up to 50 eV.

In fig.3 all longitudinal momentum components for single ionization of helium by 3.6 MeV/u Ni^{24+} impact are shown. Low energy electrons are found to be ejected mainly into forward direction (the direction of the emerging beam) with a most likely longitudinal energy of only 3 eV. The longitudinal electron momentum is not balanced, as might be expected in a two-body collision, by the projectile momentum. The recoiling target-ion is pushed into backward direction with a most probable energy of $E_{R\parallel} = 450 \mu$eV and compensates mainly the electron longitudinal momentum, except of a small contribution from the inelasticity of the reaction (right hand side of eq.1 and $\Delta p_{P\parallel}$ in fig.3). The three-body momentum balance is correctly predicted by n-body classical trajectory Monte-Carlo (nCTMC) calculations. Performing the nCTMC calculation with a reversed projectile charge of $\overline{Ni}^{24-}$ results in a also reversed emission direction for the electrons and the

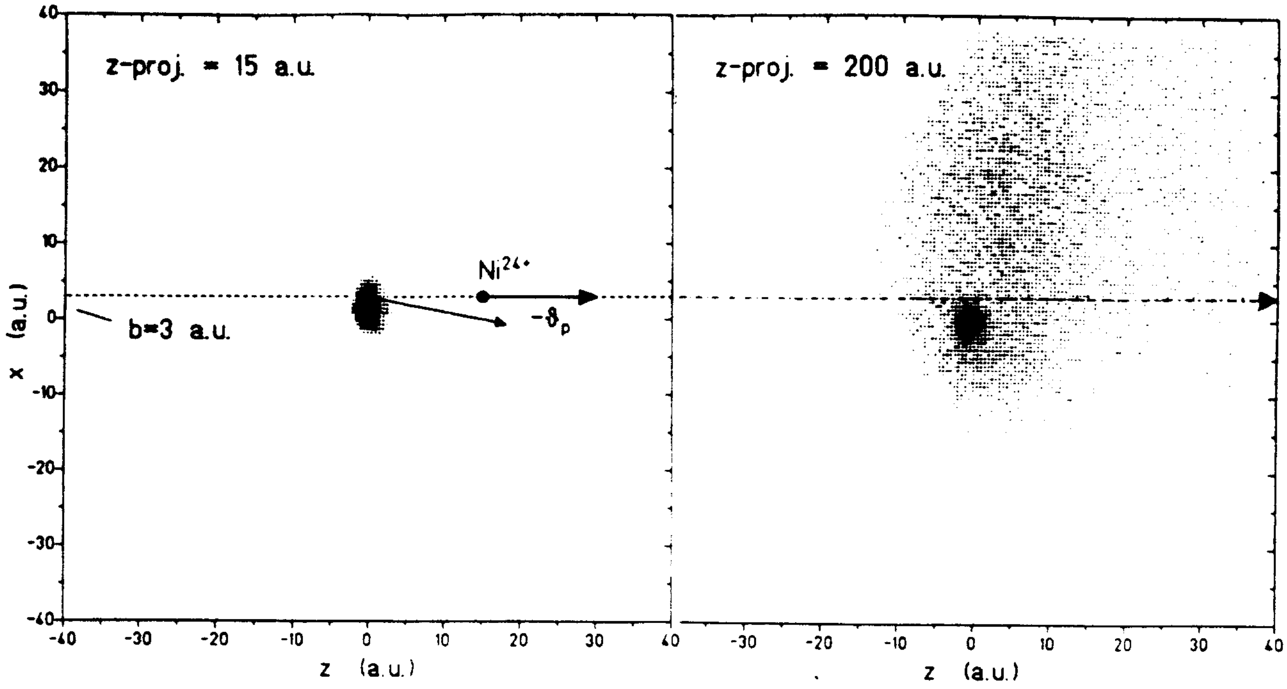

Figure 4: *Snapshots extracted from a nCTMC calculation to illustrate the time evolution of the spatial electron distribution. Although the calculation is purely classical it demonstrates the dynamics of an ionizing ion-atom collision.*

recoil-ions. The helium atom seems to dissociate in the strong and long ranging projectile potential. The emission characteristics of the electrons and the recoil-ions reflects the strength and the sign of the emerging projectile potential. These findings show that target single ionization by fast highly charged ions has to be considered as a real three-body interaction.

The transverse momentum balance reflects the deflection function of the projectile as well as the dynamic screening due to polarized target electrons. For single ionization by 3.6 MeV Ni^{24+} the impact-parameters are predicted to be large compared to the spatial extension of the target atom, the projectile does not penetrate the target electron cloud. In fig.4 two snapshots (corresponding to different positions of the emerging projectile) generated with a nCTMC-calculation illustrates the dynamic process of target ionization. The passing projectile interacts with the electrons considerably and even at large distances between target and projectile there is a considerable influence due to the strong potential of the projectile. If the leaving heavy ion is already 200 a.u. away the potential energy of the released electrons is still determined not by the singly charged target ion but by the projectile. The calculation predicts electrons to be emitted onto the side of the projectile and the recoil-ion into the opposite direction. A prediction we could now prove experimentally for the first time (see fig.5). The transverse electron momentum is roughly compensated by the recoil-ion and the momentum transfer to the projectile is comparably small. A situation quite similar than in longitudinal direction, which demonstrates again the 3-body dynamics of the collision. Moreover it justifies $|\vec{p_R}| \approx |\vec{p_e}| > |\Delta\vec{p_P}|$ and shows that the measurement of just the recoil-ion momentum already provides detailed information on the sum-momentum of several electrons emitted in a multiple ionization event. In many cases, depending on the impact parameter, the projectile is deflected to

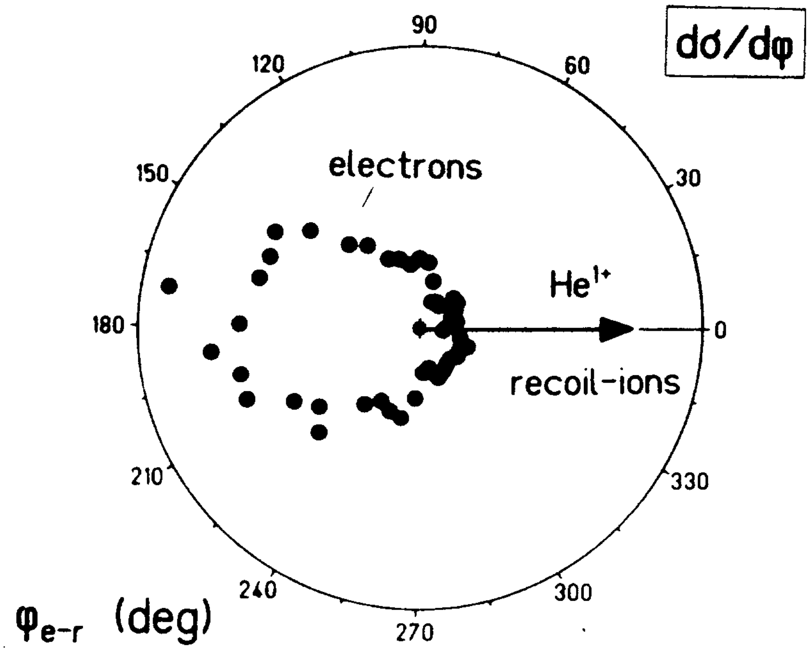

Figure 5: *Experimental result for the angular correlation between the electron and the recoil-ion in the azimuthal plane perpendicular to the initial projectile direction, where φ is the angle between the transverse momentum vector of electron and recoil-ion.*

negative scattering angles (onto the same side as the recoil-ion) which might result in rainbow scattering. In spite of the excellent resolution of $\Delta\vartheta_P < 5 \cdot 10^{-7}$ for the projectile scattering angle we are not yet sensitive enough to prove this theoretical prediction.

The combination of a high resolution recoil-ion momentum spectrometer with a full solid angle electron analyzer shows itself to be a tremendeous step towards kinematically complete experiments of many-particle atomic reactions. For fast heavy ion collisions this concept is the only possible to investigate the full dynamics of energetic ion atom encounters, since even the best accelerators can not deliver beams with a relative momentum spread of better than $10^{-5}...10^{-6}$ and conventional energy loss (gain) spectroscopy must fail. Considering the single capture of an electron the measurement of the recoil-ion only represents already a complete experiment [9] and the longitudinal recoil momentum reflects the inelasticity or the Q-value of the reaction (eq.1). Thus, with the present setup electronic binding energies are detectable with a FWHM of $0.22 \cdot v_P$. This corresponds to an energy resolution of 72 eV for the collision system discussed above. This result together with recent experiments using recoil-ion momentum spectroscopy to study state selective capture into 1.0 MeV He^{2+} [10] and 1.8 MeV/u O^{8+} [11] impressively demonstrates that energy resolutions about a factor of 10 better than the best results obtained with solid-state x-ray detectors are possible. Spectroscopy of very heavy few-electron ions (U^{91+}, Pb^{81+}, etc), which are available at the ESR with energies as low as 10 MeV/u, can be envisaged in the near future. The additional implementation of x-ray detectors with large solid angles is easily possible with our present setup and kinematically complete experiments of even more sophisticated atomic reactions like REC (radiative electron capture) and RTE (resonant transfer and excitation) are further perspectives for future applications.

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