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Ionization collision dynamics in 3.6 MeV/u Ni^{24+} on He encounters

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Abstract

The momentum balance between all emerging particles (electron, recoil ion and projectile) was explored for single ionization of helium by 3.6 MeV/u Ni^{24+} impact in a kinematically complete experiment. Technically this was achieved by integrating a novel 4π low-energy electron analyzer into a high-resolution cold-target recoil-ion momentum spectrometer. More than 90% of the "soft electrons" (0 eV $\leq E_e \leq 50$ eV) are ejected in forward direction with a most probable longitudinal energy (along the ion-beam) of $\bar{E}_{e\parallel} \approx 3$ eV. Not the projectile, but the backwards ejected recoil-ion ($\bar{E}_{R\parallel} \approx 0.4$ meV) compensates the electron longitudinal momentum except of a small contribution from the inelasticity of the reaction. Energy losses of the 0.2 GeV projectiles as small as $\Delta E_P/E_P = 3.4 \times 10^{-7}$, transverse momentum balances, as well as electron energy and angular distributions for defined final recoil-ion charge state become accessible with this technique.

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1. Introduction

Single and multiple target ionization reactions are the most likely processes in fast ion–atom collisions with large cross sections and are therefore of considerable practical interest: They decisively contribute to the total energy loss of energetic ions traversing gases, plasmas, solids or biological tissue. The detailed understanding of the macroscopic effects resulting from ion–matter interactions like ion-traces in solids, damage of DNA, heating of plasmas, in essense requires the reliable and quantitative knowledge on the facets of energy and momentum transfer in one single collision.

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 [1,2], opposite to the recoil-ion into the forward direction and onto the side of the incoming projectile [3]. 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 scattering angles") for a major part of the ionizing collisions [4].

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 one of the outgoing particles (one electron (see, for example, Ref. [5]), the recoiling target ion [4] or the projectile at low energies [6]). Only few coincidence studies have been reported so far [7–9] and therefore most of the above theoretical predictions cannot yet be proven in detail. Experimentally, this is an extremely challenging task since a considerable fraction of the electrons is 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 ("cold-target recoil-ion momentum spectroscopy": COLTRIMS [10]), have been developed which are sensitive on such small energy transfers. Efficient methods for the detection of low-energy electrons have been missing for electron energies below 5 eV [11]. Thus, the coincident high-resolution spectroscopy of electrons and the recoil-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, on the measurement of low-energy electrons including those with zero emission

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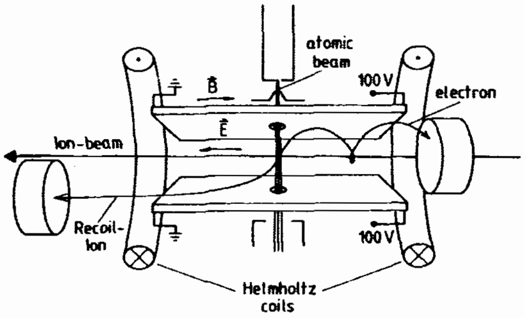

Fig. 1. Schematic drawing of the combined recoil-ion electron spectrometer.

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 (see Fig. 1). In the following sections details of the apparatus will be presented along with first results on the three-body longitudinal momentum balance in an ionizing collision. Finally, the future perspectives of the technique will be discussed.

2. Experimental setup and resolution

The experiments were performed using a 3.6 MeV/u stripped and charge state analyzed Ni^{24+} beam from the UNILAC of GSI. The beam was collimated to a size of about 1 mm × 1 mm in the target region, charge state analyzed after the collision and Ni^{24+} ions (no charge exchange) were recorded by a fast scintillation detector at a rate of up to 1 MHz.

A single stage supersonic jet (see Fig. 1) provided a well localized helium target of 3 mm diameter and a density of about 2×10^{11} atoms/cm^2 at the intersection point with the ion-beam. In order to improve the resolution the nozzle was mounted on top of the coldfinger of a cryopump and was cooled to about $T_0 = 30$ K. In this configuration (COLTRIMS [10]) the momentum of the helium atoms in the direction of the expansion is reduced to $p_{\mathrm{Jet}} = 1.86$ a.u. ($p_{\mathrm{Jet}} = (5kT_0M_T)^{1/2}$; k is the Boltzmann constant and M_T the target mass). A longitudinal temperature (along the jet-expansion and transverse to the ion beam) of 10 mK (speed ratio: $S \approx 250$) and a transverse temperature of 200 mK is expected. This would result in a recoil-ion momentum resolution along the ion-beam (transverse to the jet) of $\Delta p_{R\parallel} \approx \pm 0.05$ a.u. ($\Delta E_{R\parallel} \approx \pm 5$ μeV).

Recoil ions created at the ion-beam jet intersection were extracted by a uniform electric field of 4.55 V/cm provided over 22 cm along the beam (total voltage applied: $V_T = +100$ V; potential at the intersection point: $V_I = 50$ V). After 11 cm of acceleration, the recoil-ions drift over 22 cm to be focussed in time. They are postaccelerated ($V_a \approx -2000$ V over 2 mm) and detected by a two-dimensional position sensitive (2D PS) channel-plate detector of 40 mm active diameter mounted directly beneath the straight path of the projectile beam. The He^{1+} time-of-flight (TOF) in the entire apparatus was about 8 μs and is measured by an electron–recoil-ion–projectile coincidence. The TOF provides the recoil-ion charge state and longitudinal momentum $p_{R\parallel}$, the position on the detector gives the transverse momentum $p_{R\perp}$ and the azimuthal emission angle.

Electrons emerging from the collision with $E_{e\parallel} \leq 50$ eV are all ($\Delta\Omega_e = 4\pi$) accelerated into the opposite direction. They hit another 2D PS microchannel plate mounted at about the end of the acceleration field (12 cm flight path). The electrons are postaccelerated ($V_a \approx +200$ V over 2 mm) to guarantee optimum and energy-independent detection efficiency. The total TOF is about 50 ns for $V_{e\parallel} = 0$ (time resolution $\Delta t \approx 1$ ns). In addition to the electric field a nearly parallel solenoidal magnetic field of 12 G is generated by two Helmholtz coils forcing electrons of non-zero transverse energies to spiral trajectories. The electron longitudinal momentum is obtained from the TOF, the position gives the transverse momentum along with the azimuthal emission angle.

In order to illustrate the operation of the electron spectrometer the radial deflection of each electron (its distance from the zero position for $p_{e\perp} = 0$) is plotted versus the electron TOF in Fig. 2. At specific TOFs all electrons are observed at the origin independent of their transverse momentum. These flight-times are integer multiples of the electron cyclotron frequency ($1/t_c$) in the 12 G magnetic field. Central between the focus-points electrons are at the maximum radial distance away from their origin with the magnitude of the deflection (two times the radius of the cyclotron spiral trajectory) being proportional to their transverse momentum. Here, the optimum trans-

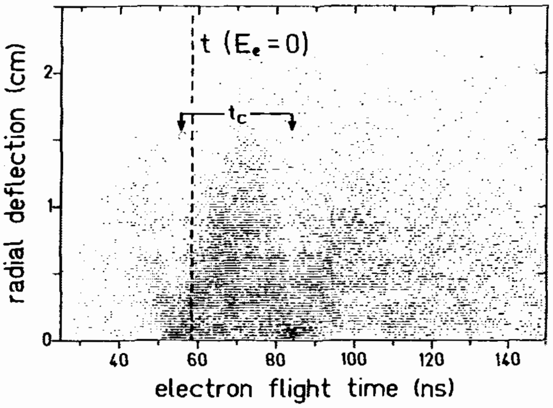

Fig. 2. Radial deflection of the electrons (distance from the zero position for $p_{e\perp} = 0$) versus the electron time-of-flight. t_c denotes the electron cyclotron frequency in the 12 G magnetic field.

verse momentum and emission angle resolution is obtained. In this experiment we have chosen the electric and magnetic fields in such a way that more than 90% of all electrons hit the detector inbetween two focus-points guaranteeing a reasonable transverse energy resolution of $\Delta E_{e\perp} \lesssim 400$ meV for all of these electrons. The resolution in the longitudinal direction of $\Delta p_{e\|} \approx 0.1$ a.u. is limited by the finite electron time-resolution ($\Delta t_{el} \approx 1$ ns) and the target extension of 3 mm.

Our new technique for low-energy electron detection removes many of the tremendous experimental difficulties of conventional spectrometers. First, the target extension is well defined by the supersonic jet [11]. Second, electrons from rest gas ionization 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 nearly independent of the solid angle. Moreover, due to the simultaneous recoil-ion detection, the coincident final target charge state is measured, the longitudinal momentum resolution is precisely controlled and the spectra are free of background on the level of 10^{-4}. We emphasize that the resolution and the energy acceptance of such a soft-electron spectrometer can be significantly and easily enhanced in the future by elongation of the electron flight-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 for the recoil-ion and the electron is controlled experimentally: For collisions with small energy and momentum transfer (both are perfectly fulfilled in this experiment on the level below 10^{-7}) it follows from momentum and energy conservation for the longitudinal momentum balance (all in atomic units):

$$p_{R\|} = Q/V_p - p_{e\|}$$

$$= \left(E_e - E_e^{\text{bind}}\right)/V_p - p_{e\|} \qquad (1)$$

or

$$p_{R\|} + p_{e\|} - E_e/V_p = -E_e^{\text{bind}}/V_p \qquad (2)$$

where Q is the total energy loss of the projectile. It is the sum of the He(1s^2) binding energy $E_e^{\text{bind}} = -0.903$ a.u. and the continuum energy of the emitted electron E_e (typically 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^2) binding energy E_e^{bind} and the projectile velocity V_p to be at +0.075 a.u. This peak is shown in Fig. 3 and a FWHM for $(\Delta p_{e\|}^2 + \Delta p_{R\|}^2)^{1/2} = \pm 0.11$ a.u. was observed with a cooled expansion nozzle. Knowing $\Delta p_{e\|}$ (see preceding paragraphs) $\Delta p_{R\|}$ is obtained to be $\Delta p_{R\|} = \pm 0.08$ a.u. ($\Delta E_{R\|} = \pm 12$ μeV), the best value ever reported. The transverse resolution is about $\Delta p_{R\perp} \lesssim \pm 0.25$ a.u. and is caused by the size of the ion-beam–target-beam overlap of 1×1 mm^2 defined by collimation of the ion beam.

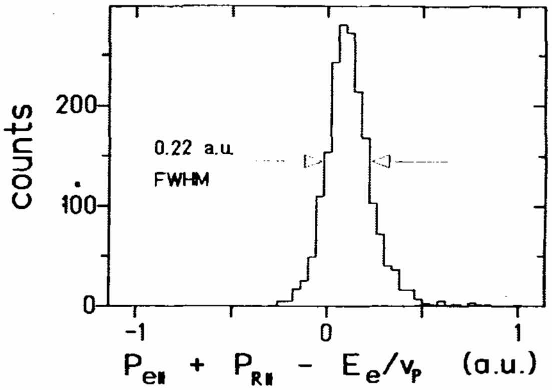

Fig. 3. Test of the longitudinal sum-momentum resolution of the combined spectrometer (see text). Plotted is $p_{R\|} + p_{e\|} - E_e / V_p$ which should give a sharp line at $-E_e^{\text{bind}} / V_p = 0.075$ a.u..

3. The three-body longitudinal momentum balance

In Fig. 4 all longitudinal momentum components for helium single ionization by 3.6 MeV/u Ni^{24+} impact are shown. Low-energy electrons (full circles) are found to be ejected mainly into the forward direction (the direction of

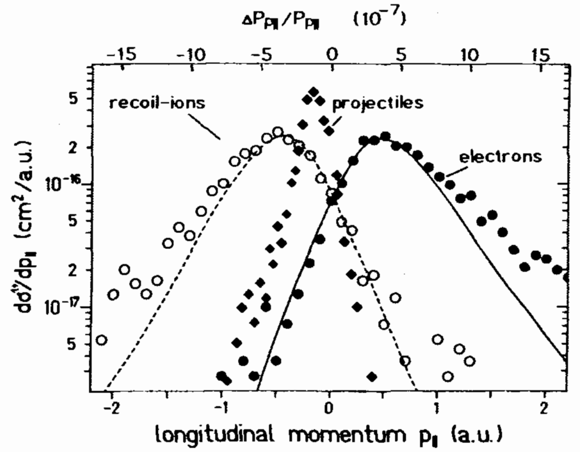

Fig. 4. Longitudinal momentum distribution $d\sigma^{1+}/dp_\|$ of low-energy electrons (full circles) and recoil-ions (open circles) for single ionization of helium in collisions with 3.6 MeV/u Ni^{24+}. Full diamonds: longitudinal momentum change of the projectile $\Delta p_{p\|}$ (relative to its incoming momentum p_p on the upper scale). Full and dashed lines: results of nCTMC calculations multiplied by a factor of 1.6.

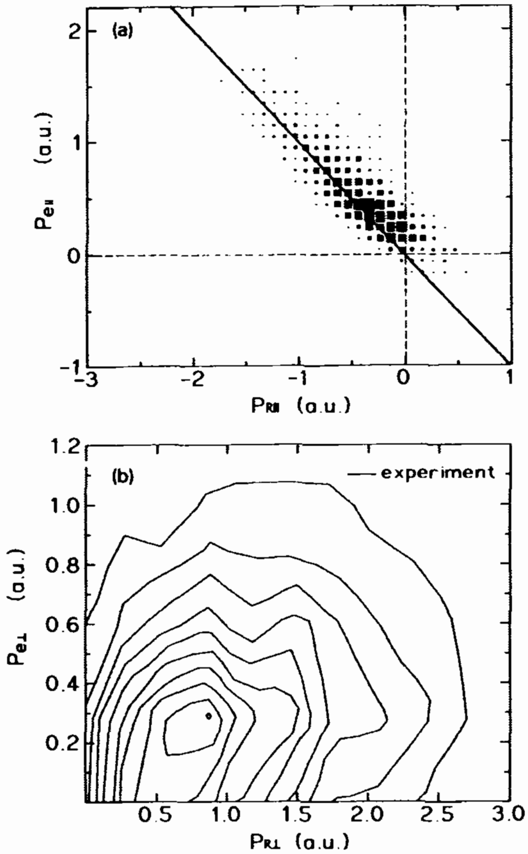

Fig. 5. Correlation between the recoil-ion and electron longitudinal (a) and transverse (b) momenta.

the emerging beam) with a most likely longitudinal energy of only 3 eV ($p_{e\|} \approx 0.4$ a.u) and a sharp decrease towards higher energies. This longitudinal electron momentum is not balanced, as might be expected, by the projectile momentum (full diamonds), but is nearly completely compensated by the recoil-ion (open circles): they are emitted backwards with a most probable energy of 450 μeV. The three-body longitudinal momentum balance is correctly predicted by *n*-body classical trajectory Monte Carlo (*n*CTMC) calculations (full and dashed lines). Since the theoretical total single ionization cross section is lower than the experimental one by a factor of 1.6 the nCTMC cross sections in Fig. 4 have been multiplied by this factor to enable a better comparison.

Plotting $p_{e\|}$ versus $p_{R\|}$ (Fig. 5(a)) shows that both momenta are strictly correlated within the experimental resolution of 0.22 a.u. A similar tendency is found in the transverse direction (Fig. 5(b)) but is less significant. Electrons and recoil-ions are preferentially emitted into opposite directions. Due to the reduced transverse resolution of about 0.5 a.u. no conclusive results on the projectile deflection can be extracted from the present data. This question was addressed in a separate experiment for 5.9 MeV/u U^{65+} on Ne collisions with improved transverse resolution and the recoil-ion extraction in the transverse direction. For this collision system negative deflection angles have been theoretically predicted for a major part of all ionizing collisions [4].

Surprisingly, the longitudinal momenta of the helium-atom "fragments", namely of the electron and the He^{1+} recoil-ion, are considerably larger than the net-momentum transfer to the target atom by the projectile (full diamonds in Fig. 4): the atom seems to "dissociate" in the strong, long-range projectile potential. The longitudinal momentum change of the projectile $\Delta p_P = -(p_{R\|} + p_{e\|})$ results from the total inelasticity of the reaction $\Delta p_P = -Q/V_p = -(E_e - E_e^{bind})/V_p$. It should display a sharp onset at $E_e^{bind}/V_p = -0.075$ a.u. and a smooth falloff towards larger momentum losses according to the continuum electron energy distribution. In spite of the excellent resolution obtained in this first experiment of $\Delta p_{P\|}/p_P = 1.7 \times 10^{-7}$, this behaviour is not yet clearly visible in the projectile momentum loss spectrum in Fig. 4 even if the slope on the left hand side is obviously less pronounced than that on the right side.

4. Conclusions and future perspectives

In conclusion, we have performed the first kinematically complete experiment on single ionization by heavy-ion impact using advanced technical concepts. The main findings of our work are the distinct forward emission of the soft electrons, the nearly complete compensation of the electron longitudinal momentum by the recoil-ion and the comparably small momentum change of the projectile. The longitudinal momenta of the emitted electron and the recoil-ion were found to be strictly correlated within the experimental resolution and a similar behaviour is seen in the transverse direction ($p_{R\|,\perp} \approx p_{e\|,\perp}$). Thus, 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 at large projectile velocities.

It was demonstrated that COLTRIMS can be combined with a new type low-energy electron spectrometer with so far unachieved specifications and future potential: electrons with energies below 50 eV, including for the first time those with $E_e = 0$, are detected with a 4π solid angle and excellent energy resolution. The whole spectrometer is completely open at two sides where in addition photon detectors can be mounted with large solid angles of several percent so that kinematically complete investigations of atomic reactions such as RTE ("resonant transfer and excitation") or REC ("radiative electron capture") and the spectroscopy of electronic states in heavy few-electron ions can be envisaged in the near future.

Finally, we want to emphasize that the coincident, precise and complete measurement of the momenta of both the electron and recoil-ion using advanced ultracold targets provides a realistic experimental approach to determine angular correlations and even the neutrino mass in β-decay experiments [10].

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