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MULTIPLE IONISATION AND COLLECTIVE ELECTRON EMISSION IN MeV/u URANIUM-ION RARE GAS COLLISIONS(1)

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Abstract

The multiple ionisation of Ne and Ar gas targets in collisions with high-energy, highly-charged Uranium projectiles (1.4 MeV/u U^{32+}, 5.9 MeV/u U^{6+}) has been investigated. Applying a recently developed experimental technique, the charge state q as well as the transverse momentum (with respect to the beam axis) p_{T\perp} of the recoiling target ion was measured in coincidence with charge-state analysed projectiles. An accuracy in the determination of p_{T\perp} relative to the momentum of the incoming projectile p_0 in the order of 10^{-6} was obtained which is comparable to laboratory projectile scattering angles \theta in the microradian regime. Thus, the multiple ionisation process and the collision dynamics could be investigated in a very sensitive manner.

The statistics of multiple ionisation for definite momentum transfer to the target nucleus is shown to follow a binomial distribution for the case of a Ne target as expected in the Independent Particle Approximation (IPA). The measured differential (with respect to p_{T\perp}) scattering cross sections were compared with the results of n-body classical trajectory Monte Carlo (nCTMC) calculations, which take into account the correct momenta of all involved particles, including the target electrons. From this joint experimental and theoretical study of the collision dynamics of high-energy heavy-ion atom collisions we conclude, that the target electrons are emitted collectively with a mean high energy (\approx 300 eV) in a cone around 60° with respect to the beam axis as was predicted by theory. The trajectories of the heavy nuclei are influenced considerably by the momenta of these ejected electrons. The strong polarisation of the target atom during the collision is found theoretically to lead to negative deflection angle scattering by the projectile at large impact parameters.

Introduction

It is well established [1-3] that fast, highly charged projectiles can nearly fully ionise rare gas target-atoms with large cross sections in a single encounter. The kinetic energy gained by the recoiling target nucleus within such a collision is only in the order of a few eV, whereas excitation energies of several keV can be transferred to the target electrons.

To enable a detailed investigation of the multiple ionisation process a new experimental technique was developed to determine simultaneously the momentum of the recoiling target atom perpendicular to the beam direction p_{T\perp} and the recoil-ion charge state q [4-6].

From a joint experimental and theoretical study of this multiple ionisation process, it becomes apparent that a considerable amount of transverse momentum is carried away by high-energy target-electrons being emitted collectively into an angular regime between about 40° and 70° with respect

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to the beam axis. This has a strong influence on the transverse momenta and thus on the scattering angles of both outgoing nuclei (Fig. 1). The comparison of experimental data with n-body classical trajectory Monte Carlo calculations (nCTMC) [7] shows, that the angular differential scattering cross sections at very small projectile scattering angles $\phi = p_{\perp 1}/p_0 \leq 10^{-5}$ rad ($p_{\perp 1} = |p_{\perp 1}|$: transverse momentum of the outgoing projectile, $p_0 = |p_0|$: incoming projectile momentum) are strongly perturbed by the electron momenta. This result is of considerable importance for the calculation of angular straggling for MeV/u Uranium beams and therefore for the beam transport in storage rings.

The investigation of multiple target-ionisation using our new technique provides the first direct measurements of transverse recoil-ion energy-distributions $E_{RI} = (p_{RI})^2/2M_e$ in the high projectile-velocity regime and establishes the earlier estimates that even highly charged recoil-ions are produced very "cold", with typical kinetic energies below 1 eV. This result is of particular interest for the design of a proposed "recoil-ion source" as well as for high-resolution x-ray measurements [12]. The experimental data are in good agreement with very recent calculations in the nCTMC approach [7].

Furthermore, the detailed investigation of the statistics of multi-electron processes was another important goal of the reported experiments, since most theories [8, 9] only calculate single ionisation probabilities and then make use of the Independent Particle Approximation (IPA) to obtain multiple ionisation cross sections [10]. From the ratios of recoil ions for different charge states, but at the same transferred momentum $p_{\perp 1}$, the IPA and the resulting binomial statistics could be tested much more accurately then by simply comparing total ionisation cross sections. The extracted experimental single ionisation probabilities are in good agreement with the theoretical results of semiclassical quantumstatistical calculations [11].

**Experimental set-up**

The experiments were performed at the UNILAC accelerator GSI Darmstadt ("Stripperhalle"). As shown in Fig. 2, the charge state analysed Uranium beam (1) is collimated to a beam spot of less than 0.2 mm diameter by three collimators (2). The last one of them is located directly in front of the time-of-flight spectrometer (TOFS) to provide a well defined beam trajectory inside the apparatus (9). Having passed the scattering region in the TOFS, the projectiles were charge state analysed by a magnetic field (11) and detected in a position-sensitive parallel-plate avalanche detector (12).

The gas target pressure inside the innermost cylinder (9) of the TOFS was about $10^{-4}$ Torr and low enough to ensure single collision conditions. The recoil ions produced via collisions drift towards the walls of the inner cylinder with the velocity $v_{RI}$ transferred from the projectile's kinetic energy, and a small fraction of them leaves the target cell through an opening of 1 mm diameter (solid angle in the azimuthal plane $\Delta\phi/2\pi = 3\%$; $\phi$: azimuthal angle). They are then accelerated in an electric field, applied between the two cylinders ($\approx 320$ V/cm), focussed by an einzel lens (8), charge state analysed in the variable field of two permanent magnets (7) and finally detected by a two-dimensional position-sensitive channelplate detector (6).
A coincidence between the delayed signal of the projectiles and the time signal of the recoil ions provides time-of-flight spectra for specific \((n',q)\)-channels \((n': \text{final charge state of the projectiles})\). These have to be corrected for the flight times of the projectiles and the recoil ions in the detection branches of the apparatus to obtain the time-of-flight (TOF), the recoil ions needed to cover the distance \(x\) \((x: \text{radius of the inner cylinder}; \text{for details see [4-6]})\).

After subtraction of background events, the obtained TOF-spectra are transformed into \(n'/n\)-or energy-dependent distributions to compare with theoretical calculations.

**Results**

1. **Statistics of multiple ionisation processes**

Provided that classical statistics are accurate for the description of multiple ionisation processes at large impact parameters of 1 - 5 a.u., the ratio of recoil-ion intensities of different charge states \(q\) at fixed impact parameter \(b\) should only depend on well defined statistical factors and on the single ionisation probability \(P_s(b)\).

For the very distant collisions investigated here, no exact relationship between the impact parameter \(b\) and the experimentally accessible quantities \(\theta\) or \(P_{s\perp}\) exists, since it is dependent on the created recoil-ion charge state \(q\). Furthermore, as will be outlined below, the nCTMC calculations show that the projectile scattering angle as well as the recoil-ion transverse momentum is influenced considerably by the momenta of ejected electrons for \(P_{s\perp}/P_0 \leq 2 \times 10^{-8}\) \((1.4 \text{ MeV/u } U^{2+}\text{ on Ne})\). Therefore no direct experimental verification of classical statistics for the description of multiple ionisation processes in the impact parameter formulation as used by most theories can be obtained.

However, a definite recoil-ion transverse momentum \(P_{s\perp}\) is correlated at least to a certain impact parameter range \(\Delta b\). Thus, binomial statistics (the multinomial statistics reduce to the very simple form of binomial statistics for negligibly small contributions of electron loss or capture channels of the projectile) could be tested quantitatively by evaluating intensity ratios of recoil-ions with different charge state \(q\) at the same transferred momentum \(P_{s\perp}\) \((\text{The relative intensities of detected recoil ions of different }q\text{ but the same }P_{s\perp}\approx\Delta b\text{ should be described by one single number, namely the single ionisation probability }P_s(P_{s\perp})\)).

In Fig. 3 experimental relative charge-state distributions of recoil ions (full circles) are shown for different recoil-ion transverse momenta \(P_{s\perp}\). At small \(P_{s\perp}\), reflecting distant collisions, mainly low charged recoil-ions are produced, whereas the \(q\)-distributions shift continuously to higher
Fig. 3: Experimental relative charge state distributions of recoil ions for different transverse recoil-ion momenta $p_{\perp}$ (full circles) for the collision system 1.4 MeV/u $U^{32+}$ on Ne. Open circles: distributions according binomial statistics calculated from experimental $P_S(p_{\perp})$ (see text). 

charge states with increasing $p_{\perp}$ (decreasing impact parameter). Mean single ionisation probabilities $P_S(p_{\perp})$ were calculated from the ratios of recoil-ions of different charge states $q$ being in good agreement with theoretical results of semiclassical quantumstatistical calculations [11]. To visualise the accuracy of the determination of the experimental $P_S(p_{\perp})$, multiple ionisation probabilities are calculated according to simple binomial statistics based on the experimental $P_S(p_{\perp})$ (open circles in Fig. 3) and compared to the original experimental data. The experimentally observed ratios of recoil-ions for different $q$ can be described satisfactorily within the error bars. This indicates that the IPA and the resulting binomial statistics are a reasonable approximation for the description of the multiple ionisation of Ne by high-energy heavy-ion impact.

2. Recoil-ion energies 
From the measured transverse momentum distributions recoil energy-distributions have been derived. In Fig. 4 the FWHM of experimental recoil-ion energy distributions are plotted for different recoil-ion charge states $q$ for the collision systems 1.4 MeV/u $U^{32+}$ on Ne and Ar and 5.9 MeV/u $U^{65+}$ on Ne. In agreement with theory [7], even highly charged recoil ions (Ne$^{7+}$) have mean transverse kinetic energies of less than 1 eV for 1.4 MeV/u $U^{32+}$ impact. At higher projectile velocities and charge states (5.9 MeV/u $U^{65+}$ on Ne) $E_{\perp}$ for Ne$^{7+}$ recoil-ions is even smaller: $E_{\perp} < 600$ meV. This underlines the feasibility of producing an "ESR pumped" recoil-ion beam providing highly charged, very cold ions.
3. Collision dynamics - collective emission of electrons

As described in detail in Ref. 11, total differential (with respect to the relative transferred momentum) cross sections \( \frac{d\sigma}{d(\frac{p_{R\perp}}{p_0})} \) can be obtained from the measured transverse momentum distributions of the recoil ions by summing over all final recoil-ion and projectile charge states. Note that for isotropic electron emission with respect to the azimuthal angle relative to the scattering plane (i.e. \( |\Sigma p_{\perp}| = 0 \) or \( |p_{\perp}| = |p_{R\perp} = 0| = p_0 \)); see Fig. 1) the measured differential cross section \( \frac{d\sigma}{d(\frac{p_{R\perp}}{p_0})} \) equals the angular differential cross section \( \frac{d\sigma}{d\theta} \) for collisions, where the projectile actually has ionised the target.

In Fig. 5 the experimental \( \frac{d\sigma}{d(\frac{p_{R\perp}}{p_0})} \) are shown together with nCTMC...
calculations for \( \langle \text{d} \sigma / \text{d} \theta \rangle \) (\( \theta \) being the relative transverse projectile momentum \( p_{p,l}/p_0 \)): good agreement can be observed for projectile scattering angles \( \theta \approx 2 \times 10^{-8} \) rad, where the theory is very close to a Rutherford differential cross section using \( Z_P = 32 \) (charge state of the incoming projectile) and \( Z_T = 5 \) (which represents an average value for the produced target charge state). The nCTMC results at \( \theta \leq 2 \times 10^{-8} \) remain increasingly smaller than the \( \langle \text{d} \sigma / \text{d} \theta \rangle_{R} \) due to increased screening by the target electrons and to the decreasing total ionisation probability at large impact parameters, and are in disagreement with the experimental data. This disagreement is not due to the target thermal motion, which influences the \( p_{p,l} \) determination at very small \( p_{p,l} / p_0 \leq 6 \times 10^{-6} \).

To visualise the predicted influence of anisotropically emitted high-energy electrons (i.e. \( \sum_{\text{d} \sigma / \text{d} \phi} > 0 \)), nCTMC differential scattering cross sections \( \langle \text{d} \sigma / \text{d}(p_{p,l}/p_0) \rangle \) are also shown in Fig. 5 which take into account the correct momenta of all target electrons. A striking difference between both calculations can be observed mainly for recoil-ion momenta \( (p_{p,l}/p_0) \approx 2 \times 10^{-3} \). This indicates, that at large impact parameters the recoil-ion momentum is mainly compensated by the momentum of the emitted electrons, whereas the final projectile transverse momentum remains small.

The nCTMC calculations even predict that the projectile is deflected to negative scattering angles: the momentum balance is due to the collective, "jet-like" electron emission as illustrated qualitatively in Fig. 6 for a 1.4 MeV/u \( \text{U}^{32+} \) on Ne collision event at an impact parameter of 2 a.u. Even at a distance of 10 a.u. (\( t_1 \) in Fig. 6), the target electron cloud is strongly polarised by the strong Coulomb force of the projectile. At the distance of closest approach (\( t_2 \)) a part of the target electrons are pulled along behind the projectile and, since they cannot follow the swift Uranium ion, are emitted collectively with high average energy of more than 300 eV into angles of about 60° with respect to the beam axis (\( t_3 \)). The projectile is scattered off to a laboratory scattering angle in the order of \( 10^{-6} \) rad, whereas the recoil ion, being highly ionised (\( q = 6 \)), gains a kinetic energy of only 100 meV.

**nCTMC-picture of \( \text{U}^{33+} \) on Ne collision process at \( b \approx 2 \text{a.u.} \):**

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<th>( t_1 )</th>
<th>( t_2 )</th>
<th>( t_3 )</th>
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<tbody>
<tr>
<td>( \text{U}^{33+} )</td>
<td>( \sum_{\text{d} \sigma / \text{d} \phi} \approx 60° )</td>
<td>( \sum_{\text{d} \sigma / \text{d} \phi} \approx 10^{-6} \text{rad} )</td>
</tr>
<tr>
<td>R=10 a.u.</td>
<td>( \sum_{\text{d} \sigma / \text{d} \phi} \approx 60° )</td>
<td>( \sum_{\text{d} \sigma / \text{d} \phi} \approx 10^{-6} \text{rad} )</td>
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**Fig. 6:** Qualitative picture of the "time development" of a 1.4 MeV/u \( \text{U}^{33+} \) on Ne collision at an impact parameter of about 2 a.u. as predicted in the nCTMC approach.

Since the theoretical \( \langle \text{d} \sigma / \text{d}(p_{p,l}/p_0) \rangle \) (open triangles in Fig. 5), which are absolute values and free of any adjustable parameters, are very close to the experimental data over more than three orders of magnitude, we conclude that at very small projectile scattering angles the scattering of high-energetic highly-charged heavy ions is influenced considerably by the collective target-electron emission. This conclusion is underlined by experimental emission angle dependent \( \delta \)-electron cross sections obtained for 1.4 MeV/u \( \text{U}^{32+} \) on Ar showing a distinct maximum at about 60° with respect to the beam axis for electron energies between 150 eV and 1500 eV. As shown in Fig. 7 for 500 eV \( \delta \)-electrons, the measured dependence of the emission angle is in good agreement with the results of nCTMC calculations.
A new experimental technique has been applied to investigate multiple ionisation processes in high-energy heavy-ion atom collisions differentially with respect to the transferred recoil-ion momentum perpendicular to the beam direction. This technique enabled measurements of the relative momentum transfer down to \( (p_{\perp}/p_0) \approx 10^{-6} \), which is comparable to an angular resolution in the microradian regime, and allowed a very detailed investigation of the multiple ionisation process and especially, in connection with recent nCTMC calculations, of the dynamics of very distant heavy-ion atom collisions.

Thus, the IPA and the resulting binomial statistics, underlying at least implicitly all available theoretical calculations of the multiple ionisation, could be tested more quantitatively than has been possible up to now on the basis of total cross sections and was shown to be a reasonable approximation for the case of a Ne target.

The measured transverse recoil-ion energies for different collision systems are typically below 1 eV. Helium-like Neon was produced with a very low most probable energy of 1.7 eV for 5.9 MeV/u \( \text{U}^{3+} \) impact underlining the possibility of producing very cold, highly charged ions in a single encounter.

Experimental results for differential cross sections \( (d\sigma/d(p_{\perp}/p_0)) \) and angular dependent 5-electron emission cross sections together with theoretical results of nCTMC calculations, which for the first time take into account the correct momenta of all involved particles, lead to the conclusion that the dynamics of heavy-ion atom collisions are strongly influenced by the momenta of the ejected target electrons. The electrons are ejected collectively in an anisotropic manner at angles of about 60° with respect to the beam axis and in the scattering plane. The influence of the ejected electrons on the trajectory of both heavy nuclei, is most important at very distant collisions and becomes small as the relative momentum transfer becomes greater than \( 2\times10^{-2} \) for 1.4 MeV/u \( \text{U}^{2+} \) on Ne. The large impact parameter collisions, where the trajectory of the heavy and fast projectile is strongly perturbed by the electron momenta make the most important contributions to the total ionisation cross section. This indicates that theoretical models which separate the projectile's nuclear motion from the electronic processes on the target atom are not suitable for the determination of the collision dynamics in ionising collisions.

Since the nCTMC calculations predict a collective, "jet-like" electron emission at about 60° to the beam axis, the measurement of electron multiplicity in this angular regime in coincidence with charge-state and momentum analysed recoil ions becomes desirable and would provide a direct experimental proof of the theoretical results.
References