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Multiple ionization collision dynamics in 10 MeV F^{6+} on Ne collisions

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Abstact. Recoil-ion momentum distributions, measured in coincidence with the final projectile momentum transverse to the beam direction, have been investigated in order to obtain information on the sum momentum of the ejected electrons for the multiple ionization and capture reaction: 0.53 MeV u^{-1} $F^{6+}+Ne\rightarrow F^{5+}+Ne^{q+}+(q-1)e^{-}$. For close collisions, at projectile polar scattering angles between $0.1\leq\vartheta\leq 1$ mrad, the many-particle momentum exchange (emitted electrons, projectile and target recoil ion) was found to be strongly dominated by the momentum transfer between the nuclei for Ne final charge states $q=5$ and 6. In accordance with theoretical results in the *n*CTMC and the semiclassical quantum statistical (ionization channel) approaches, the projectile azimuthal and polar scattering is to a large extent compensated by the transverse momentum transfer to the recoil ion. No 'out-of-plane' scattering, in the sense as reported for the double capture plus multiple ionization channel in 0.53 MeV u^{-1} F^{8+} on Ne collisions by Gonzales *et al*, was observed for any of the final recoil-ion charge states.

The investigation of the mechanisms of momentum transfer from a fast charged projectile to a many-electron target in a multiple ionization reaction has become the subject of increasing experimental and theoretical efforts within the past couple of years. Rapid progress in the development of the experimental techniques along with a considerable improvement in theoretical approaches has resulted in a much more detailed understanding of the momentum exchange in ionizing collisions. Measurements of total multiple ionization cross sections (Cocke 1979, Kelbch *et al* 1985, Müller *et al* 1986, Tawara *et al* 1990) in concidence with the final charge state of the projectiles were followed by the investigation of the projectile scattering angle dependence (Schuch *et al* 1988, Kelbch *et al* 1990, Kamber *et al* 1988a, b, Giese and Horsdal 1988, Kristensen and Horsdal-Pedersen 1990) and the recoil-ion transverse momentum dependence (Ullrich *et al* 1988, Olson *et al* 1987) of such processes.

The coincidence measurement of the projectile deflection in a plane perpendicular to the beam axis with the transverse recoil-ion momentum has for the first time provided a complete experimental determination of the momentum balance between the projectile, the target nucleus and the ionized electrons in singly ionizing proton on helium collisions (Dörner *et al* 1989). For distant collisions ($\vartheta\leq 1$ mrad) a strong coupling between the electronic and nuclear motion was observed, manifested by a considerable influence on the nuclear trajectories. In accordance with theoretical calculations (Dörner *et al* 1991, Horbatsch 1989, Fukuda *et al* 1991) the deviation from the nucleus-nucleus scattering was found to amount to less than 20 meV in the mean

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recoil-ion transverse energy $\langle E_{R\perp}\rangle$, the corresponding mean electron momentum $\langle p_{e\perp}\rangle$ thus being below 3.5 au.

Using similar experimental techniques, the final charge states and mean transverse momenta of projectile and recoil ion were determined in coincidence for 0.53 MeV u^{-1} F^{8+} on Ne collisions in the double electron capture plus multiple ionization channel (Gonzales *et al* 1990). Thus, for the first time experimental information on the sum momentum of all ejected electrons could be obtained for multiple electron transition events with three up to six electrons being ionized to the continuum and two electrons transferred into bound states of the projectile. At projectile scattering angles of $\vartheta = 0.28$ and $\vartheta = 1.1$ mrad the sum momentum of the ejected electrons was found by Gonzales *et al* to be extremely large, corresponding to mean transverse momenta per emitted electron between 5.8 and 12 au under the assumption that all electrons are emitted exactly into the same azimuthal scattering angle φ_e (the corresponding mean transverse electron energy per emitted electron ranges between 457 eV and 1958 eV). If the electrons are scattered into a broader φ_e angular regime, their mean transverse momenta have to be even higher in order to explain the observed sum momentum. These values have to be compared with the maximum possible transverse energy transfer to a free electron by the fluorine projectile of less than 300 eV. Even more surprising, a strong 'out-of-plane' scattering was observed: the projectiles were found to be not predominantly scattered at 180° to the recoiling target ion in the plane perpendicular to the beam, but to have a maximum in their emission yield up to 43° out of the scattering plane defined by the deflected recoil ion.

In order to investigate the role of the ejected electrons for the transverse momentum balance in multiple ionization plus capture reactions, we measured transverse recoil-ion momentum distributions in coincidence with the projectile scattering perpendicular to the beam axis in addition to the final charge states of the projectile and the recoil ion for 0.53 MeV u^{-1} F^{6+} on Ne collisions. At projectile polar scattering angles between 0.1 and 1 mrad, the many-particle momentum exchange was found to be strongly dominated by the nuclear Coulomb repulsion for the high final recoil-ion charge states where up to five electrons are simultaneously transferred into continuum states. The length of the mean recoil-ion and projectile momentum vectors in the plane perpendicular to the beam axis is nearly identical, they are directed exactly opposite to each other within the experimental resolution. Along with theoretical results in the *n*CTMC approach (Olson *et al* 1989), no 'out-of-plane' scattering could be observed in this experiment.

The experiments were performed at the Max-Planck-Institut (MPI) für Kernphysik at Heidelberg, Federal Republic of Germany using the 13 MV MP tandem Van de Graaff accelerator. At a terminal voltage of 5 MV, singly charged F ions were accelerated up to 10 MeV and stripped in a 100 μg carbon foil stripper. The equilibrium charge state $n = 6$ was selected by a switching magnet and, after collimation over a total distance of 7 m, directed into the static gas target of the recoil-ion momentum spectrometer. The scattered projectiles then were charge state analysed in a magnetic field and, after a total drift length of 6.25 m, detected by a two-dimensional position-sensitive parallel plate avalanche detector (PPAD). The position information was obtained by a charge dividing technique using a 'wedge-and-strip' geometry (Martin *et al* 1981) on the anode of the PPAD (a detailed description of the PPAD can be found in Sharabati *et al* (1990)); a resolution of less than 200 μm was obtained throughout the experiment. Since we were interested in the single capture reaction, the final projectile charge states were magnetically separated and deflected in such a way that only F^{5+} ions hit the active area of the detector. The full charge exchanged beam was monitored during the experiment at a typical rate of 5000 particles/s. The scattering distribution for random coincidences provided precise information on the combined effects of beam collimation and position resolution and a FWHM of 1 mm, resulting in a reasonable polar angular resolution of 1.6×10^{-4} rad being achieved during the experiment.

The recoil-ion momentum spectrometer was a doubly differentially pumped gas cell, cooled to 77 K to reduce the influence of the target thermal motion. The cell is a gold-plated copper cylinder of 10 mm diameter and 40 mm length, designed as a Faraday cage to be 'free' of electric fields aligned with its axis collinear to the beam direction (the spectrometer is described in detail by Dörner *et al* (1989) and Ullrich *et al* (1991)).

The recoil-ion transverse momentum $p_{R\perp}=m_R\Delta x/\Delta t$ (m_R is the recoil-ion mass) is measured by a time-of-flight (TOF) technique. Recoil ions produced by the projectile ions along the beam axis drift from the axis to the wall in a time interval Δt inversely proportional to their transverse momentum. The drift length Δx can be varied between $\Delta x=2.5$ to 7.5 mm and a Δx of 3.5 mm was used in this experiment. The ions are then accelerated and charge state analysed; Δt is obtained from a coincidence with the scattered projectiles. Previous experiments (Dörner *et al* 1989, 1991) indicate that electric potentials present inside the target cylinder due to contact potentials or contaminations influence the recoil-ion energy determination by less than 5 meV for singly charged ions. In order to control possible perturbations by rest potentials, the recoil-ion momentum distributions were also taken for a drift length of $\Delta x=5$ mm and identical mean recoil-ion energies have been obtained within this experimental resolution. The measured mean transverse recoil-ion energy $\langle E_{R\perp}\rangle$ for Ne^{2+} production in the direct ionization channel of $\langle E_{R\perp}\rangle=40$ meV allows for a maximum electric potential inside the cylinder of 17 mV assuming that the recoil ions were created with 'zero' energy (40 meV $=2\times17$ meV+6 meV); the 6 meV offset in the mean transverse energy is due to the remaining influence of the target thermal motion at 77 K. The optimum target pressure was found to be 10^{-2} Torr; pressure dependences taken for the relative ratios of recoil ions with different charge states, integrated over their momenta, ensured that the recoil ions did not undergo charge exchange reactions after their creation and guaranteed single collision conditions. The ratios agree within 30% with data reported previously by Kelbch *et al* (1990) using a completely different spectrometer for the recoil-ion detection. The pressure in the beamline was on the order 2×10^{-6} Torr even in the first stage of the differential pumping system outside the static gas target, which ensured that only a minor part of the beam was charge exchanged before the collision.

As illustrated in figure 1, the apparatus is designed such that the scattering plane S is defined by the beam axis and the recoil-ion aperture. In addition, since the exact location of the interaction zone along the beam is not specified within the extended target area, only one momentum component, namely p_{Rx}, is determined by the spectrometer (the time Δt needed by the recoil ions to drift from the beam axis to the aperture independent of their emission angle ϑ_R). Recoil-ion scattering angles ϑ_R in the scattering plane S between 20° and 150° are accepted with the same solid angle and detection efficiency. The coincidence measurement of the projectile transverse momenta in x and y direction (D plane) enables a direct deduction of the transverse sum momentum of the ejected electrons by applying momentum conservation.

One important feature of our apparatus is that, due to the field-free drift area within the target cylinder, the scattering plane as well as the solid angle is exactly defined

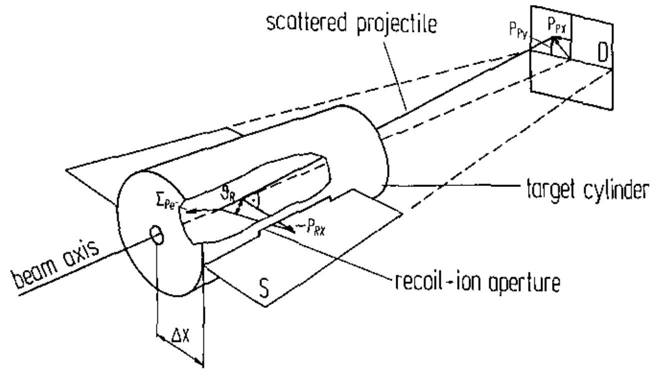


Figure 1. Outline of the scattering geometry. S, scattering plane defined by the beam axis and the recoil-ion aperture; p_{Rx}, recoil-ion momentum component into the x direction as determined by the spectrometer; ϑ_R, recoil-ion polar scattering angle; D, scattered projectile detection plane; p_{px}, p_{py}, transverse projectile momenta.

only by geometrical parameters of the spectrometer. Therefore, a complicated deconvolution of the TOF spectra, bearing many sources of possible errors (Levin *et al* 1987, Grandrin *et al* 1988), is not necessary to get the recoil-ion momenta or energies. Our measured TOF spectra directly reflect the recoil-ion momentum or energy distributions for fixed and well defined $\Delta\varphi_R$; the mean recoil-ion momentum (energy) can be obtained by a simple transformation of the TOF spectra into momentum (energy) spectra and calculation of the centre-of-mass of these distributions. Due to the shielding of the reaction volume, the ion-optical elements, necessary for the charge state selection of the recoil ions, also cannot influence the measurement in any way.

In figure 2 the maximum of the two-dimensional scattering pattern (in mrad) of F^{5+} projectiles in the plane perpendicular to the beam direction (x, y-plane D in figure 1) is presented in coincidence with recoil ions of charge state $q=6$ scattered into the $-x$ direction in the recoil-ion spectrometer as indicated by the arrow in the figure (note: the recoil-ion aperture allows for a φ_R angular acceptance of $\Delta\varphi_R = 19°$).

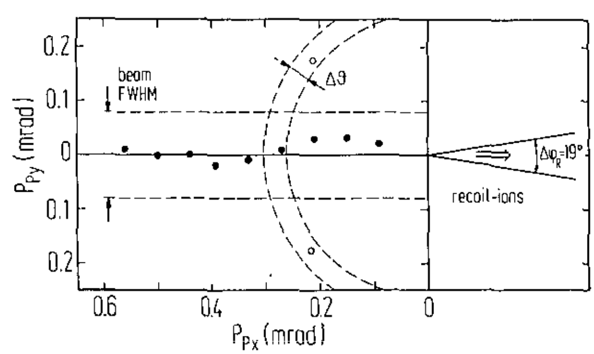


Figure 2. Two-dimensional representation of the transverse projectile detection plane D (figure 1). The projectile deflection in x, y direction is indicated in mrad. Full circles, maxima of the scattered projectile distributions in the y direction concident to Ne^{6+} production for the single capture channel in 0.53 MeV u^{-1} F^{6+} on Ne collisions. Broken lines: FWHM of the undeflected beam. Arrow, recoil-ion deflection. $\Delta\varphi_R$, recoil-ion detection aperture. Open circles, maxima reported by Gonzales *et al* (1990).

This maximum of the distribution in the y direction (full circles in the figure) is found to be located exactly opposite the recoil-ion deflection ($p_{py}(\max) = 0$) for projectile scattering angles 0.1 mrad $\leqslant \vartheta \leqslant$ 0.6 mrad. A similar behaviour is obtained for recoil-ion charge states $q = 3$, 4 and 6. As is illustrated in figure 3 for 0.25 mrad $\leqslant \vartheta \leqslant$ 0.3 mrad, a narrow distribution in φ (φ is the projectile azimuthal scattering angle), which is not corrected for the recoil-ion aperture and for the extension of the undeflected beam, is observed in this reaction channel, where one target electron is transferred to the projectile and five others are excited into the continuum (broken lines in figure 2: FWHM of the undeflected beam corresponding to $\Delta\vartheta = 0.16$ mrad). From this it becomes obvious that the nuclear Coulomb repulsion strongly dominates the many-particle momentum exchange in this collision system. No 'out-of-plane' scattering—$p_{py}(\max) \neq 0$—as measured by Gonzales *et al* for the 10 MeV F^{8+} on Ne double capture channel for the same number of ejected electrons can be observed. For this latter collision system, maxima in the projectile scattering distribution were reported at $\vartheta = 0.28$ mrad to deviate by $\varphi = \pm 43°$ from two-body scattering (open circles in figure 2).

A more quantitative analysis of the projectile φ angular distribution for fixed projectile polar scattering angle is presented in figure 4, where the FWHM in φ, corrected for the actual beam extension and for the recoil-ion acceptance angle, is plotted against ϑ for the recoil-ion charge state $q = 6$ (full circles). The distribution is found to be

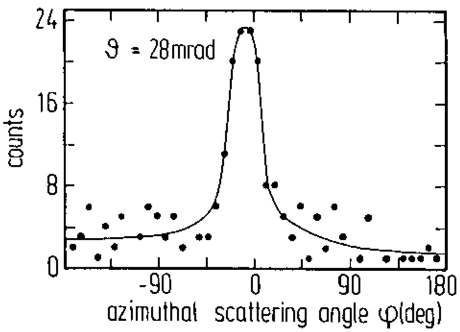


Figure 3. Projectile φ-angular scattering distribution for $0.25 \leqslant \vartheta \leqslant 0.3$ mrad (window indicated by broken lines in figure 2) coincident with Ne^{6+} production in the single capture channel of 0.53 MeV u^{-1} F^{6+} on Ne collisions (not corrected for the extension of the undeflected beam and the recoil-ion aperture).

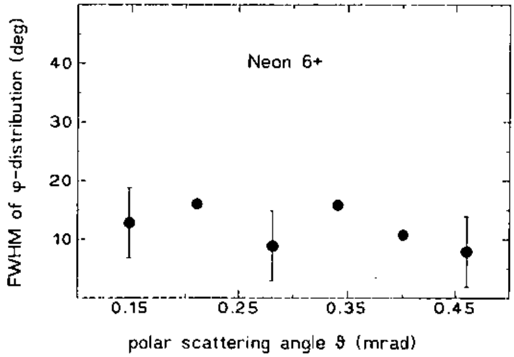
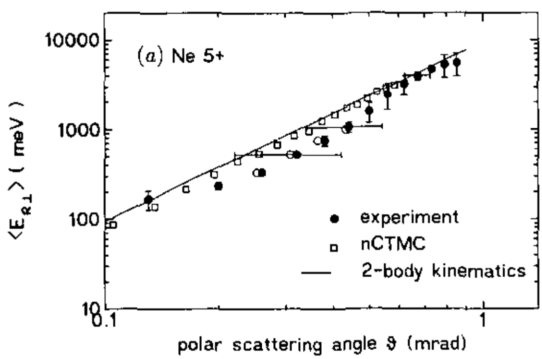


Figure 4. Full width half maximum (FWHM) of the projectile polar scattering angle distribution in dependence on the projectile azimuthal scattering angle ϑ for Ne^{6+} production (full circles) in the single capture channel of 0.53 MeV u^{-1} F^{6+} on Ne collisions.

slightly broader than the experimental resolution by about 12° with a large error bar (±5°) due to the beam extension. The broadening may be due to the momentum carried away by the emitted electrons: At a scattering angle of 0.28 mrad and five electrons in final continuum states this corresponds to a mean sum momentum of the emitted electrons of about 9 ± 3.5 au. As has been mentioned before, the F^{6+} projectile can transfer a maximum transverse momentum of 4.5 au to a free electron in a binary collision. Thus, only two fast electrons can be responsible for the measured sum momentum, the others might be emitted isotropically. No conclusion on a collective electron emission and out-of-plane scattering can be drawn from our experimental results for this collision system.

We further investigated the mean recoil-ion energy in dependence with the projectile scattering angle ϑ for Ne charge states $q = 5$ (figure 5(*a*)) and $q = 6$ (figure 5(*b*)). No deviation from a two-body scattering behaviour (full line) can be observed for Ne^{6+} ions, whereas the mean energies for Ne^{5+} ions are consistently below the two-body value in the ϑ regime between 0.2 and 0.6 mrad. This deviation is partly caused by a combined effect of the experimental projectile scattering angle resolution (indicated in the figure) and the decrease in the angular differential cross section for Ne^{5+} production towards larger ϑ (Kelbch *et al* 1990). Thus, for a fixed angular window $\Delta\vartheta$, the number of counts is increasing toward smaller ϑ within $\Delta\vartheta$, which leads to a systematic shift of the coincident mean recoil-ion energies to lower values. Taking this



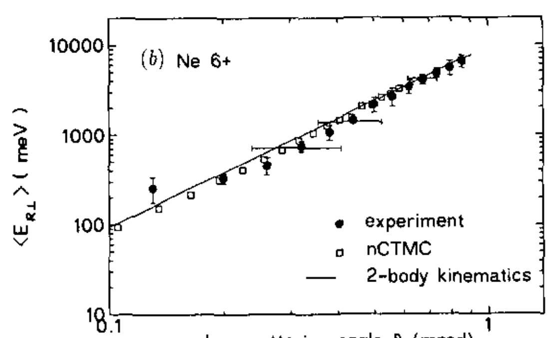


Figure 5. Mean recoil-ion transverse energy $\langle E_{R\perp} \rangle$ for Ne^{5+} (figure 5(*a*)) and Ne^{6+} (figure 5(*b*)) production in dependence on the projectile scattering angle in mrad for the single capture channel of 0.53 MeV u^{-1} F^{6+} on Ne collisions (full circles). Open circles, approximate correction of the experimental data for the influence of the scattering angle resolution (see text). Open squares, results of *n*CTMC calculations.

approximately into account (open circles in the figures), a small but significant deviation from a two-body scattering behaviour, though much smaller than that reported by Gonzales *et al*, might be presented in our data. A closer analysis of the theoretical nCTMC results (squares in the figure) shows indeed that small deviations from the nuclear two-body momentum exchange are predicted. At scattering angles between 0.04 and 0.6 mrad the mean recoil-ion energies are found to be smaller than the corresponding projectile scattering angles by less than 2 meV, which is far below the present experimental resolution. This deviation corresponds to a mean sum momentum of the ejected electrons opposite the projectile deflection of about 2.3 au (73 eV), a value which is even less than that found in 0.5 MeV singly ionizing proton–helium collisions (Dörner *et al* 1989). This result indicates that theoretically the angular correlation between the four emitted electrons and the deflected projectile is less pronounced than for single ionization. Thus, also the nCTMC results do not predict any significant collective behaviour of the emitted electrons for the collision system under consideration for the close collisions investigated.

Calculations for the pure ionization channel of 10 MeV C^{6+} ions colliding with Ne have previously been reported by Horbatsch (1991a) using the semiclassical quantum statistical approach, where the influence of the emitted electron momenta on the projectile deflection has also been implemented. At an impact parameter of 0.5 au, resulting in a mean scattering angle of about 0.21 mrad, a slight broadening of the projectile scattering distribution of up to 0.07 mrad for fourfold ionization is observed. This corresponds to a mean sum energy of the emitted electrons in to a certain direction of less than 90 eV. However, no significant shift in the maximum of the distribution from the corresponding two-body value is present in these calculations, indicating that the electrons are not predominantly scattered into a particular azimuthal angular regime relative to the projectile deflection. Also, no out-of-plane scattering in the sense that the maximum in the projectile scattering distribution deviates from a back to back deflection from the recoil ion, has been recognized for this collision system. The maxima of the projectile scattering distributions for $b = 0.4$ and 1 au ($\vartheta \simeq 0.275$ and 0.18 mrad) are found to be in the scattering plane with widths in the φ distributions ($b = 0.4$ au) of about 7° (Ne^{+}), 12° (Ne^{3+}) and 13° (Ne^{5+}) (Horbatsch 1991a, b). These values are in good agrement with our experimental results of about 12° for Ne^{6+} production in the single capture channel.

In conclusion, we have investigated the collision dynamics for multiple ionization plus single capture events in 0.53 MeV u^{-1} F^{6+} on Ne collisions using recoil-ion momentum spectroscopy (RIMS) along with a detection in coincidence of the transverse projectile scattering. At projectile laboratory scattering angles between 0.1 and 1 mrad with four or five electrons transferred into continuum states, the many-particle momentum exchange was found to be strongly dominated by the Coulomb interaction of the nuclei. Only minor deviations from a two-body behaviour, very close to the present experimental resolution, might be present for Ne^{5+} recoil ions which were found to carry away a smaller transverse momentum than the coincident projectiles. Within the error bars, our results are in agreement with the theoretical results of nCTMC as well as of semiclassical quantum statistical calculations, the latter carried out for the same number of ejected electrons but for the pure ionization channel. Both theories predict an influence of the emitted electron momenta on the heavy particle trajectories which is, however, much smaller than the achievable experimental precision. The large effects reported by Gonzales *et al* (1990) for the double capture channel or 10 MeV F^{8+} ions are not substantiated in the present collision system.

However, our experimental results indicate that the influence of the electrons might be larger than calculated by theory, which will be the subject of further systematic investigations with improved polar scattering angle resolution. In addition our experimental results contain much more information as to the differential multiple ionization plus capture cross sections for the projectile as well as for recoil-ion scattering. A complete analysis of these differential cross sections in comparison with earlier experimental data and semiclassical quantum statistical results (Kelbch *et al* 1990) as well as with *n*CTMC calculations will be reported in a subsequent extended publication.

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