Dynamic mechanisms of He single ionization by fast proton impact

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Triple-differential ionization cross sections $d^3\sigma/d\vartheta_p d\varphi_p dp_{\text{rec}}$, the momentum distributions of singly charged recoil ions transverse to the beam direction as a function of the projectile polar (ϑ_p), and azimuthal (φ_p) scattering angle were measured in order to elucidate the dynamics of 3-MeV H^+ on He single ionization. For projectile polar deflections $0.2 \leq \vartheta_p \leq 1$ mrad and azimuthal scattering angles $0^\circ \leq \varphi_p \leq 360°$, the kinematic regimes where two-body interactions dominate the three-body momentum exchange of the single-ionization reaction were separated experimentally.

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Single and double ionization of He in collisions with fast projectiles has become a subject of growing experimental and theoretical interest, stimulated by rapid experimental progress within the last five years. This progress has not only been due to the recent availability of antimatter (positron, antiproton) beams of sufficient intensity and quality to perform total-cross-section measurements [1,2], but was also based on the development of new detection techniques for the determination of highly differential cross sections for electron impact [3].

Single-differential cross sections in dependence of the projectile scattering angle ϑ_p for helium single ionization in collisions with 3- and 6-MeV protons display a distinct shoulder at $\vartheta_p \approx 0.55$ mrad [4]. Systematic experimental investigations show that the shoulder slowly disappears at lower projectile velocities [5]. Plane-wave-Born-approximation (PWBA) calculations [4] attributed this behavior as being due to the dominant contribution of projectile–target-electron scattering (p-e) events to the differential cross section for $\vartheta_p \lesssim 0.55$ mrad, which is the maximum deflection angle for protons being scattered off a free electron at rest. The PWBA calculations were followed by classical [6], semiclassical quantum-statistical [7], as well as by quantum-mechanical approaches in the Born [8], the Glauber [9] and eikonal distorted wave (EDW) approximations [10]. They all include the interaction of the projectile with both the target electron and the target nucleus to calculate the projectile deflection.

A recently developed experiment, where the kinematics of the single-ionization reaction was studied directly using a coincidence determination of the projectile deflection and the recoil-ion scattering in a plane transverse to the beam direction (double-differential cross sections), showed that the projectile scattering around 0.5 mrad is indeed dominated by its interaction with the ionized electron [11]. A large fraction of the projectile transverse momentum (ϑ_p) is not found in the recoil-ion momentum and therefore must be transferred to the ionized electron even at collision energies of 0.3 or 0.5 MeV. At these lower energies a shoulder in the single-differential cross section is not apparent due to the increased influence of the initial momentum distribution of the bound target electrons (Compton profile).

In this paper we report on a joint experimental and theoretical study of helium single ionization for high-energy proton impact at $E_p = 3$ MeV. Using recoil-ion momentum spectroscopy (RIMS), triple-differential cross sections have been measured and the kinematic regimes where two-body interactions (projectile–target-electron, p-e; projectile–target-nucleus, p-α) dominate the three-body momentum exchange could be clearly separated. The experimental data are compared to the results of n-body classical-trajectory Monte Carlo (n-CTMC) calculations [12] which include both electrons such that all interactions are incorporated except for the electron-electron correlation. The electrons have equal binding energies of 0.903 a.u.; experimental total cross sections are well reproduced. For the calculation of triple-differential cross sections at large ϑ_p, 5×10^7 trajectories were evaluated in order to obtain statistically significant results.

The experiments were performed at the Max-Planck-Institut (MPI) für Kernphysik. The 3-MeV proton beam was collimated to a divergence of less than 0.1 mrad. Having passed the recoil-ion-momentum spectrometer, the deflected protons were detected by a two-dimensional position sensitive parallel-plate avalanche detector [13]. The overall projectile polar scattering angle resolution was $\Delta\vartheta_p = \pm 0.07$ mrad. The part of the beam deflected into $\vartheta_p \leq 0.2$ mrad was stopped by a small Faraday cup mounted directly in front of the detector. The recoil-ion transverse momentum $p_{\mathrm{rec}\perp} = m_R \Delta x / \Delta t$ (m_R is the recoil-ion mass) is measured by a time-of-flight (TOF) technique. The ions drift in a field-free target area over Δx, are then accelerated, focused by an einzel lens and charge-state analyzed by magnetic deflection. Δt is obtained from a coincidence of the recoil ions with the scattered projectiles. The He gas in the target cell was cooled to 77 K to reduce the influence of the target thermal motion on the recoil momentum transferred to the target atom in the collision [14]. Previous experiments [11,14] 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. Recoil-ion polar scattering angles ϑ_R between 20° and 150° are accepted with the same solid angle and detection efficiency [14]. The recoil-ion azimuthal acceptance angle $\Delta\varphi_R$ was 16.3°, corresponding to a solid-angle fraction of 4.5%. Taking into account the extension of the beam in the spectrometer the overall φ_R resolution was $\Delta\varphi_R = \pm 9.5°$.

Figure 1 shows differential cross sections for helium single ionization as a function of the transverse momentum transfer to the projectile $d\sigma/dp_{\mathrm{pro}\perp}$ (solid circles) and to the recoil-ion $d\sigma/dp_{\mathrm{rec}\perp}$ (solid squares). The transverse momentum transfer is plotted in units of the incoming-projectile longitudinal momentum p_0 and therefore, for the projectile scattering, is equivalent to the polar laboratory angle $\vartheta_p \approx p_{\mathrm{pro}\perp} = p_\perp / p_0$. Also indicated are previous experimental $d\sigma/d\vartheta_p$ (open circles) [4] and theoretical $d\sigma/d\vartheta_p$ from n-CTMC calculations (solid line), results of calculations in the Born [8] (dashed-dotted line), the Glauber [9] (dashed line), and in the EDW approximation [10] (dotted line). Our projectile angular differential cross sections have been normalized to the data of Ref. [4] in a ϑ_p regime between 0.2 and 0.4 mrad. Since the $d\sigma/dp_{\mathrm{rec}\perp}$ have been measured in coincidence, they are simultaneously placed on an absolute scale by this procedure. The shape of our experimental cross sections $d\sigma/d\vartheta_p$ ($\vartheta_p \approx p_{\mathrm{pro}\perp}$) is in agreement with the experimental results reported previously [4] within experimental error bars. The latter not only contain statistical errors but also uncertainties due to the background subtraction. They are relatively large since in this experiment an extended time window of 20 μs was necessary to measure the recoil-ion time of flight which ranges up to 7 μs (this has to be compared to a typical time resolution of about 6 ns in an experiment where the recoil ions are extracted by an electric field with a 4π solid angle and only their charge state is determined [4]). The shoulder at 0.55 mrad as well as the absolute value of the cross sections is predicted by the n-CTMC, Glauber and EDW calculations within the experimental error bars. The Born approximation of Salin lies below the experimental cross sections at $\vartheta_p \approx 0.55$ mrad. This was attributed [10] to the trunctation of the partial wave expansion at high l values, resulting in an under estimation of high energetic electrons which are preferentially produced at that scattering angle.

In the region between 0.2 and 0.7 mrad, the recoil-ion $d\sigma/dp_{\mathrm{rec}\perp}$ drastically deviate from the projectile $d\sigma/dp_{\mathrm{pro}\perp}$ which have been shown to be dominated by the projectile interaction with the ionized electron. The smooth slope of the $d\sigma/dp_{\mathrm{rec}\perp}$ shows that the target nucleus, as the third particle involved, mainly acts as a spectator. It is only slightly deflected by the screened nuclear charge of the projectile as a function of the impact parameter between the two nuclei. n-CTMC calculations indicate that the transverse recoil-ion momentum can be closely related to an impact parameter b, which opens the only experimental possibility to measure b-dependent ionization probabilities in distant collisions. Such encounters at large b contribute more than 95% to the total ionization cross section. For close collisions and $p_\perp/p_0 \gtrsim 0.7 \times 10^{-3}$, where the three-body momentum exchange is dominated by the p-α nuclear interaction, the differential cross sections $d\sigma/dp_{\mathrm{rec}\perp}$ and $d\sigma/dp_{\mathrm{pro}\perp}$ are identical within the experimental error bars. The n-CTMC calculations (solid line) predict the overall behavior of the $d\sigma/dp_{\mathrm{rec}\perp}$, but underestimate the cross section between $0.2 \times 10^{-3} \leq p_{\mathrm{rec}\perp} \leq 0.4 \times 10^{-3}$ by up to 50%.

In order to illuminate the dynamic mechanisms of helium single ionization in detail, recoil-ion-momentum distributions for different projectile polar (ϑ_p) and azimuthal (φ_p) scattering angles are shown in Figs. 2 and 3. The polar scattering angle windows are $\vartheta_p = \pm 0.05$ mrad, the azimuthal windows are $\varphi_p = \pm 10°$, where the experi-

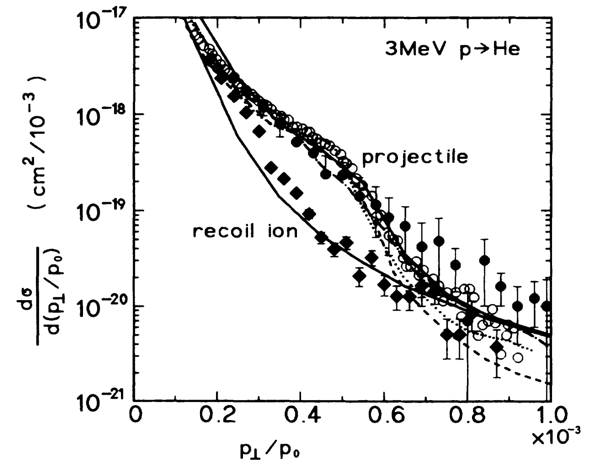

FIG. 1. Differential single-ionization cross sections of He by 3-MeV protons as a function of the transverse momentum transfer to the projectile $p_{\mathrm{pro}\perp}$ (●, experiment; ○, experiment Ref. [4]; ——, n-CTMC; —·—·—·, Born [8]; — — —, Glauber [9]; · · · ·, EDW [10] approximation) and to the recoil ion $p_{\mathrm{rec}\perp}$ (♦, experiment; ——, n-CTMC).

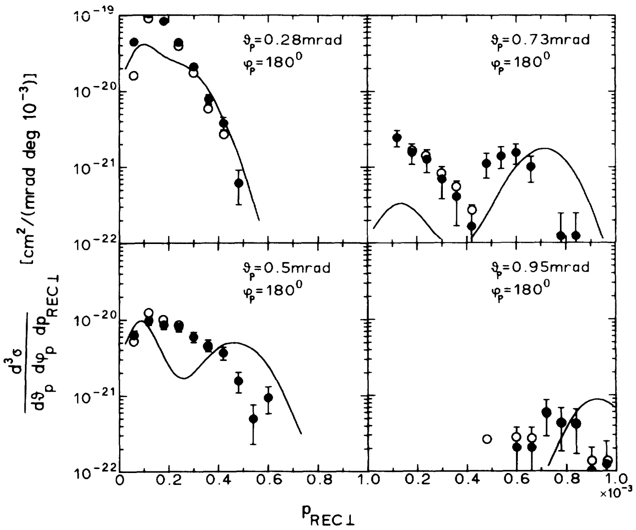

FIG. 2. Triple-differential single-ionization cross sections of He by proton impact for different projectile polar deflections ϑ_p as indicated in the figure and fixed azimuthal scattering angle of $\varphi_p = 180°$ as a function of the transverse recoil-ion momentum $p_{\mathrm{rec}\perp}$ (symbols: experiment using different background subtractions, ——, n-CTMC).

mental resolution is not implemented. Different symbols denote different background subtractions. The momentum distributions for $\varphi_p = 180°$ are shown in Fig. 2. Here the projectiles are scattered opposite to the recoil-ion and an increase of $p_{\mathrm{rec}\perp}$ with increasing ϑ_p can be observed as

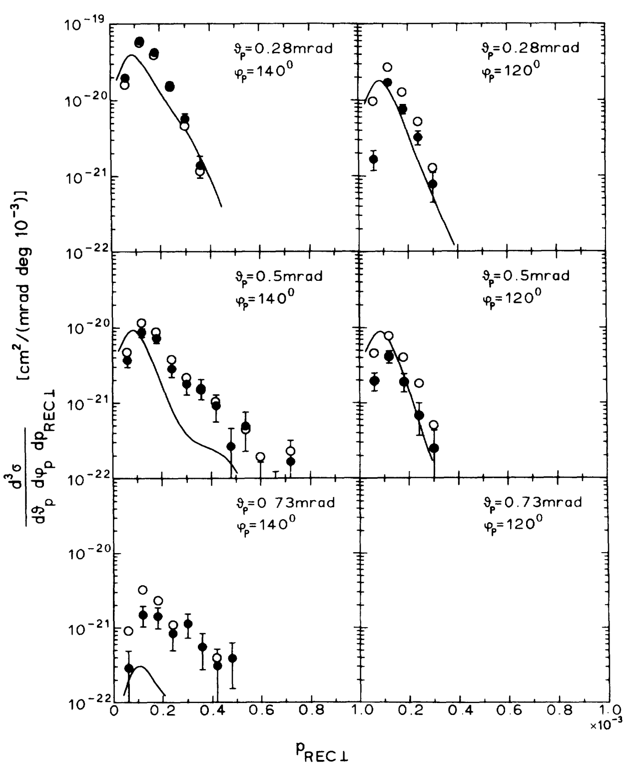

FIG. 3. Same as Fig. 2 for $\varphi_p = 140°$ and $\varphi_p = 120°$.

expected for p-α scattering. The distribution is broad at small ϑ_p, where p-α and p-e scattering cannot be separated experimentally. This changes to a dramatic double peak structure at $\vartheta_p = 0.73$ mrad. The peak located at a recoil-ion transverse momentum close to that of the projectile ($\vartheta_p = 0.73$ mrad) is due to p-α scattering events with little momentum transfer to the ionized electron. A considerable amount of recoil ions, however, is found to have only very small transverse momenta and therefore, in these cases, the projectiles are deflected off the ionized electron. This spectrum directly displays the distinct scattering of the projectiles from either the helium nucleus or one of its electrons. At large ϑ_p only one peak, namely, the one for p-α nuclear scattering, is present, being broadened by the momentum transfer to the ionized electron and by the experimental resolution. Also indicated in the figure (solid lines) are results of n-CTMC calculations which have been folded with the experimental ϑ_p and φ_p resolution as well as with the thermal motion distribution of the target atoms. Reasonable agreement in shape and absolute magnitude of these triple-differential cross sections can be observed. However, significant deviations are present in the cross section for low recoil-ion momenta at $\vartheta_p = 0.28$ mrad, where theory underestimates the experimental value by up to a factor of 3. This is consistent with the underestimation of the $d\sigma/dp_{\mathrm{rec}\perp}$ at small $p_{\mathrm{rec}\perp}$. The absence of the double peak structure for $\vartheta_p = 0.5$ mrad in the experimental data might be due to a slightly weaker experimental resolution than was convoluted into the theoretical results. For $\vartheta_p = 0.73$ mrad the double peak due to "soft" and "hard" collisions of the recoil ion with the projectile is predicted by theory. The larger experimental cross section for small $p_{\mathrm{rec}\perp}$ might still partly be due to the background subtraction in the time spectra. Due to the sensitivity of the results at this angle, only a slight variation in ϑ_p angle causes large changes in the relative intensities of the "soft" and "hard" component of the scattered recoil ions.

For $\varphi_p = 120°$ (right-hand part of Fig. 3), 60° out of the p-α scattering plane, the recoil-ion transverse momentum distribution is completely independent of ϑ_p demonstrating the dominance of p-e scattering in this kinematic window. Consequently, within the experimental sensitivity, no recoil ions are found in this window for $\vartheta_p \geq 0.73$ mrad. With a large probability, such angles can only be obtained in hard p-α collisions and therefore have to lie within the p-α scattering plane. The electrons emitted during such collisions exhibit high transverse and longitudinal momenta. In this φ_p window, the n-CTMC results are in good quantitative agreement with the experimental data within the error bars.

In the left-hand part of Fig. 3, recoil-ion transverse momentum distributions are shown for different ϑ_p and a projectile azimuthal deflection of $\varphi_p = 140°$. This is only slightly out of the p-α scattering plane if one takes into account the φ_p window ($\Delta\varphi_p = \pm 10°$) and the experimental φ_p resolution of $\pm 9.5°$. At $\vartheta_p = 0.28$ mrad the distribution is nearly identical to the corresponding one for $\varphi_p = 120°$ but significantly shifted to smaller energies in comparison with the corresponding distribution in the

p-α scattering plane. This behavior continues up to $\vartheta_p = 0.73$ mrad illustrating that in this kinematic window neither p-α nor p-e two-body scattering dominates the momentum exchange. These data show that the complete three-body nature of the single ionization process has to be taken into account in order to understand the ionization collision dynamics in this regime. The overall agreement with theory is reasonable, minor deviations are present at $\vartheta_p = 0.28$ mrad for small $p_{\text{rec}\perp}$. For $\vartheta_p = 0.73$ mrad the experimental cross sections are above the theoretical results, which again might partly be due to the background subtraction.

In conclusion, absolute single- and triple-differential cross sections have been measured using recoil-ion-momentum spectroscopy in coincidence with a two-dimensional detection of the deflected projectiles in order to investigate dynamic mechanisms of helium single ionization in collisions with 3-MeV protons. The different dynamic regimes, where p-α, p-e, or three-body interactions mainly contribute to the differential cross sections could be experimentally separated and their relative importance has been measured. The overall behavior of these highly differential cross sections is quantitatively predicted in shape and absolute magnitude by four-body classical n-CTMC calculations; however, significant deviations can be found in the detailed comparison. Another result of our study is that the recoil-ion transverse momentum seems to be closely related to the mean projectile impact parameter. This is not only concluded from the smooth behavior of the single-differential cross sections as a function of the transverse momentum transfer to the recoil ion but also predicted by the calculations: plotting b versus the projectile scattering angle shows that for $\vartheta_p \lesssim 0.6$ mrad all b contribute to the ionization whereas the recoil-ion momentum is found to be closely related to a certain b regime down to the smallest recoil-ion momenta where ionization occurs. This opens the possibility to measure impact-parameter-dependent ionization probabilities at large b, where the projectile deflection is dominated by the momentum transfer with the ionized electron.

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