Projectile–Residual-Target-Ion Scattering after Single Ionization of Helium by Slow Proton Impact

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We have measured fully differential single ionization cross sections for 75 keV p + He collisions. At this relatively small projectile velocity, signatures of the projectile–residual-target-ion interaction, which are not observable for fast projectiles and for electron impact, are revealed rather sensitively. In fact, this interaction appears to be more important than the postcollision interaction, which so far was assumed to be the most important factor in higher-order effects for slow ion impact. These features are not well reproduced by our three-distorted-wave calculations.

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Ionization processes in atomic collisions have been studied extensively for several decades. The extraordinary relevance of this type of research to the yet unsolved and fundamentally important few-body problem has been emphasized frequently (e.g., [1,2]). Because the Schrödinger equation is not analytically solvable for more than two mutually interacting particles, detailed experimental studies are essential to guide theoretical modeling efforts. Investigations of atomic few-body systems are particularly important because the underlying fundamental interaction (electromagnetic) is basically understood for two mutually interacting particles. As a result, comparisons of experimental data with calculations are essentially testing the treatment of the few-body aspects in theory. Therefore, such studies can also help to advance our understanding of basic concepts in other areas of physics. For example, our understanding of the underlying fundamental interactions in nuclear systems (strong and weak) is still rather incomplete. Once successful techniques for the description of few-body aspects in atomic systems are developed and tested by experiment, they can be applied to nuclear scattering theory. Comparisons with experimental data can then be used to extract more detailed information about the nuclear potential.

In the case of ionization of atoms by electron impact, fully differential cross sections (FDCS), which offer the most sensitive tests of theoretical calculations, have been measured routinely since the pioneering work of Ehrhardt *et al.* [3,4]. For very energetic electron impact, data were routinely very well reproduced even by the relatively simple first Born approximation (FBA) [5,6]. For many years, it was therefore generally held that single ionization is basically understood, at least for small perturbations η (projectile charge to velocity ratio) where the assumptions of first-order perturbation theory were expected to be valid.

For ion impact the measurement of FDCS for single ionization is much more challenging because it is very difficult to measure the scattered projectile momentum directly. The first experimental FDCS were reported only about a few years ago [2,7,8], where the momenta of the ejected electron and the recoil ion were measured and the scattered projectile momentum was deduced from the conservation laws. Similar to electron impact, the data at small η for electrons ejected into the scattering plane (defined by the initial and final projectile momenta) were very well reproduced by a calculation based on the continuum distorted wave approach [9]. However, for large η dramatic discrepancies were found [8]. These can be traced to an incomplete description of the postcollision interaction (PCI) between the outgoing projectile and the electron after the actual ionization process. Since that force is attractive for ion impact and repulsive for electron impact, it leads to a general shift of the observed features in the forward (ion impact) and backward (electron impact) direction relative to the predictions of the FBA.

More importantly, outside the scattering plane the data were significantly underestimated even for very small perturbations [2]. These discrepancies between experiment and theory were attributed to a higher-order ionization mechanism involving the projectile–residual-target-ion (PT) interaction. First indications for a surprisingly important role of this force were found earlier in doubly differential cross sections [10,11] and later confirmed in FDCS for 1 GeV/amu U^{92+} + He collisions ($\eta = 0.8$) [12,13]. However, it now becomes clear that even for very small η the theoretical description of effects due to the PT interaction is alarmingly incomplete.

In this Letter we investigate the role of the PT interaction on the FDCS for single ionization in 75 keV p + He collisions ($\eta = 0.58$) using a new experimental method. For these relatively slow projectiles, we found new effects due to this interaction which are impossible to observe for fast projectiles and which are very difficult to distinguish from other effects for slow electron projectiles.

A kinematically complete experiment on single ionization requires that the momentum vectors of all three collision fragments (the scattered projectile, the ejected electron, and the recoil ion) are determined. This, in turn, means that two momentum vectors must be measured directly; the third one is then readily given by momentum conservation. So far, FDCS were obtained either by measuring the ejected electron and projectile momenta (electron impact) or the ejected electron and recoil-ion momenta directly [2,7,8,12,13]. In our approach, the fully momentum-analyzed projectiles and recoil ions are measured in coincidence. The main advantage of this method is that, from a direct measurement of the projectile momentum, a better resolution in the momentum transfer q (defined as the difference between initial and final projectile momentum) can be obtained. Thereby, smaller transverse momentum transfers become accessible, a region which turned out to be particularly interesting. Of course at the same time, our electron momentum resolution is somewhat worse, but this only starts presenting a significant restriction for electron energies of less than about 2 eV.

A proton beam was extracted with a 5 kV potential from a hot cathode ion source, accelerated to an energy of 75 keV, and collimated by a set of slits 0.1×0.1 mm in size located just before the collision chamber. It was then crossed with a cold ($T < 1$ K) neutral helium beam from a supersonic gas jet. The projectiles which did not change charge state were selected with a switching magnet, decelerated to 5 keV and energy analyzed by an electrostatic parallel plate analyzer [14]. The entrance and exit slits have a length in the $x$direction of about 2 cm and a width in the y direction of about 75 μm. The analyzer voltage was set for a projectile energy loss of $\varepsilon = 30$ eV corresponding to an ejected electron energy of $E_e = \varepsilon - I =$ 5.5 eV (where I is the ionization potential). The resolution (defined as half width at half maximum) in ε was ± 1.5 eV. Finally, the projectiles were detected by a position-sensitive channel plate detector with a position resolution of ± 50 μm. The longitudinal component (z direction) of q is given by $q_z = \varepsilon / v_p = 0.638$ a.u., where $v_p = 1.73$ a.u. is the projectile speed. Because of the narrow width of the analyzer slits, the y component of q is kept fixed at 0 and the x component is obtained from the position information. The achieved resolutions are ± 0.03 a.u. [1 atomic unit (a.u.) is the momentum of an electron in the K shell of $H = 1.99 \times 10^{-24}$ Ns $= 3.73 \times 10^{-3}$ MeV$/c$] in q_y and q_z and ± 0.05 a.u. in q_x.

The recoil ions were extracted perpendicular to the incident projectile beam by a weak, nearly uniform electric field of 1.6 V/cm. After the electric field region, the recoil ions traveled through a field-free region and were detected by a two-dimensional position-sensitive detector with about the same resolution as the projectile detector. From the position information the y and z components of the recoil-ion momentum could be determined. The x component was obtained from the time of flight from the collision region to the detector, which, in turn, is obtained from the coincidence time spectrum. The main contributor to the resolution is the temperature of the He beam, which mostly affects the y direction. Here, the achieved resolution is ± 0.1 a.u. and in the x and z directions it is ± 0.075 a.u.. The resolution in the electron momentum, which is determined from momentum conservation, is about ± 0.1 a.u. in all three directions. In the magnitude the resolution is significantly better (± 0.04 a.u.) because it is given by the resolution in ε.

In Fig. 1, a three-dimensional image of the FDCS $= d^5\sigma/(d\Omega_e d\Omega_p dE_e)$ is shown for an ejected electron energy $E_e = 5.5 \pm 1.5$ eV and a momentum transfer of $q = 0.77 \pm 0.08$ a.u. as a function of the solid angle for electron ejection Ω_e and a fixed solid angle for the scattered projectile Ω_p. The detected projectiles have a fixed azimuthal scattering angle $\Phi_p = 0°$ and a polar scattering angle Θ_p. The arrows labeled p_o and q indicate the initial beam and momentum transfer directions. A pronounced peak structure is seen approximately in the direction of q. Similar maxima are routinely observed in FDCS both for electron and ion impact [2–8,12,13] and can be explained in terms of a binary interaction between the projectile and the atomic electron (i.e., the residual-target ion is assumed to be essentially passive). It is therefore commonly referred to as the binary peak. We do not observe any noticeable contributions at all in the direction of $-q$, where one would expect to see the so-called recoil peak which is predicted by the FBA and usually observed in experimental data. The recoil peak is due to a backscattering of the ionized electron (initially ejected by a first-order interaction with the projectile in the direction of q) by its parent nucleus.

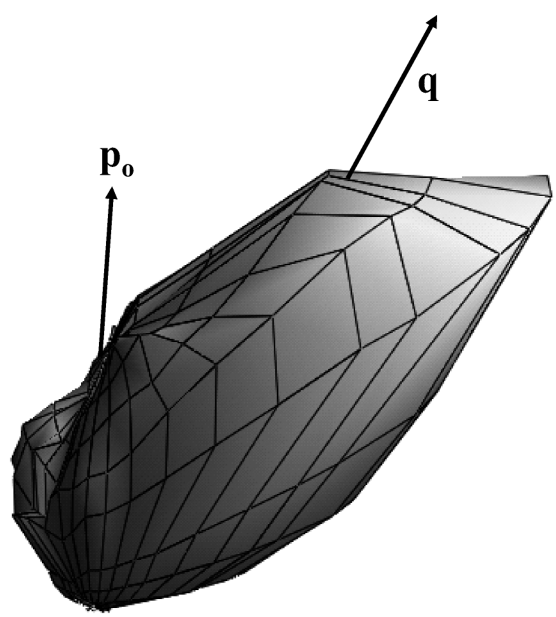

FIG. 1. Measured three-dimensional fully differential angular distribution of electrons with an energy of 5.5 eV ejected in 75 keV p + He collisions. The momentum transfer is 0.77 a.u. The arrows labeled p_o and q indicate the directions of the initial projectile momentum and the momentum transfer, respectively.

A closer inspection of Fig. 1 reveals that the binary peak is not pointing exactly in the direction of q, but rather it is somewhat shifted in the backward direction (i.e., away from the beam direction). This is more clearly seen in a cut through Fig. 1 for the scattering plane, which is shown in the center of Fig. 2 along with the corresponding cuts for momentum transfers of 0.67 ± 0.05 a.u. (bottom) and 0.97 ± 0.15 a.u. (top). Electrons ejected into the scattering plane are selected within a bin of $\Delta\Phi_e = \pm 10°$. In Fig. 2 the emission angle θ_e is measured relative to the beam direction. Angles between 0° and 180° refer to the half-plane containing q and negative angles as well as those between 180° and 270° correspond to the half-plane containing $-q$. The backward shift of the binary peak relative to q systematically decreases with increasing q from about 15° at $q = 0.67$ a.u. to no significant shift at $q = 0.97$ a.u. Furthermore, at small q a second structure is visible with a maximum at an angle approximately equal to $-\Theta_q$, where Θ_q is the direction of q. Both effects, the backwards shift of the binary peak for ion impact and a structure at $-\Theta_q$, have never been observed in any previous experiment.

The dashed curves in Fig. 2 show calculations based on the FBA. Significant discrepancies to the data are apparent. Indeed, as mentioned above, a clear recoil peak is present at $\Theta_q + 180°$, in contrast to the data. Furthermore, the absolute magnitudes are overestimated. Finally, neither the structure around $-\Theta_q$ nor the backward shift of the binary peak is reproduced. In any first-order treatment, the binary peak must be pointing in the direction of q because of momentum conservation (since any momentum transfer from the projectile to the residual-target ion is ignored). The initial momentum distribution of the electron in the bound target state gives rise to the finite width of the peak but for symmetry reasons does not affect the peak location. Therefore, the deviation in the experimental data from the direction of q is a clear signature of a higher-order mechanism.

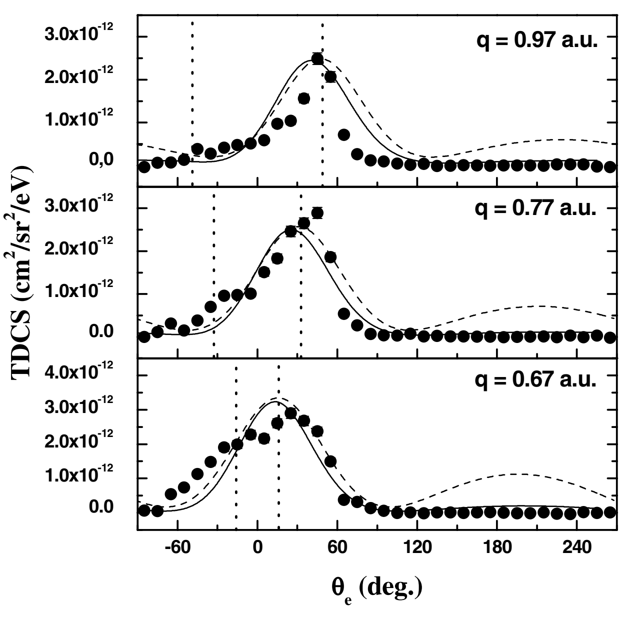

FIG. 2. Fully differential cross sections for electrons with an energy of 5.5 eV ejected into the scattering plane in 75 keV p + He collisions. The electron emission angle θ_e is defined in the text. The momentum transfers are 0.67 a.u. (bottom), 0.77 a.u. (center), and 0.97 a.u. (top). The dotted lines indicate the angles Θ_q and Θ_q, where Θ_q is the direction of q with respect to the incident projectile direction. It is given by $\cos\Theta_q = q_z/q$. Dashed lines, FBA calculations multiplied by 0.5; solid lines, three-distorted-wave (3DW) calculations multiplied by 0.2 (0.67 a.u.), 0.25 (0.77 a.u.), and 0.6 (0.97 a.u.), respectively.

The solid curves in Fig. 2 show our 3DW calculations. Although it is, like the FBA, a perturbative approach where the operator contains the projectile-electron interaction only to first order, the interactions within all particle pairs in the collision system are treated to all orders in the final state wave function. However, this wave function is exact only if at least one particle is far away from the other two. At small q the shape of the binary peak can be fitted very well (and even better in the FBA) by $A\{\cos^2[B(\Theta_e - \Theta_q)]\}$ (where A and B are constants), illustrating the large contributions from electric dipole transitions to ionization in this model. The details of this model were recently published [15]. An improved agreement with the data relative to the FBA is seen to the extent that the recoil peak is strongly reduced. But again, no backwards shift of the binary peak and no structure near $-\Theta_q$ are found. On the contrary, at large q the calculation is even shifted slightly in the forward direction relative to q. As mentioned above, this can easily be explained in terms of the PCI (i.e., a higher-order interaction between the projectile and the electron), which for ion impact cannot lead to a backwards shift. The shift observed in the experimental data must therefore be due to a higher-order process involving the PT interaction. Such a mechanism is discussed in the following.

Since the backward shift of the binary peak increases with decreasing q, which in turn favors large impact parameters, we consider cases where the projectile passes the target atom at a large distance (let us say on the left side of the target atom) and the electron stays between both nuclei. First, the projectile interacts with the electron and, since this interaction is attractive, gets scattered to the right. The corresponding momentum transfer q_e, which exclusively goes to the electron, points to the left and in the forward direction. In the second step, the projectile elastically scatters from the residual-target ion. Since that interaction is repulsive, this time the projectile is deflected to the left relative to the direction after the projectile-electron interaction. The corresponding momentum transfer q_r, which goes exclusively to the recoil ion, points to the right (for elastic scattering, the longitudinal momentum transfer is negligible). The total momentum transfer is $\vec{q} = \vec{q}_e + \vec{q}_r$. The transverse component of q is in the same direction, but smaller than the one of q_e because q_e and q_r point in opposite directions and $q_e > q_r$ since the projectile passes closer to the electron than the nucleus. At the same time, the longitudinal component of q is equal to the one of q_e so that the direction of q_e is shifted backwards relative to q. The direction of the final electron momentum p_e is basically given by q_e convoluted with the initial momentum distribution on the target. The centroid of this convolution is for symmetry reasons still the same as the direction of q_e.

A closer inspection of the 3DW results shows that the effects due to the PT interaction observed in the data is, in weaker form, present in the calculation as well. It is known that PCI becomes increasingly important with decreasing q [16,17]. Indeed, for much faster projectiles, the forward shift in 3DW calculations is most pronounced at small q. In the present case, in contrast, the opposite trend is observed. This can be explained by the present model which predicts that the ionization mechanism involving the PT interaction counteracts the PCI. At small q, the PT interaction seems to be more important in the experimental data, while in the calculation both effects are similar but opposite and cancel each other. At large q the PCI is more important in the theory leading to the forward shift in the calculation. Therefore, the role of the PT interaction appears to be significantly underestimated by theory (especially at small q), a conclusion which was also drawn from studies for fast projectiles [2].

One question that needs to be answered is why a backward shift of the binary peak was never observed in earlier studies for fast heavy-ion impact. This can easily be understood by recalling that the longitudinal momentum transfer component is given by $q_z = \varepsilon/v_p$ (see above), which is close to 0 for large v_p. Therefore, the direction of both q and q_e is usually close to 90° regardless of the momentum transfer occurring in the elastic scattering between the projectile and the residual-target ion. For electron impact, on the other hand, PCI readily leads to a backward shift, which cannot be distinguished from effects due to the PT interaction.

The peak structure near $-\Theta_q$ may be due to essentially the same mechanism as the one described above, except that here the residual-target ion stays between the projectile and the active electron [18]. Now the interaction of the projectile with the residual-target ion is stronger than with the electron. Therefore, the transverse component of q is opposite to the one of q_e while the longitudinal component is still in the forward direction. An alternative explanation is that electrons originating in the recoil peak are shifted in the forward direction by the PCI (see Ref. [8]).

In summary, we have measured for the first time fully differential cross sections for single ionization by slow ion impact. We have observed signatures of the projectile–-residual-target-ion interaction which are, because of the different kinematic boundary conditions, not observable for fast projectiles or electrons. Other signatures of this interaction, which are not discussed here, are present in the data outside the scattering plane and will be analyzed in detail in a forthcoming paper. Indications are accumulating that the description of the projectile–residual-target-ion interaction is the largest remaining problem in the theoretical treatment of the atomic few-body problem. In order to address this problem it is probably necessary to develop full four-body codes (i.e., to account for the passive electron). It makes a significant difference whether the projectile interacts with a He^+ ion (treated as one particle) or with the He^{2+} nucleus and the passive electron separately.

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