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Fully Differential Three-Dimensional Angular Distributions of Electrons Ionized in Ion-Atom Collisions

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Abstract. We compare experimental fully differential three-dimensional angular distributions of electrons ionized from He in collision with ionic projectiles covering a broad range of perturbations (0.065 to 4.4). Even at very small perturbations clear signatures of higher-order contributions are observable. At large perturbations, such contributions become even dominant, especially those involving the post-collision interaction between the outgoing projectile and the ionized electron. Our results show that single ionization is not nearly as well understood as was assumed previously.

One of the fundamental processes occurring in plasmas is obviously ionization of atoms and ions by electron and ion impact. The properties of plasmas are determined by numerous factors, which are often interrelated. Calculations of various quantities of plasmas therefore require significant modeling efforts. One important property, the degree of ionization, is to a large extent determined by the equilibrium between ionization and recombination processes. As a result, plasma modeling has to heavily rely on accurate cross sections for these processes. Usually, the demands on such data do not go beyond total or singly differential cross sections. However, if calculated data are used, it is important to test the theoretical model for its accuracy. To this end, experimental multiple differential cross sections, in the ideal case fully differential cross sections (FDCS), are most suitable as they provide the most sensitive tests.

For electron impact FDCS for ionization have been measured for several decades ((e,2e) studies) [1-3]. The vast majority of these studies were restricted to electrons ejected into the scattering plane defined by the initial projectile momentum vector $\mathbf{p_o}$ and the momentum transfer vector $\mathbf{q} = \mathbf{p_o} - \mathbf{p_f}$, where $\mathbf{p_f}$ is the scattered projectile momentum. Theoretically, rapid progress was achieved in recent years and now the experimental FDCS are well reproduced for a broad range of projectile energies by

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various models [4-6]. While qualitative discrepancies between experiment and theory remain for heavy targets [7], it was generally held that ionization of light targets (H and He) by charged particle impact is essentially understood. However, this assumption is to a large extent based on experiments performed for restricted ejected electron geometries and exclusively on studies for electron impact.

FDCS measurements for ionization by ion impact are significantly more challenging than for electron impact. The reason is that for heavy ions at large energies, a direct measurement of the scattered projectile momentum is practically impossible because the scattering angle and the projectile energy loss are usually immeasurably small. The only fully differential data obtained from a direct projectile momentum analysis were reported recently for H_2^+ and proton projectiles at intermediate energies [8,9]. For heavy ions at large energies, fully differential measurements on ionization processes became feasible only with the development of recoil-ion momentum spectroscopy [10]. Since then several fully differential experiments have been performed by measuring the momentum-analyzed recoil ions and electrons in coincidence and deducing the scattered projectile momentum from momentum conservation [11-14]. For electrons ejected into the scattering plane and for small perturbations (projectile charge to velocity ratio), similarly good agreement between theory and experiment for electron impact was obtained [15]. However, serious discrepancies were found at very large perturbations [13] which are not accessible by electron impact (because it would require a projectile energy below the ionization threshold).

The advent of recoil-ion momentum spectroscopy not only made possible fully differential measurements on single ionization by ion impact, but more importantly, the use of two-dimensional position sensitive detectors for both the recoil ion and the ejected electron allows for efficient measurements of the FDCS for the entire three-dimensional space in a single experiment. In contrast, to obtain the equivalent data in a traditional (e,2e)-experiment would require tens of thousands of measurements. Recently, we reported three-dimensional plots of the FDCS for single ionization of He for ion impact at very small perturbation [12]. While the data were well reproduced for the scattering plane, surprisingly large discrepancies were found outside the scattering plane.

Both the results for ion impact at large perturbation and outside the scattering plane show that single ionization is not nearly as well understood as was assumed previously. Furthermore, they hint that the underlying ionization mechanisms for electron and ion impact may not be the same. Therefore, a rich collection of fully differential data for ion impact is needed. Here, we present three-dimensional images of FDCS for a broad range of perturbations and different kinematic conditions.

The experiments were carried out with 3.6 MeV/amu Au^{53+}, 100 MeV/amu C^{6+}, 2 MeV/amu C^{6+}, 6 MeV p, and 75 keV p projectiles. For the first four projectiles the momentum vectors of the recoil ion and the ionized electron and for the last projectile those of the recoil ion and the scattered projectile were measured directly. The beams collided with He-atoms from a supersonic gas jet. In the former method, the projectiles which did not change charge state were selected by a switching magnet and detected by a scintillator. The recoil ions and the ionized electrons were extracted in the longitudinal direction (defined by the initial projectile direction) by a weak electric field and detected by two-dimensional position-sensitive channel plate detectors. The electron detector was set in coincidence with both the projectile and the recoil ion detectors. A weak uniform magnetic field forced the electrons into cyclotron motion and guided them onto the detector. The transverse momenta of the electrons and the recoil ions were calculated from their position on the respective detector and their longitudinal momentum components were determined from the time of flight. The momentum vector of the scattered projectile was deduced from momentum conservation.

In the experiment using the second method (applied to the 75 keV p projectiles) the ionized electron was not detected. Instead, the scattered projectiles were momentum analyzed. This was accomplished by measuring the energy loss with an electrostatic parallel plate analyzer, thus providing the magnitude of the momentum. In order to achieve sufficient energy resolution, the projectiles were decelerated to an energy of 2 keV before entering the analyzer. The direction of the momentum vector was obtained by measuring the scattering angle defined by two collimators located before and after the target chamber. The scattering angle could be varied by rotating the entire set-up from the target chamber to the ion source about the center of the target chamber. The recoil ion momentum spectrometer is very similar to the one used in the first experiments. The most important difference is that the recoil ions were extracted in the transverse rather than in the longitudinal direction.

In Fig. 1 we show three-dimensional images of the fully differential angular distributions of the ionized electrons for a) 6 MeV p+He, b) 100 MeV/amu C^{6+} + He, c) 75 keV p + He, d) 2 MeV/amu C^{6+} + He, and e e) 3.6 MeV/amu Au^{53+} + He. The electron energy/momentum transfer combinations are a) and b) 6.5 eV/0.75 a.u., c) 5.5 eV/0.65 a.u., d) 1 eV/1.5 a.u., and e) 20 eV/1.0 a.u.. The arrows labeled p_o and q indicate the direction of the initial projectile momentum and the momentum transfer (defined as the difference between initial and final projectile momentum), respectively. The plots are presented in order of increasing perturbation.

For the small perturbations (parts a) and b) in Fig. 1) the data for the scattering plane exhibit the characteristic double lobe structure, well known from electron impact studies (e.g. [2]), with the binary peak in the direction of q and the recoil peak in the direction of –q. Earlier, we reported that although a state-of-the-art calculation based on the continuum distorted wave approach (CDW) reproduced the data for the 100 MeV/amu C^{6+} projectiles very well in the scattering plane, there were distinct discrepancies outside the scattering plane [12]. More specifically, in the theoretical cross sections the recoil peak is completely separated from the binary peak by a sharp minimum at the origin. In the data, in contrast, these peaks are only separated in specific planes (those containing the initial beam axis). In three-dimensional space the recoil peak emerges as a “recoil ring” with a “hole” in the middle which in the xy-plane smoothly merges into the binary peak. These discrepancies were attributed to a higher-order mechanism involving the interaction between the projectile and the residual target ion. The relative importance of such a higher-order process was quite surprising, especially considering the small perturbation of 0.1. In the case of the 6 MeV p + He data, the perturbation is even smaller (0.065). Nevertheless, the shapes of the three-dimensional FDCS for these two projectiles are essentially identical. This suggests that the mechanism leading to the “ring-like” shape of the recoil peak does

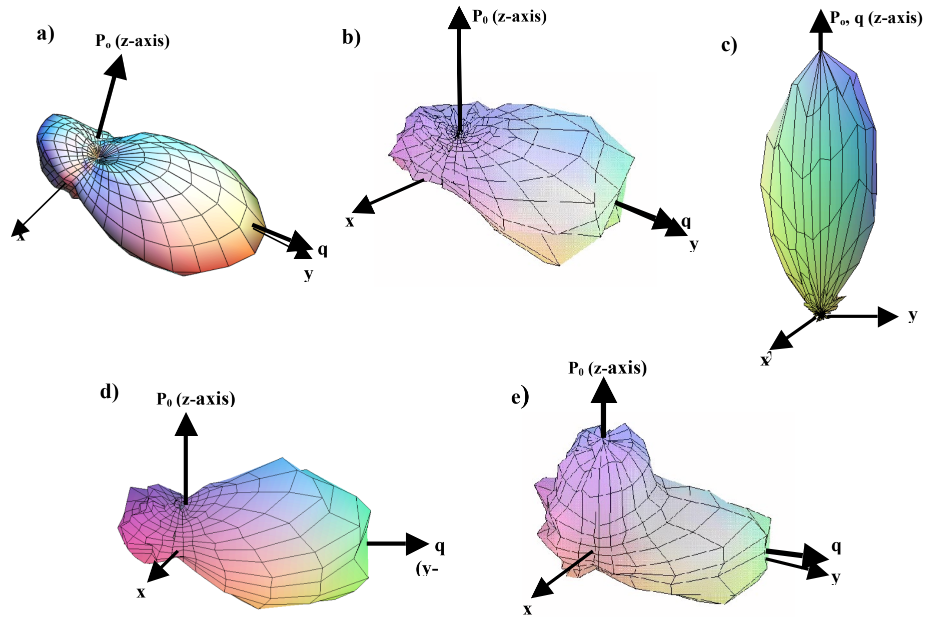

Figure 1. Fully differential three-dimensional angular distributions of electrons ionized from He in collisions with a) 6 MeV p, b) 100 MeV/amu C6+, c) 75 keV p, d) 2 MeV/amu C6+, and e) 3.6 MeV/amu Au53+.

not depend strongly on the projectile mass and charge. Therefore, one might expect similar features for electron impact as well.

With increasing perturbation, in addition to the "ring-like" shape of the recoil peak (which is always present except for the 75 keV projectiles, which will be discussed below) a new feature is observed in the forward direction. As mentioned above, for small perturbations we find a pronounced minimum in the direction of p_o. For the 2 MeV/amu C^{6+} projectiles (perturbation of 0.8), the "hole" in the middle of the "recoil ring" is filled up so that here we no longer find a minimum in the forward direction. Increasing the perturbation further to 4.4 (3.6 MeV/amu Au^{53+} projectiles) finally leads to a pronounced and separate peak in the forward direction. This forward peak is a signature of the post-collision interaction (PCI) between the outgoing projectile and the ionized electron. Earlier, we found that even state-of-the-art calculations accounting for PCI do not reproduce this feature [13]. More recently, we demonstrated that a complete description of PCI is required to account for the projectile–residual target ion interaction [16]. Therefore, the theoretical difficulties in describing the forward peak at large perturbations and the shape of the recoil peak at small perturbations may originate from the same source.

The data for the 75 keV p projectiles do not seem to follow the trend, with increasing perturbation, of the other data sets. We observe as the only structure a peak in the forward direction, which might lead to the impression that here PCI is even more important than for the 2 MeV/amu C^{6+} projectiles although the perturbation is smaller. However, it should be noted that in the p case the momentum transfer is pointing in the forward direction, i.e. the forward peak can be associated with a binary peak and is thus not necessarily related to PCI. Nevertheless, another observation does point to strong PCI effects: there are no contributions at all to the FDCS in the backward direction, i.e. the recoil peak is completely absent. This is an unexpected finding since it is well known that in the first Born approximation the recoil to binary peak intensity ratio increases monotonically with decreasing q [3]. Within a first-order approximation, the data for the 75 keV p projectiles thus should show the largest recoil peak among the data sets shown in Fig. 1. On the other hand, in CDW-EIS calculations, which account for both PCI and the projectile–residual target ion interaction, the recoil peak was also completely absent [9]. However, these calculations showed serious discrepancies in magnitude to experimental data.

The data for the 75 keV p projectile raises the question of why for 2 MeV/amu C^{6+}, which corresponds to a slightly larger perturbation, PCI effects don't appear to be as pronounced. The reason is that the importance of PCI does not only increase with perturbation, but also with decreasing relative speed between the projectile and the ionized electron [17] and with decreasing transverse momentum transfer (i.e. scattering angle) [18]. In the p case the relative speed and transverse momentum transfer are about 1.0 a.u and 0 compared to about 9 a.u. and 1.5 a.u., respectively, for the C^{6+} projectiles.

In summary, we have presented an overview of the experimental work that has been done on three-dimensional imaging of fully differential single ionization cross sections in atomic collisions. The results show that our understanding of ionization processes is not nearly as complete as was assumed earlier based on measurements for restricted collision geometries. Even for very small perturbations higher-order contributions are not entirely negligible and are not yet satisfactorily described by theory. At very large perturbations, where higher-order contributions can even dominante, not even qualitative agreement between experiment and theory is achieved [13,14].

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