Triply differential ionization of Ar by 500 eV positron and electron impact

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Abstract. Coincidences between recoil ions-ejected electrons and recoil ions-scattered projectiles have been used to study the kinematics of electron and positron impact ionization. Triply Differential (TDCS) data for 500 eV positron and electron impact on Ar are presented here as function of scattering angle for a given range of energy losses. Binary and recoil interactions can be distinguished allowing us to determine the relative intensity between those interactions. Preliminary integration of the data indicate an enhancement of the binary region for positron interaction while for electron impact the intensity of the recoil and binary interactions is comparable.

1. Introduction
For decades, studies of inelastic atomic processes have played a major role in atomic physics. Basic properties such as energy and momentum transfer can be used to provide information about how the particles interact before, during, and after the collision. This, in turn, provides information about the time evolution of the Coulomb forces, how the energy is deposited into the target, and which ionization channels are active for different collision systems and energies.

With respect to the traditional electron impact studies [1,2], collisions involving positrons provide a powerful tool since they allow probing regimes where electron impact cannot provide new information. For instance, if we consider ionizing interactions in which the projectile has a large energy loss, for electron impact it is impossible to determinate if the observed electron was ejected from the atom or if it was a scattered projectile. Positron studies also address the question of how the projectile charge affects the collision. As an example, is well known that for large impact velocities, single ionization cross sections follow the Born approximation which is proportional to the square of the projectile charge; therefore they are independent of the sign of the charge. (We should point out, however, that a recent study performed by Cavalcanti et al. [3] imply that differences due to projectile mass or charge occur in single ionization of heavy atoms.) In contrast, a comparison between positron and electron impact show that double ionization cross sections for electron impact are about 2 times larger [4]. Thus, positron impact studies combined with electron impact information provide additional insight into the kinematics and mechanisms associated with inelastic atomic interactions.

From the theoretical point of view, differential, rather than integral, measurements are more attractive since they provide a very sensitive testing ground for models of the atom and descriptions of the mechanisms taking place during the interaction process. Differential measurements contain
information that is often hidden within integral cross sections. In order to advance towards a full description of the dynamics dominating the collision and to test the theoretical models in the most critical fashion, fully differential studies are required. A number of theoretical predictions exist for positron impact [5-7]. But on the experimental side, few studies involving differential measurements are available. The main difficulties in measuring positron impact differential cross sections are related to the low intensity of the positron beams. Advances on the methods for beam production, transport and detection (see for example the review of Surko et al. [8]) and the development of techniques such as RIMS, COLTRIMS, as well as multi-coincidence measurements [9,10] are now making it possible to start performing differential studies for positron impact. To date, positron impact experiments have included total scattering cross sections measurements [11] in which information for elastic and inelastic processes are presented, measurements of positronium formation cross sections [12-14] and measurements of partial cross sections for inelastic processes [15-18]. Plus a few groups have been able to acquire singly differential data [19] as well as perform doubly differential electron emission studies [20-22].

In this paper we describe experiments in progress at the University of Missouri-Rolla in which over the last several years we have developed techniques which are allowing us to perform even more detailed studies for positron interactions with atoms [23-25]. These studies have evolved to the point where we have recently gone beyond all previous studies and measured doubly and triply differential cross sections (DDCS and TDCS, respectively) for single ionization of Argon induced by 500 eV positron impact. In addition, singly differential cross sections have been measured for double and triple ionization. Examples and comparisons to electron impact data which we have obtained under identical experimental conditions are presented. These comparisons illustrate projectile charge related differences which will hopefully provide new insights and test theoretical models in greater detail than previously possible.

2. Experimental
For a detailed description of the experimental device the reader is referred to [26] and references therein. In brief, our apparatus consists of a positron beam produced by a $^{22}$Na radioactive source and a tungsten mesh moderator. The beam is conducted to the extraction region by means of an electrostatic transport system. At the interaction region, the beam interacts with a target consisting of a simple gas jet emerging from a needle. To identify ionizing collisions, target ions are extracted by means of a weak uniform electric field (see Figure 1). Because the electric field influences the trajectories of low energy ionized electrons, which we also measure, field uniformity was tested by observing the 2D recoil ion distributions as a function of the position and small voltages applied to the needle. As seen in Figure 2, uniform field conditions produce a recoil target ion distribution that is symmetric and centered on the beam path whereas non uniform conditions do not.

![Figure 1](image)

**Figure 1.** (Colour online) Experimental apparatus used for TDCS and DDCS data acquisition. The green (red) arrows correspond to binary (recoil) events. Binary events being collisions with a “free” target electron and leading to the electron being ejected in the forward direction. Since it is detected above the beam direction, the projectile must scatter below the beam direction. In recoil events, the ejected and scattered particles are both above the beam direction.
Referring again to Figure 1, after the ions and ejected electrons exit the extraction region they pass through a couple of grids used to generate “field free” regions. After this, the ions are counted by a channeltron detector and the ejected electrons by a position sensitive (PSD) channelplate detector. The electron detector is sensitive to a cone of emission angles which is normal to the direction of the beam. Thus emission angles, $\theta_e$, between 45 and 135 degrees along the beam direction and $\phi_e$ between $\pm45^\circ$ perpendicular to the scattering plane (defined by the incoming and scattered beam directions) are measured. Note that these angles are in the absence of the extraction field; when the electric field is present the angular acceptance is altered, with the amount dependent upon the ejected electron energy. Any post-collision projectiles that are scattered within $2.4^\circ$ horizontal and $7.5^\circ$ vertical, $\phi_p$ and $\theta_p$, pass through a vertical slit which defines a scattering plane. They then enter an electrostatic energy analyzer (indicated only schematically in Figure 1) which focuses projectiles with different $\phi_p$ scattering angles but the same energy onto a second PSD. There is no focusing for the $\theta_p$ direction; thus projectile scattering angle information is preserved. Therefore, two dimensional spectra are generated by the projectile detector to provide information about both the energy loss, $\Delta \varepsilon$, and scattering angle, $\theta_p$, of the projectiles.

![Figure 2](image.png)

**Figure 2.** (Colour online) Recoil profile for a 500 eV electron beam, 3mm width. The needle is +3 mm above where the beam position was defined for the left figure, and -0.5 mm for the right figure. In this case the extraction voltage used was ±10 V.

Finally, data are acquired and stored in list-mode fashion using a multi-input time-to-digital converter and a computer. One portion of the TDC is devoted to scattered projectiles and another to ejected electrons with all being measured in coincidence with recoil ions. This generates time of flight (TOF) spectra for both the scattered projectiles and the ejected electrons. By analyzing these spectra it is possible to identify different ionization states. Sorting the 2D projectile and electron spectra can then be done for different degrees of ionization while sorting and combining the 2D spectra provides information on the kinematics for single or multiple ionization processes.

### 3. Analysis of Results

To determine the TDCS, the ejected electron 2D single ionization data, e.g., electron-recoil ion coincidences, were sorted using conditions where a small range of projectile energy losses and scattering angles are selected for the scattered projectile-recoil ion 2D single ionization coincidence spectra (see Fig. 3, left side). These data, shown in the polar plot (Fig. 3, right side) for a particular energy loss, e.g., ejected electron energy, and projectile scattering angle, provide a fully kinematic description of the collision. However, it is important to note that these data are influenced by several experimental factors which include geometrical factors due to angular dependent transmission probabilities through the grids, large interaction volume, small projectile scattering angles, and overlap of the beam and target. In addition, extraction field effects which depend on the ejected electron energy and the initial ejection angle and a range of energy losses because of the large beam diameter and sorting parameters must be taken into account. All of these influence the shapes and magnitudes of the TDCS polar plots. Therefore a detailed model of the electric fields and apparatus geometry was used to convolute “ideal” binary and recoil distributions over these experimental conditions [26]. The results based upon a best fit are the solid curves shown in figure 3. The red curves indicate the contributions from “real” binary and recoil events while the blue curves represent “false” events which
result from low energy ejected electrons being turned around by the extraction field and being falsely identified as recoil rather than binary events and visa versa. The black curve is their sum and is seen to fairly well represent our measurements.

Another way of analyze the same data is by sorting the projectile TDCS 2D data corresponding to forward and backward electron emission. Because forward electron emission is predominantly due to binary interactions while backward emission is primarily due to recoil interactions, this method provides information about the relative intensities of binary and recoil interactions as a function of energy loss and scattering angle. Following this procedure, 2D spectra were generated as shown in figure 4. For zero electric field in the interaction region and if the binary and recoil lobes do not overlap, the left portion should contain only projectiles which scatter down (see Fig. 1 caption) and the right portion should contain only projectiles which scatter up. For 500 eV impact, each horizontal channel corresponds to an energy loss of approximately 1 eV and each vertical channel to a scattering angle of 0.2°. As before, the yellow dots represent the beam size and location and therefore the position for zero scattering and energy loss.

Figure 4 illustrates how the TDCS projectile binary events form a well defined ridge, although some false events associated with electrons which were turned around by the electric field appear above the zero scattering angle (the beam position). For electron impact (not shown here), the same sorting was made. In this case, the binary ridge was broader and the data much more diffuse along the energy loss axis. Then, for both positron and electron impact, the relative intensities of binary to recoil events were determined as a function of energy loss and scattering angle. This has been done for a range of energy losses of 5 to 15 eV as shown in Figure 5. Here the horizontal arrow corresponds to the halfwidth of the beam. These preliminary results indicate that for positron impact the relative
intensity of binary to recoil interactions increases with projectile scattering angle. In contrast, for electron impact both interactions have practically equal probabilities for the same angular range.

**Figure 5.** (Colour online) Ratios of binary to recoil interactions as a function of projectile scattering angle. Data are for single ionization of Ar induced by 500 eV electron and positron impact. The horizontal arrow corresponds to the beam halfwidth.

**Figure 6.** (Colour online) Ratios ($R_{2,1}$) of double to single ionization, $d\sigma_2(\theta_e) / d\sigma_1(\theta_e)$, for differential electron emission for positron (upper figure, see ref. [28]) and electron (lower figure) impact. Lines are to guide the eye.

Our methods also allow us to go beyond single ionization. Here the subject of interest is to describe the different multiple ionization mechanisms. To approach this issue, we have considered the angular distributions for electron emission (the integral over all ejected electron energies). In this case, ejected electron-recoil ion coincidences are used in order to generate 2D ejected electron spectra for single, double, and triple ionization. Then, angular distributions were obtained by taking slices along the beam direction. To reduce uncertainties due to electric field and geometry effects, ratios of multiple to single ionization ($R_{q,1}$) are used to compare positron and electron impact double ionization data in figure 6 where distinct differences are noted. For electron impact, the ratio is flat within statistics while for positron impact the ratios increase in the backward direction. Although not shown here, the triple ionization ratios exhibit the same shape for both electron and positron impact with the shape being similar to that shown here for double ionization by positrons. A possible explanation for the increase in the backward direction is many body effects, specifically with the nucleus. A possible explanation of the flat ratio for electron impact is that here the double ionization is achieved via two independent ionization processes where each interaction is effectively equivalent to a single ionization process. Thus, a constant ratio is expected. Additional data may help explain these observations.

4. Remarks

TDCS information has been presented for single ionization of Ar by positron and electron impact. Typically previous studies have presented such information only for the ejected electron channel, but our method allows us to also generate TDCS information for the scattered projectile channel. This has permitted us to observe distinct differences between electron and positron impact ionization kinematics. In addition, our method allows us to go beyond single ionization and to observe differences in the double ionization channel. Future studies are planned to investigate both features further and possibly over a larger range of experimental parameters.
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