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Differential Cross Sections for Ionization of Argon by 1 keV Positron and Electron Impact

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Abstract. Differential information was generated by establishing coincidences and imposing conditions on data recorded for target ions, scattered projectiles, and ejected electrons, as a function of projectile energy loss and scattering angles; in order to describe the interaction between a positron (electron) 1 keV beam and a simple Ar jet. Single ionization triply differential cross section (TDCS) results exhibit two distinct regions (lobes) for which binary (events arising from 2-body interaction) and recoil (events which can only be produced by many-body interactions) interactions are associated. Results indicate that binary events are significantly larger for positron impact, in accordance with theoretical predictions. A similar feature is found for different energy losses and scattering angles. Intensity of the recoil lobe for both projectiles, positron and electron, is observed to depend on the energy loss and scattering angle. Also, it can be noticed that for positron impact the recoil interactions intensity is larger than that observed for electron impact.

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. Generally these kind of studies focus on measurements of ionization probabilities or attempts to describe the kinematics involved during and after the collision process. More recently, ionization by anti-particle impact (positron and anti-proton) has been a trending topic for both theoretical and experimental physicists. Recent experimental studies involving positrons use gas atoms in the form of a jet [1], in which individual interactions between the involved particles can be easily described. The aim of such experiments is to provide accurate information on the similarities or differences between the particle-matter and antiparticle-matter interactions; isolating certain channels or processes, in order to test theoretical models in detail. The importance of such tests arises from the fact that while first-order

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perturbation theories, like the Born approximation, predict identical total and differential cross sections for high-energy particle and antiparticle impact, recent more sophisticated approximations predict differences. Specifically, these theories predict that the electron emission distributions as a function of the momentum transfer depend on the projectile charge [2,3,4]. The interactions may be classified into two types: binary electron emission, in which the other bound electrons and target nucleus act as spectators, and recoil emission, which are interactions where the ejected electron interacts with the target nucleus as it leaves. Theory predicts an enhancement (decrement) of the binary electron emission for positron (electron) impact, whereas for recoil emission the opposite effect is expected. There is also expected to be a dependence on the sign of the projectile charge, and that directions of the binary and recoil lobes will shift with respect to the momentum transfer direction [5].

This work is part of a series of experiments that allowed us to achieve a direct comparison of positron and electron impact with fully kinematic data, measured for a range of electron emission angles and energies. The use of identical experimental conditions for both positron and electron impact, allowed to minimize uncertainties associated with the use of different apparatuses. The outcome of such work is that, after decades, the different results provided by diverse theoretical predictions can finally be tested. Through the results from this work and previous studies [6,7,8] it is possible to establish how atomic interactions such as electron exchange, polarization effects, and postcollision interactions influence important physical magnitudes, e.g. momentum transfer, allowing to achieve a better understanding of positron interactions, which is a trending topic in a variety of fields, ranging from fundamental studies of quantum electrodynamics (QED), gravitational forces on antimatter [9], to diverse applications such as positron emission tomography (PET) imaging in medicine [10,11,12], or characterization of materials by techniques such as angular correlation of annihilation radiation (ACAR) [13,14,15]. A more comprehensive list of applications of positrons in different areas can be found in [16]. In this work triply differential cross section (TDCS) information is presented for 1 keV positron and electron impact single ionization of Argon. Results are arranged in two fashions, one presents TDCS data as a function of projectile scattering angle and energy loss considering electron emission for a broad range of angles, allowing to describe relative intensities for binary and recoil interactions. The other presents TDCS data as ejected electrons angular distributions, measured as a function of momentum transfer, is this sort of data that directly provides information for comparing experiments and theoretical predictions for the intensities and directions of the electrons emitted in the binary and recoil lobes

2. Experimental Method

A positron beam was produced by a ^{22}Na radioactive source and a tungsten moderator, and then delivered to the target by means of an electrostatic transport system. While the electron beam was generated by an electron gun inserted into the same beamline, in such a way that the electron beam entered the scattering chamber via the same input aperture and following the same trajectory used for positron impact. As displayed in Figure 1, Argon ions coming from a simple gas jet and created during the collision of the projectile and the target were extracted by a weak electric field (1.2 V/cm) and then recorded by a channeltron (recoil detector). Charge state and mass are distinguishable by means of Time of Flight (TOF) techniques. Projectiles leaving the interaction region are selected and then recorded as a function of their scattering angle and energy loss using an electrostatic energy analyzer (spectrometer) followed by a position sensitive detector (PSD) in the form of a channelplate. Electrons emitted from the collision were recorded as a function of their detection angle using a second PSD positioned above the interaction region and forming a normal angle with respect to the beam direction. By establishing coincidences between singly ionized target atoms and scattered projectiles it was possible to generate doubly differential cross section (DDCS) information as a function of both scattering angle and energy loss. Coincidences between target ions, scattered projectiles, and ejected electrons provided TDCS that could be associated either for the scattered projectile or for the ejected electron. It is important to note that the TDCS data presented here corresponds to electrons of a single given energy, which are detected between roughly 30 and 150 degrees with respect to the beam direction. Thus, they represent an integral intensity of the portions of the binary and recoil electron emission lobes that we can observe. In the 2D spectra generated for scattered projectiles, the vertical axis corresponds with the projectile scattering angles, in degrees, and the horizontal axis is the energy loss in eV. Negative (positive) scattering angles imply that the projectile is scattered vertically downwards (upward). Because of the location of our electron detector (see figure 1), only "upward" emitted electrons were recorded. Thus, the TDCS intensities for negative scattering angles, i.e. correlated downward scattered projectiles and upward emitted target electrons, are a direct indication of binary events since the scattered projectile and ejected electron are detected in opposite hemispheres. Likewise the intensities for positive scattering angles indicate recoil events since here both particles are detected in the same hemisphere. Forward scattered projectiles were limited to a horizontal scattering range of 0° ± 2.4° by a slit at the entrance to the energy analyzer and to vertical scattering angles less than ± 7°, this is a geometric restriction due to projectile channelplate size and its distance from the interaction region. It is possible to select diverse energy loss ranges, by adjusting the electrostatic spectrometer voltages. But typical maxima for energy losses were of about 25% of the impact energy, mostly due to insufficient statistics at higher energy loss. In this work, impact energies of 1 keV have been investigated. No direct energy analysis of the ejected electrons was used. Instead, their energies were determined by the coincidences with projectiles that suffered a particular and known energy loss, which in turn, for single ionization unequivocally defines the ejected electron energy.

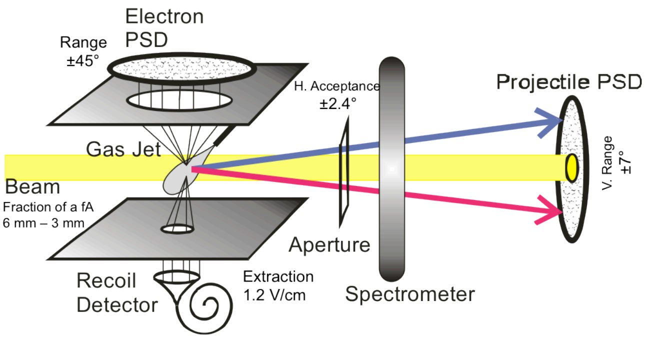

Figure 1. Experimental apparatus used for differential measurements, and some of the experimental parameters employed.

It is well known that energies, angles, and probabilities for the ejected electrons are strongly influenced by some of the experimental conditions. For example, the electric field used to extract the target ions can significantly modify both the directions and acceptance ranges of the recorded ejected electrons. This is even more noticeable for very low ejected electron energies, which, depending upon their initial energy and direction can even be turned around. To minimize the presence of such problems, the extraction field was kept as low as possible. By using SIMION simulations and a detailed model of the interaction volume and fields, we found that such problems were minimal for emission energies above a few eV. Since it was essential to achieve sufficient statistics for positron impact, a relative large beam diameter (6 mm) and projectile scattering angle and energy loss bins of 1° and several eV were used. Resulting in a range of emission energies (energy losses), rather than a single energy, which contribute for any particular energy loss data point. Because a range of electron energies is involved, a range of electric field effects and uncertainties in correlating the observation and emission angles of the detected electrons results. This inhibits a direct solid angle adjustment of the raw data in order to compare with theory. Because of this, raw data has to be convoluted with experimental parameters in order to be compared with other experiments or theoretical predictions. A program for doing this was developed and briefly described in a recent publication [14]. Additional experimental details can be found in references [12,13,14]

3. Data Analysis and Results

Raw data were recorded under list mode files by using Cobold software. Such files can be resorted afterwards in different fashions in order to generate different information, which can be displayed like a TOF or two-dimensional (2D) spectra. Analysis of TOF spectra allowed distinguishing different ionization degrees of the target ions. By imposing different conditions on coincidence events, it is possible to go further than the TOF information, allowing for data to be sorted as 2D spectra in two different fashions: the first one takes into account the scattered projectiles and then sorts the rest of the information, and the second one by looking at the ejected electrons and then sorting the other data.

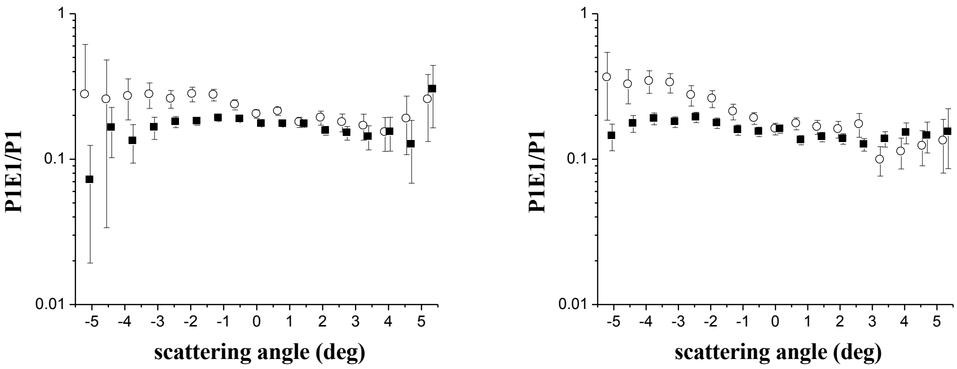

Figure 2. Comparison of the ratios of projectile and ejected electron coincidence P1E1 (broken symmetry) over scattered projectile events P1 (symmetric) for 17 eV (left) and 70 eV (right) energy losses as a function of projectile scattering angle. Empty circles correspond to positron impact and solid squares correspond to electron impact.

The projectile scattering can be described by comparing the single ionization projectile-electron coincidence 2D scattered projectile spectra (P1E1) and the single ionization scattered projectile spectra (P1) for different energy losses (see Figure 2). There is an important difference between P1 and P1E1 coincidences. P1 interactions show symmetric scattering with respect to the beam axis. However, if scattering is measured in coincidence, then symmetry is broken and two types of interactions, named binary and recoil can be distinguished. Since the position of the emitted electron detector is above the scattering center, the indication of a binary interactions is when a projectile scatters down and is in coincidence with an upward emitted electron i.e., P1E1 coincidences for negative scattering angles. Vice versa, the upward scattering P1E1 coincidences indicate recoil interactions, i.e., where the projectile scatters upwards and the electron is emitted in a downward direction but is turned around by the nucleus and ends up being detected in the upward direction. In order to remove any experimentally introduced scattering non-symmetry for downward and upward scattering, ratios shown in figure 2 were calculated for each energy loss. These ratios show that electron impact results in near-isotropic projectile scattering compared to a positron ratio that displays larger binary scattering yield.

The single ionization electron-projectile coincidence 2D electron emission spectra (E1P1) in combination with P1E1 spectra will provide all kinematic (triply differential) information for every single ionization event. Traditional method of displaying TDCS is a plot of angular distributions for the emitted electron-scattered projectile coincidence intensity as a function of the emission angle, as is shown in figure 3. Positron impact induced emission intensity results have been scaled by a factor of 3.9 as a result of the raw P1 statistics and due to the fact that positron and electron impact total single ionization cross sections are roughly equal. For different energy loss ranges and for both projectiles, the binary to recoil intensity ratio is shown to increase with increasing scattering angle and momentum transfer. Also, as expected for intermediate momentum transfer, $0.2 \leq q \leq 1$ a.u., the symmetry of the recoil lobe no longer coincides with the momentum transfer direction [17]

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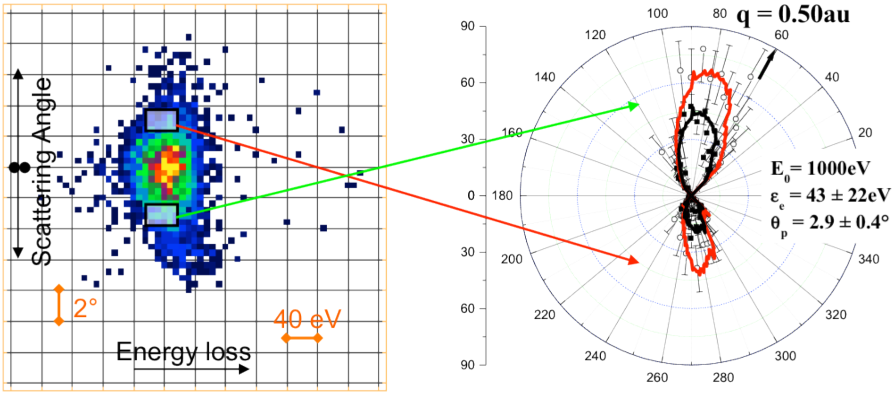

Figure 3. TDCS for single ionization of Ar by 1 keV positron (open circles) and electron (solid squares) impact. Left: Projectile TDCS data (P1E1) as a function of energy loss (eV) and scattering angle (degrees), calibration is as indicated in the figure. Right: TDCS emitted electron intensity (vertical axe), as a function of emission angle for positron (open circles) and electron (solid squares) impact. The lines are fits to the data. Proejctile energy loss is 43 eV and scattering angle is 2.1°.

TDCS information (Figure 4) provides differences between positron and electron impact emission, positron impact yields higher binary intensity in agreement with theoretical predictions [18], though larger recoil intensity for electron emission due to positron impact is shown as well. There is also indication of a broader recoil lobe for positron impact, suggesting different charge effects with respect to projectile-ion interactions. These parameters also indicate a forward shift of binary emission for positron impact and differing recoil lobe centers (see figure 4).

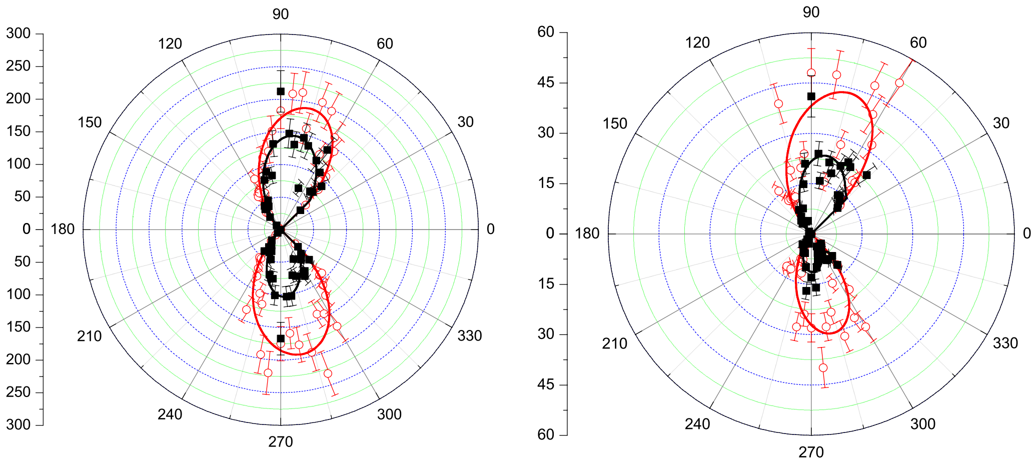

Figure 4. TDCS emitted electron intensity (vertical axe), as a function of emission angle. Positron impact is represented by red hollow circles and electron impact by black solid squares. Both figures correspond to an average projectile energy loss of 21±16 eV. Projectile scattering angles are 1.2±0.4 (left) and 2.9±0.4 (right), with corresponding momenta transfer of 0.24 au and 0.46 au. Solid lines are polynomial fits to the data and intended only to guide the eye.

4. Remarks

TDCS information has been presented for single ionization of Ar by 1 keV 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.

A convolution of the raw experimental information and experimental parameters lead to a direct comparison of the positron and electron impact data, showing in turn that binary events are significantly larger for positron impact. This same feature is found for different combinations of energy losses and scattering angles. Such enhancement could arise from the impact parameter changing as a result of interactions between the incoming projectile and the partially screened target nucleus; a reduced binding of the atomic electrons due to the attractive potential of the incoming positrons; or the change on the interaction probabilities as a result of polarization of the target's atomic cloud by the incoming particle. While for recoil events, its relative intensity for both, positron and electron impact, is observed to depend on the energy loss and scattering angle and, opposite to lower energy collisions, here the recoil relative intensity increases significantly when decreasing the projectile scattering angle. Another substantial difference found from TDCS information is that, for positron impact, the recoil interactions intensity is always noticeably larger than that observed for electron impact.

There is a growing interest for performing direct comparisons on how the particles and anti-particles interact with the matter, and since it could be possible to perform similar studies for protons and anti-protons in a near future, such comparisons will provide a contribution in order to acquire a detailed knowledge of charge and mass effects on the interaction dynamics.

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