Differential Positron and Electron Ionization Studies: How a Plus or Minus Sign Makes a Difference

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Abstract. Doubly and triply differential data for single ionization of argon, neon and molecular nitrogen have been measured for positron and electron impact energies of 200, 250, and 500 eV. Ratios of triply to doubly differential ionization yields as functions of the projectile scattering angle and energy loss are compared in order to investigate differences associated with the sign of the projectile charge. For all three systems, systematic differences are observed in the relative contributions of binary interactions. These differences are shown to increase with increasing scattering angle. Nearly identical recoil intensities are found for positron and electron impact ionization of the atomic targets but not for the molecular target.

1. Introduction

Since the advent of atomic physics, a multitude of experimental and theoretical investigations have studied inelastic interactions between atomic particles. The vast majority of these studies employed electrons and ions as one of the collision partners and many studies measured ionization probabilities or studied the inelastic interaction kinematics. With the discovery of the positron, and later of the antiproton, similar studies have been performed using antiparticles. These studies are performed in part to provide information about similarities and differences between matter-matter and antimatter-matter interactions and in part to isolate and study specific interaction channels and processes in order to test theoretical models in more detail.

Several commonly used theoretical models treat the interaction using first-order perturbation theory. For these models, since the interaction probabilities are proportional to the square of the projectile charge, identical total--and differential cross sections are predicted at higher energies for matter and antimatter impact. In contrast, more sophisticated treatments predict distinct differences in the differential electron emission measured as a function of the momentum transfer for positron and electron impact. Examples of this are the triply differential ionization cross section calculations for ionization of helium and atomic hydrogen [1-3]. With respect to a first Born model, these models predict that the binary intensities in fully differential positron impact studies are enhanced while the recoil intensities are reduced. For electron impact, just the opposite effects are predicted, e.g., a reduction in the binary intensity and an increase in the recoil intensity. These models also predict that the directions of the binary and recoil lobes will be shifted with respect to the momentum transfer direction, with the direction of the shift depending on the sign of the charge. More recent calculations predict similar features for ionization of H2 [4].
Unfortunately, testing these predictions was not possible until recently. This is because limited positron beam intensities restricted experimental measurements of individual atomic interactions to integral type measurements, for example, to total cross section measurements of single and multiple target ionization or to total probabilities for positronium formation. Detailed information such as that obtained from differential type studies and as required to stringently test theory was available in only a small handful of cases. For example, Falke et al. [5] measured probabilities for single and double ionization, positronium formation, and transfer ionization, all as functions of observation angle for 120 eV positron impact on argon. At MS&T (Missouri University of Science and Technology), DuBois and coworkers measured energy loss spectra for single and double ionization of argon and krypton at 750 eV [6,7]. Moxom et al. [8] measured the energy spectrum for electron emission from argon resulting from 50-150 eV positron impact. All of these were singly differential measurements, capable of testing theory in some detail but unable to test the predictions discussed above. Doubly differential studies provide more stringent tests, but here again data for positron impact are very limited. Schmitt et al. [9] measured 15 eV electron emission between 20 and 90 degrees at 100 eV and Kövér, Larricchia and coworkers at University College-London (ULC) measured electron emission from argon at 30° and 45° for 60 and 100 eV impact energies [10,11].

The first triply (fully) differential studies for positron impact were performed by the ULC group 15 years ago [12-14]. The reason that triply differential studies are particularly useful in testing our theoretical understanding of atomic interactions is that the interaction kinematics are fully defined and because there is no need to integrate theory over energies or angles of one of the particles before comparing with experiment. This results in a much more stringent test of theory. But, as the primary interest of the ULC group was in studying electron capture to the continuum processes, their studies were all performed for 0° electron emission and projectile scattering. As a result, these triply differential data can only test limited aspects of theory. With regard to testing theory, it should be mentioned that very sophisticated triply differential data can be obtained for electron impact. See for example, ref. 15. But, uncertainties in both the experimental magnitudes and the theoretical models preclude using only electron impact data to test the theoretical predictions of the changes in magnitudes of the binary and recoil lobes as compared to those predicted using perturbation theory. For this purpose, data for both positron and electron impact are required and, ideally, such data should be obtained under identical conditions in order to minimize or eliminate any experimental uncertainties.

At MS&T we have developed an apparatus and techniques precisely for this purpose. In the next section, a brief description of the apparatus and techniques being used will be given. Following this, examples of triply differential data which we have obtained for both positron and electron impact are presented and compared. The purpose of this manuscript is to illustrate differences associated with the sign of the projectile charge rather than to test specific theoretical models such as was done in a recent Letter [16].

2. Experimental Method

The method being used in these studies is to ionize a gas jet of target atoms (or molecules) by a beam of leptons and to measure coincidences between the various ionization products. The beams crossed at the center of two biased plates used to produce an electric field perpendicular to the beam direction. By using a single apparatus for these studies and as identical conditions as possible, experimental uncertainties between the positron and electron impact data are minimized or totally eliminated.

Our positron beam was produced using a ²²Na source, a tungsten moderator, and an electrostatic transport system. To switch to electron impact, an electron gun plus a 90° deflector were inserted into the positron beamline such that the deflected electron beam entered the scattering chamber via the same input aperture and trajectory used for positron impact. Target ions were extracted by a weak electric field and detected by a channeltron. Time of flight techniques established their charge states and masses. Scattered projectiles were measured as a function of their scattering angle and energy loss using an electrostatic energy analyzer and a position sensitive channelplate. Electrons ejected
from the target were measured as a function of their detection angle using a second position sensitive channelplate positioned close to the interaction region and at 90° with respect to the beam direction. List mode data collection allowed correlations between the various particles, angles, and energies to be established. For example, coincidences between singly ionized target atoms (or molecules) and scattered projectiles provided doubly differential cross section (DDCS) information as a function of scattering angle and energy loss. Coincidences between target ions, scattered projectiles, and ejected electrons provided triply differential cross section (TDCS) information which could be generated either for the scattered projectile or for the ejected electron. It is important to note that the TDCS data presented here are for all electrons of a particular energy that are detected between roughly 30 and 150 degrees with respect to the beam direction. Thus, they represent the integral intensity of the portions of the binary and recoil electron emission lobes that we can observe.

Examples of DDCS and TDCS data for 250 eV positron impact on molecular nitrogen are shown in Fig. 1. Here, the vertical axis is the projectile scattering angles, in degrees, which the horizontal axis is the energy loss in eV. Negative scattering angles imply that the projectile is scattered vertically downwards while positive angles imply upward scattering. Because our electron detector is located above the interaction region, “upward” emitted electrons are detected. Thus, the TDCS intensities for negative scattering angles, e.g., 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° because of the projectile channelplate size and distance from the interaction region. Various energy loss ranges could be set by adjusting the spectrometer voltages. But typical energy losses were less than 25% of the impact energy because of insufficient statistics at higher energy loss. With the present setup, impact energies between 200 and 1000 eV have been investigated. The ejected electron channelplate was sensitive to geometric emission angles between 30° and 150° along and perpendicular to the beam direction. No energy analysis of the ejected electrons was used. Rather, their energies were
determined using coincidences with projectiles that suffered a particular energy loss which for single ionization unequivocally defines the ejected electron energy.

However, the energies, angles, and probabilities for the ejected electrons are subject to various experimental conditions. For example, the electric field used to extract the target ions modifies both the directions and acceptance ranges of the ejected electrons that are detected. This is particularly true for very low ejected electron energies which, depending upon their initial energy and direction, can even be turned around by the field. To minimize this problem, a small extraction field of 1.2 V/cm was used. SIMION simulations and a detailed model of the interaction volume and fields showed that such problems were minimal for emission energies above a few eV. But, to achieve sufficient statistics for positron impact, a relative large beam diameter (approximately 5-6 mm) and projectile scattering angle and energy loss bins of 1° and several eV were used. This results 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, at present theory must be convoluted over our experimental parameters in order to compare with our data. A program for doing this was written and briefly described in a recent publication.[16] Additional experimental details can be found in references 16-18.

3. Results

Using background subtracted 2D spectra such as shown in Fig. 1, doubly and triply differential intensities were determined for scattering angles between -6° and +6° and for a range of energy losses. To reduce the statistical uncertainties, data within angular and energy loss bins of 1° and 7-17 eV were summed. Identical conditions were used for positron and electron impact. Ratios of triply to doubly differential cross sections were then calculated from the integrated intensities. Using ratios removes any problems associated with electric field effects on the ejected electron trajectories as well as any solid angle effects since these influence both the doubly and triply differential data in the same fashion. It also removes any experimental asymmetries between positive and negative scattering angles since by definition the DDCS must be symmetric with respect to zero degrees.

In Figure 2, we present three examples of these ratios and their full statistical uncertainties, all for an energy loss of approximately 37 eV. (To relate these data in terms of the ejected electron energy, the appropriate single ionization potentials must be subtracted.) Positron impact data are shown by the filled red circles; electron impact data by the open blue triangles. In order to provide a picture as to how impact energy and target species influence these data, the left figure is for 200 eV impact single ionization of argon, the middle figure is for 250 eV ionization of molecular nitrogen, and the right figure is for 500 eV ionization of neon. The curves in the argon figure are polynomial fits to the data, serving only to guide the eye.

![Figure 2](image-url)
solid curves in the left figure are polynomial fits to the data. Negative (positive) scattering angles correspond to binary (recoil) interactions.

As seen, the general trend in all cases is relatively isotropic ratios for positive scattering angles and a monotonic increase for increasing negative scattering angles. The reader is reminded that negative scattering angles indicate binary interactions while positive angles indicate recoil interactions. Thus, these data show that the relative number of binary to recoil interactions increases as a function of scattering angle, i.e., as a function of increasing momentum transfer. This appears to be independent of target species and also of impact energy. This increase may be in part due to a rotation of the binary lobe to larger angles with increasing momentum transfer, see for example figure 3 in reference 15. However, the present data also show that the increase is larger for positron impact. Larger binary intensities for positron impact are predicted by theory but theory also predicts that the binary lobe for positron impact should be shifted toward smaller angles whereas for electron impact it should be shifted toward larger angles. Thus, if the observed increase is simply due to a rotation of the binary lobe one would expect a larger increase for electron impact, just the opposite as what the data show.

Theory also predicts smaller recoil lobe intensities for positron impact as opposed to electron impact. But, our argon and neon data show nearly identical recoil lobe contributions for positron and electron impact. A possible interpretation of this is that recoil interactions involve an additional interaction between the ejected electron and the nuclear core and this interaction may smear out any initial differences associated with the projectile charge.

For ionization of nitrogen the relative recoil lobe contributions are different for positron and electron impact. Whether this is associated with differences between a single or multiple nuclear core or not will require further studies.

4. Comments and summary
Doubly and triply differential data for single ionization of argon and neon atoms plus nitrogen molecules have been measured for both positron and electron impact. Comparisons of the positron and electron impact data show systematic differences associated with the sign of the projectile charge. Specifically, binary interactions for positron impact have larger intensities than for electron impact. This is consistent with long standing theoretical predictions. Theory also predicts that just the opposite effect will be observed for the recoil lobe intensities. However, for argon and neon, any such effects are observed to be quite small. Comparisons made for ionization of molecular nitrogen yield similar qualitative results but show quantitative differences.

Although not shown or discussed in the present manuscript, it should be noted that our experimental method has also been used to investigate projectile charge effects on double ionization. In this case, by combining positron and electron impact data, information about first- and second-order doubly ionization plus about how they interfere, can be obtained. [19]

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