Doubly and triply differential ionization measurements using femtoamp beams of positrons and electrons

R D DuBois
Missouri University of Science and Technology, Rolla, MO 65409, USA
E-mail: dubois@mst.edu

New Journal of Physics 14 (2012) 025004 (15pp)
Received 31 October 2011
Published 3 February 2012
Online at http://www.njp.org/
doi:10.1088/1367-2630/14/2/025004

Abstract. Experimental methods and techniques being used to generate doubly and triply differential ionization data for positron and electron beams are discussed. It is shown that even for femtoamp, or smaller, beam intensities, highly detailed differential studies can be performed and differences resulting from kinematic effects due to the sign of the projectile can be identified. Examples using 250 eV impact ionization of molecular nitrogen are provided.

1. Introduction

Ever since the first fully kinematic studies of electron impact ionization were performed several decades ago [1–3], one of the goals of antiparticle researchers has been to perform similar highly differential measurements for positron impact. Such data would provide detailed information about how antimatter–matter atomic interactions are similar to, or different from, matter–matter
interactions. In addition, from comparisons of positron and electron impact data, features associated with specific interaction channels could be identified in the spectra and information about how different interaction kinematics influence the observed spectra could be obtained. Overall, the combination of highly differential positron and electron impact data can uncover specific weaknesses of theory that otherwise might be overlooked if only electron impact data are available.

The number of theoretical papers predicting differences between positron and electron impact ionization is extensive. As has been illustrated numerous times for electron impact, different theories and approximations yield different results. The same is found for positron impact. Using procedures outlined by Brauner et al. [4] many years ago, several different models are currently being used. Examples include various forms of the 3D distorted wave model (the 3DW models) [5], the distorted wave Born approximation (the DWBA) [6, 7], and the continuum distorted wave-eichonal initial state model (CDW-EIS) [8]. The ultimate purpose for the experimental studies described here is to determine which model is best and to help improve all of the models.

However, positron based measurements are severely restricted by the simple fact that achievable positron beam intensities using radioactive sources are extremely weak in comparison to those used for electron impact studies. For example, in the first fully differential electron impact studies, the beam intensities were a few tenths of a microamp. In sharp contrast, radioactive sources and moderators typically produce positron beam intensities in the femtoamp range or less. By using nuclear reactors or electron storage rings, higher positron yields can be obtained. But the positrons must be transported from a high radiation production region to a radiation free experimental area. Efficient transport using magnetic fields is possible; however extraction of the positron beams into a field free region required for studying ionization kinematics usually results in considerable loss of beam intensity. Another option for producing more intense positron beams is the so-called Surko trap. However, this apparatus also involves the use of magnetic fields. Plus, significant monetary and manpower resources are required. Therefore, for many current and prospective research groups, the bottleneck in performing highly differential positron-based atomic physics studies is the available beam intensity and signal rates.

In spite of this limitation, a few differential positron impact studies have been performed. For example, a singly differential study by Moxom et al. [9] measured the energy spectrum for electron emission from argon resulting from 50–150 eV positron impact. Doubly differential studies have been performed by Schmitt et al. [10] who measured 15 eV electron emission between 20° and 90° at 100 eV and by Kővér et al. at University College-London (UCL) who measured electron emission from argon at 30° and 45° for 60 and 100 eV impact energies [11, 12]. The first triply (fully) differential studies for positron impact were performed by the ULC group 15 years ago [13–15]. However, these studies only investigated processes where the scattered and ejected particles leave in the extreme forward direction.

In the past decade, systematic progress in overcoming the bottleneck of low beam intensities and extending experimental differential studies to a wider range of kinematic conditions has been made at the Missouri University of Science and Technology. Our work has culminated in fully kinematics measurements of single ionization [8, 16] plus singly differential measurements of double ionization [17]. In both cases, differential data have been obtained using subfemtoamp beam intensities. The primary purpose of this paper is to outline the experimental methods being used which are allowing these highly differential ionization data
Figure 1. Schematic of apparatus showing the incoming beam, target region, projectile spectrometer and position sensitive detectors (PSDs). The inset shows a top view of the spectrometer.

to be obtained and to provide details about the apparatus and methods that were only briefly described in our recent publications. This description will be augmented by examples of doubly and triply differential ionization data we have obtained.

2. Experimental method

Our basic method consists of measuring, in coincidence, all three particles, i.e., the ejected electrons, the forward scattered projectiles and the singly charged target ions, which are produced in single ionization. By using the same apparatus and as identical conditions as possible for both positron and electron impact, systematic uncertainties in these fully kinematic data are reduced, thus allowing more sensitive comparisons between positron and electron impact. Position-sensitive channelplates are used for detecting the emitted electrons and scattered projectiles. This allows simultaneous collection of data for a wide range of emission angles and for a range of kinematic conditions, e.g., scattering angles and energy losses. When combined with recoil ion detection, background events associated with interactions along the beam path, scattering from surfaces, and interactions with residual chamber gases can be totally eliminated or drastically reduced in intensity.

2.1. Apparatus

As shown in figure 1, the apparatus consists of a collimated positron or an electron beam passing between two biased plates where the beams intersect a gas jet. Following the interaction region and in line with the incoming beams is an electrostatic energy analyzer, also shown as an overhead view in the inset in the upper left corner of the figure. In the interaction region, a
weak electric field between the biased plates extracts target ions downwards where they pass through a short time-of-flight spectrometer before being detected by a channeltron electron multiplier. This is shown in more detail in figure 2. These ions provide a common stop signal for an 8-input channel time-to-digital converter (TDC). Ionized target electrons are detected by a channelplate detector located just above the upper biased plate. Signals from the ends of the x and y delay line anode wires are used as four of the TDC input signals while the other four input signals are generated by similar signals from a second position-sensitive channelplate that detects energy analyzed, forward scattered projectiles. These signals provide 2D information about the emission angles of the ionized target electrons and the scattering angles and energy losses of the scattered beam particles.

For the positron studies, positrons were produced using a $^{22}$Na radioactive source and a tungsten moderator. They were transported to the target chamber using electrostatic lenses before and after a 15° bend which prevented high energy positrons or photons originating at the source from entering the target chamber. The entire source and transport system were surrounded by lead shielding and enclosed in a magnetic shielding box. A small turbopump kept the pressure in the source and transport region at high vacuum.

SIMION simulations, used to test beam transport conditions, showed that because of the finite diameter of the source and moderator used (approx. 5 mm), transport of positrons that were produced off-axis at the source was poor. Unfortunately, geometry implies that most positrons will be produced off-axis. Therefore, to increase the available beam intensity, a 6 mm diameter input aperture was used for beam collimation at the target chamber entrance. Even so, the on-target beam intensity was only $\sim 0.5 \text{ kHz}$, i.e., approximately 0.08 fA. This necessitated long data collection times (approximately 2–3 months of continuous run time) plus relaxing the energy and angular resolution parameters used in the data analysis.

**Figure 2.** Side view of interaction region showing ionization products, e.g., scattered beam particles for binary and recoil events, ejected electrons (red arrows, online) impacting on the electron detector, and recoil ions (large arrow) passing through the time of flight spectrometer to the recoil detector. The darker circle overlapping the main beam indicates the target gas jet. The ejected electron arrows show how the extraction field influences the trajectories for low, medium and high energy ejected electrons.
For the electron impact studies, an electron gun positioned perpendicular to the positron beam path was used. In order that the electron beam entered the target chamber through the same input aperture and followed the same path as the positron beam, a 90° electrostatic deflector was attached to the end of the gun and the gun assembly could be moved linearly, rotated, and tilted. For the electron impact studies, a beam intensity of $\sim 5 \text{ kHz}$ was used. This intensity was a compromise between acceptable random coincidences and the data collection time required. Collection time for the electron studies was roughly one week.

The target was a simple gas jet emerging from a hypodermic needle centered between the biased plates and terminating just outside the beam diameter. The plates below and above the target were biased at $\pm 1.5 \text{ V}$ respectively, thus creating a uniform $1.2 \text{ V cm}^{-1}$ field. The extracted recoil ions exited the field region through a 6 mm diameter aperture located in the lower plate directly below the beam-gas jet overlap region. The ions then passed through a 2.5 cm long field free time-of-flight tube and were detected by a channeltron electron multiplier. See figure 2. The channeltron entrance was biased at $-3 \text{ kV}$ with a slightly larger voltage being applied to a grid in front in order to avoid loss of secondary electrons and thus improve the recoil ion detection efficiency. For data accumulation, target gas was admitted via a leak valve until the target chamber pressure was approximately $2 \times 10^{-5} \text{ Torr}$. By reversing the extraction field and changing the bias on the electron detector (described below), images of ionization occurring along the beam path showed that the maximum target density was approximately 30–50 times higher than the average chamber pressure. These images were also used to model the target gas profile for the data analysis that will be described later.

The projectile electrostatic energy analyzer, located directly after the target region, had a vertical entrance slit which allowed the main beam plus any projectile which scattered between $0^\circ \pm 2.4^\circ$ horizontally and roughly $\pm 15^\circ$ vertically to enter. For positron impact, the back plate of the analyzer was biased negative and a small inner cylinder near the entrance was biased positive. As shown schematically in the inset, resister chains terminating at these two voltages biased a series of vertical wires located just inside the side and exit plates of the spectrometer. The biased wires, back plate and inner cylinder produced an electric field which horizontally focused entering positrons at the exit plane of the spectrometer. The scattered projectile channelplate, biased at $-100 \text{ V}$ in order to reject any scattered or secondary electrons produced within the spectrometer, was located just after the exit plane. Because of the finite spacing of the biased wires at the exit plane, it was found that if the main beam exited near one of the wires, a one-dimensional lensing effect caused a distorted image of the main beam on the projectile detector. These distortions were minimized by adjusting the spectrometer voltages to position the main beam between two wires. For the ionization continuum, any distortions were smoothed out because of the continuous energy distribution.

For the present work, the back and inner plates of the spectrometer were biased such that projectiles which had lost just enough energy to ionize the target were detected near the horizontal center of the projectile detector. For this setting, the main beam also was detected. For the data shown here, the energy resolution was $\sim 0.9 \text{ eV pixel}^{-1}$. This was measured by fixing the spectrometer voltages and then recording the position of the main beam on the channelplate for several different beam energies. The absolute scattered projectile energy scale was determined using the center of the main beam intensity profile and the known beam energy.

Although a larger range of vertical scattering angles entered the spectrometer, the projectile channelplate size and distance from the interaction region limited the maximum detectable vertical scattering angular range to $\pm 6^\circ$ where the centroid of the main beam defined the
zero scattering angle. For the present experiment energy losses up to approximately 60 eV and scattering angles less than 6° were measured. But, in both cases, available statistics due to rapidly decreasing cross sections determined the useable upper limits for both the scattering angle and energy loss.

For detection of the ejected electrons, the upper extraction plate had a 50 mm hole covered by a 78% transmission grid. Again, see figure 2. Above this grid was the ejected electron detector which was identical to that used for the scattered projectiles except for the input bias being +200 V in order to more directly image electrons emerging from the grid in the upper extraction plate. No energy analysis of the ejected electrons was used. Rather, their energies were determined using coincidences with projectiles that suffered a particular energy loss. For single ionization, the measured energy loss and the ionization potential are sufficient to unequivocally define the ejected electron energy. The detectable geometric emission angles were 30–150° and 210–330° along the beam direction for binary and recoil events. Perpendicular to the beam direction, angles between roughly ±20° were used in order to improve statistics. Also, to improve statistics, the electron emission angles were binned every 5° along the beam direction in the data analysis.

As shown in figure 2, the extraction field influences the trajectories of lower energy ejected electrons. As illustrated, the trajectories can even be turned around. However this only occurs if the energy is less than the bottom extraction plate voltage (1.5 V for the present study). For ‘higher’ energy electrons extraction field effects become less and less important. For plotting these data, ‘geometric observation angles’ are used. These were calculated using the assumptions that the interaction region was a point and that the electric field between the grid in the upper extraction plate and the electron detector was sufficiently strong to directly map any emerging electrons on to the channelplate. Under these assumptions, as stated above, the ejected electron detector was sensitive to observation angles between 30° and 150° along the beam direction. However, for interpreting the data and for comparing to theory a detailed analysis taking into account the finite interaction volume and extraction field effects, particularly for low emission energies, was performed. This will be discussed in the next section.

2.2. Data accumulation and analysis

Standard electronics were used to amplify and process the recoil ion, scattered projectile and ejected electron signals. Using the recoil ion as a common stop and the ejected electron and scattered projectile signals as start signals to a PC based multi-input TDC data collection card, coincidence data were collected in list mode fashion and then sorted in various ways.

The first step in generating fully kinematic single ionization data was to produce time-of-flight spectra as shown in the left portion of figure 3 for ionization of argon. The upper spectra are electron-recoil coincidences and the lower spectra are projectile-recoil coincidences. Beyond the differences in statistics, the most obvious differences between these electron and positron time-of-flight spectra is the much higher background for electron impact and the absence of double ionization peaks in both the electron and positron impact scattered projectile-recoil ion coincidence spectra. The higher background is due to higher random rates because of the higher electron beam intensities used while the double ionization peaks are missing because the larger momentum transfers required for double ionization lead to scattering angles and energy losses for the majority of the projectiles that are outside our viewing region. Also seen in these spectra are molecular nitrogen ion peaks which come from interactions with the residual chamber gas.
Figure 3. 200 eV positron and electron impact data for single ionization of argon. Left portion: 1D time-of-flight ejected electron-recoil ion (upper figure) and scattered projectile-recoil ion (lower figure) coincidence spectra for positron (dashed curves) and electron (solid curves) impact on argon. Right portion: 2D coincidence spectra with logarithmic intensity scales for positron (upper figures) and electron (lower figures) impact. The vertical and horizontal axes of the 2D spectra show the scattering angles in degrees and energy losses in eV respectively. Left 2D figures are doubly differential data obtained from recoil ion-scattered projectile coincidences; right 2D figures are triply differential (fully kinematic) data obtained from recoil ion-scattered projectile-ejected electron coincidences.

Next, windows are set on the single ionization peaks and the adjacent backgrounds and the list mode data are resorted. When this is done for the upper spectra, singly differential information for electron emission as a function of emission angle is obtained. Similar sorts performed using the lower spectra yield doubly differential information for projectile scattering as a function of scattering angle and energy loss. Examples of these doubly differential data are shown in the left 2D graphs in figure 3; the upper graph is for positron impact; the lower graph is for electron impact. Here, the raw data have been background subtracted and a conversion of the vertical and horizontal axes to scattering angles and energy losses using the calibration procedures discussed above has been done. For display purposes, a lower limit threshold has been used. The intensity scales are logarithmic with the ranges being from 10 (blue) to 140 (yellow) for positron impact and from 10 (blue) to 100 (yellow) for electron impact. Residuals of the main beam after background subtraction can be seen at zero scattering angle and energy loss.

By combining the electron-recoil and projectile-recoil coincidences, triply differential (fully kinematic) information as shown in the far right portion of figure 3 are obtained. Again, the upper spectrum is for positron impact while the lower spectrum is for electron impact. Here, the intensity scales are from 3 (blue) to 30 (yellow) for positron impact and from 5 (blue) to 25 (yellow) for electron impact. These spectra represent single ionization yields for projectile
scattering as a function of scattering angle and energy loss in coincidence with electrons whose energies are defined by the energy loss minus the first ionization potential. For emission energies larger than the extraction plate voltages, e.g., for almost all the triply differential data shown in the figure, the data for negative scattering angles represent binary interactions. This is because the electron detector is located above the beam which means the coincidences are between electrons that are emitted upwards and projectiles that are scattered downwards, i.e., in opposite directions. Similarly, the data for positive scattering angles, where the emission and scattering angles are in the same hemisphere, indicate recoil events.

Generally, triply differential (fully kinematic) data are presented by selecting a particular kinematic condition, e.g. scattering angle and energy loss (or emission energy), and plotting the electron emission as a function of emission angle. Our method of generating such data is to set windows on both the energy loss and scattering angles in the projectile 2D spectra and sort the 2D electron emission list mode data one final time. As stated above, the negative scattering angle window corresponds to a selection of binary events while the corresponding positive scattering angle window selects recoil events. By repeating this for different energy losses and/or scattering angles, electron emission for different momentum transfers can be studied. For example, in the data shown in figure 3, scattering angles up to $4^\circ$ and energy losses less than 25–30 eV can be studied. This corresponds to momentum transfers ranging from approximately 0.1 to 0.3 au with the range being determined by available statistics.

Because our method uses relatively large diameter beams, a weak electric field in the interaction region, and a position sensitive detector (PSD) located close to the interaction region, corrections to the energy losses and emission angles, as well as to the yields that are measured, are required. With regard to the energy loss, it is determined from the separation of a selected energy loss window and the beam location. But, because of the finite diameter of the beam, (see figure 4) a convolution of the beam profile across each energy loss window

**Figure 4.** Energy loss spectra for zero degree projectile scattering resulting from 250 eV positron impact ionization of molecular nitrogen. The data for scattered projectile-recoil ion coincidences show real + random events, random events, and their difference.

New Journal of Physics 14 (2012) 025004 (http://www.njp.org/)
is necessary to determine which energy losses contribute and how much each contributes. To perform this convolution, every part of the beam was assumed to consist of an exponential energy distribution of positrons emitted from the tungsten moderator or, for electron impact, of electrons being emitted by the hot electron gun filament. This means that for each portion of the energy loss window chosen, contributions from all energetically accessible parts of the beam were considered. This entailed calculating each particular energy loss and its relative contribution which was determined by the beam intensity profile. These weighted contributions were then average to determine the mean energy loss for each portion of the energy loss window.

These assumptions were tested and confirmed by using different values for the exponential half width to calculate the average energy loss and contributing intensity at each energy loss pixel and comparing the results with the measured ionization onset profile. Good agreement was achieved for a source exponential half width of 1–1.25 eV.

Figure 5 shows Gaussian fits to the energy loss distributions for some of the energy loss ranges chosen that were obtained by this method. The widths of these Gaussians are due to both the width of the beam and the energy loss window used. Note that as the mean energy loss approaches the ionization threshold, the low energy tail of the Gaussian, i.e., contributions from the nearest portion of the beam, is truncated because they are not energetically accessible. Subtracting the ionization potential from these Gaussian energy losses yields the means and half widths of the corresponding electron emission energies.

To account for the extended beam-target overlap volume, extraction field effects on the ejected electron trajectories, and grid transmission and solid angle effects, a program was written which used model functions for isotropic binary and recoil emission for different emission energies and performed a convolution over all experimental parameters. In addition, again assuming a point interaction region and isotropic emission, SIMION was used to model the target and detector regions and electric fields. This was used to calculate the intensity that would be observed at each detector observations angle.

Figure 6 illustrates how the electric fields, grid transmission, and solid angle influence the intensity distributions that are observed by our electron detector. As seen, strong distortions
Figure 6. SIMION predictions for the relative intensities that are detected for isotropic electron emission between 0–360° for several electron emission energies. Angles less/greater than 180° representing emission toward/away from the electron detector correspond to binary/recoil events in the data analysis.

occur for electron energies less than the plate voltages (1.5 V for the data and simulations provided here). Also, there is a rapid falloff in observed intensity for observation angles in the forward and backward directions. This falloff results from both a decreasing grid transmission and a mapping of the emission solid angle onto a planar detector. For a point source and a perfect grid, a falloff of inverse cosine cubed is expected. However, comparisons of our electron emission as a function of emission angle with measured cross sections [18] show that a cosine cubed correction works well for angles between 60 and 120° but overestimates the falloff for emission angles outside this range. This is probably a result of our extended target volume. An added complication in applying any corrections is that for angles near the extremes of our observation region the statistical uncertainties become large. Therefore, the most accurate method of comparing our differential electron emission data with theoretical or experimental cross sections is to perform a convolution of the cross sections with our experimental parameters. Efforts are in progress to parameterize such convolutions in order to provide a table of values that can be used in order to make comparisons.

The final step in our data analysis was to normalize the positron and electron impact data to each other using the total scattered projectile intensities collected for each projectile. Although our experiment was only sensitive to scattering angles less than approximately ±6° and energy losses less than approximately a quarter of the beam energy, this normalization is justified since differential and integral electron impact data for ionization of argon and molecular nitrogen are very similar and because these ranges include the majority of ionization events [18]. Furthermore, total cross sections for single ionization of argon by positrons and electrons [19] agree within 10% above 100 eV which is smaller than most of our statistical uncertainties. Therefore, this single normalization establishes the positron and electron impact data relative to one another and allows direct comparisons between the experimental data to be made.
3. Results

In this section, examples of doubly and triply differential data plus comparisons of these data for positron and electron impact will be given. We begin with an example of how the raw data can be used to extract information about differences between positron and electron impact. In figure 3, the 2D triple coincidence spectrum for positron impact (the upper far right spectrum) illustrate that the probability for binary events (negative scattering angles) is larger than for recoil events (positive scattering angles). It can also be seen that the relative probability for binary events increases with energy loss. In contrast, for electron impact (the lower far right spectrum) binary and recoil events appear to have nearly equal probabilities and that this is independent of energy loss, at least for the range of energy losses shown.

Doubly differential information as shown in figures 7 and 8 can be obtained by taking horizontal and vertical slices of the left 2D spectra. In figure 7, ionization probabilities as a function of energy loss are compared for two different scattering angles for positron and electron impact. Although these data have been normalized such that the total ionization probabilities are equal, for most of the energy loss range shown the differential yields for positron impact are larger than those for electron impact. At higher energy losses, where the statistics become poorer, our data appear to merge. The larger yields for smaller energy losses, e.g., for large impact parameters, could indicate a polarization of the electron cloud by the incoming particle, although polarization effects generally are associated with lower impact energies than those used here. These data also imply that the yields for electron impact increase very rapidly and then monotonically decrease with energy loss whereas the yields for positron impact turn on more slowly before maximizing and decreasing. Whether this feature is associated with our energy deconvolution or results from differences associated with very distant collisions remains to be determined.

New Journal of Physics 14 (2012) 025004 (http://www.njp.org/)
Figure 8. Ratio of doubly differential yields as a function of scattering angle for positron and electron impact. Data are an average for energy losses between 19 and 40 eV.

Figure 8 compares the scattering angle dependences for positron and electron impact. Here, ratios and a polynomial fit are shown in order to more clearly illustrate the differences. The ratios, which are averages for energy losses between approximately 19 and 40 eV, again illustrate how positrons are scattered more than electrons, even though the energy loss is the same.

Figure 9 shows the most detailed comparison of positron and electron impact ionization yields possible, namely a comparison of triply differential electron emission yields. These data contain all kinematic information about the inelastic interaction where a single electron is removed from the target. In this figure, our positron and electron impact data are shown by the filled red and blue dots, respectively, and the error bars are statistical uncertainties. Here, again, the electron yields have been normalized to the positron data using our measured total ionization yields. For binary interactions (angles less than 180°), these data show a clear enhancement for positron impact with respect to electron impact. Plus, a shift of the binary lobe toward smaller emission angles for positron impact is indicated. For recoil interactions (angles larger than 180°), within statistical uncertainties no clear differences can be seen between positron and electron impact. Included in the figure are the measurements of Avaldi et al [20], shown by the blue open circles. For comparison purposes, these data have been convoluted with our experimental parameters and normalized to our electron impact binary yields. Reasonable agreement is seen for binary events. However, for recoil events our measured yields are significantly smaller. Whether this is simply because of the limited statistics of our present data or is due to some other reason is uncertain at the present time but is being investigated.

Although we have shown that our method can be used to generate highly differential data, a major limitation of the method is with regard to the decrease in the detectable electron emission in the forward and backward directions. As a result, we are either totally, or partially, unable
Figure 9. Triply differential yields as a function of the detection angle for electrons emitted from molecular nitrogen by positron (filled red circles) and electron (filled blue circles) impact. Data are for a projectile scattering angle of 3° and an energy loss of 28 eV. The present data are compared to the electron impact measurements of Avaldi et al [20] shown by the open blue circles. See text for details.

Figure 10. Triply differential yields as a function of projectile energy loss and scattering angle illustrate clear differences between positron and electron impact. In this figure, rather than to directly compare our triply differential data, we have performed a normalization to our doubly differential yields that are measured simultaneously. This removes any experimental asymmetries in the data and allows the relative binary and recoil intensities to be compared with greater sensitivity.

Because these triply differential data result from coincidences with our full range of detectable electron emission angles, they correspond to integral measurements of the binary and recoil lobe intensities. Also, the statistical uncertainties are significantly reduced. It is important for the reader to recognize that even though our method is totally blind to angles that can contain a large portion of the binary and recoil lobes and that a significant loss of measurable intensity occurs at the extreme angles we are able to measure, these integral intensities provide information about both the total magnitude of the binary and recoil lobes as well as about any increase or loss of magnitude due relative shifts in the directions of the lobes for positrons and electrons. Thus, these data provide sensitive information about kinematic differences between positron and electron impact.

As seen in the figures, for positron impact binary interactions are significantly more probable than recoil interactions and that this probability increases with both scattering angle and energy loss, i.e., with momentum transfer. Although this has been known since the first
Figure 10. Ratio of triply to doubly differential yields as a function of scattering angle for positron and electron impact. Data are for two energy losses. The solid lines are fits to the data.

triply differential electron impact measurements were performed, figure 10 shows that the enhancement for binary interactions is much less for electron impact than for positron impact. For electron impact, binary and recoil interactions have nearly the same probabilities which is in agreement with the data of Avaldi et al shown in figure 9. In addition, for electron impact the dependence on momentum transfer appears to be much less than it is for positron impact. Another feature illustrated in figure 10, particularly for positron impact, is that with increasing scattering angle, i.e., with decreasing impact parameter, binary interactions increase in probability whereas the probability for recoil interactions remains rather constant.

4. Summary

Experimental methods being used to obtain doubly and triply differential information about ionization by positron and electron impact have been described in detail. It has been shown that highly detailed measurements are possible, even for femtoamp and smaller beam intensities. Thus, the major barrier in performing highly differential positron impact studies can be overcome and kinematic differences associated with the sign of the projectile charge can be investigated. Doubly and triply differential data for ionization of molecular ionization by positrons and electrons has been used to illustrate some of these differences. It is hoped that this paper will serve to initiate new differential studies for positron impact plus triply differential calculations of not just for the emitted electron but also for the scattered projectile and that, as a result, greater insight into the similarities and differences between antimatter–matter and matter–matter interactions will result.

Acknowledgments

The work reported here is the result of many years of effort by several postdocs and students, both graduate and undergraduate. Support by the National Science Foundation is gratefully acknowledged.
References

[1] Ehrhardt H, Schulz M, Tekaat T and Willmann K 1969 Phys. Rev. Lett. 22 89
[2] Ehrhardt H, Hesselbacher K H, Jung K and Willmann K 1972 J. Phys. B: At. Mol. Phys. 5 2107
[3] Ehrhardt H, Hesselbacher K H, Jung K, Schubert E and Willmann K 1974 J. Phys. B: At. Mol. Phys. 7 69
[4] Brauner M, Briggs J S and Klar H 1989 J. Phys. B: At. Mol. Opt. Phys. 22 2265
[5] Naja A et al 2007 J. Phys. B: At. Mol. Opt. Phys. 40 3775
[6] Benedek A and Campeanu R I 2008 Nucl. Instrum. Methods Phys. Res. B 266 458
[7] Purohit G, Patidar V and Sud K K 2011 Nucl. Instrum. Methods Phys. Res. B 269 745
[8] de Lucio O G, Otranto S, Olson R E and DuBois R D 2010 Phys. Rev. Lett. 104 163201
[9] Moxom J, Laricchia G, Charlton M, Jones G O and Kövér Á 1992 J. Phys. B: At. Mol. Opt. Phys. 25 L613
[10] Schmitt A, Cerny U, Möller H, Raith R and Weber M 1994 Phys. Rev. A 49 R5
[11] Kövér Á, Laricchia G and Charlton M 1994 J. Phys. B: At. Mol. Opt. Phys. 27 2409
[12] Kövér Á, Finch R M, Charlton M and Laricchia G 1997 J. Phys. B: At. Mol. Opt. Phys. 30 L507–12
[13] Kövér Á, Laricchia G and Charlton M 1993 J. Phys. B: At. Mol. Opt. Phys. 26 L575
[14] Kövér Á and Laricchia G 1998 Phys. Rev. Lett. 80 5309
[15] Kövér Á, Paludon K and Laricchia G 2001 J. Phys. B: At. Mol. Opt. Phys. 34 L219–22
[16] de Lucio O, Gavin J and DuBois R D 2006 Phys. Rev. Lett. 97 243201
[17] DuBois R D, de Lucio O G and Gavin J 2010 Europhys. Lett. 89 23001
[18] DuBois R D 1975 PhD Thesis University of Nebraska–Lincoln
[19] Knudsen H et al 1990 J. Phys. B: At. Mol. Opt. Phys. 23 3955
[20] Avaldi L et al 1992 J. Phys. B: At. Mol. Opt. Phys. 25 3551