Doubly-differential ionization cross sections of positron impact on argon

A. Schmitt, U. Cerny, T. Falke, H. Möller, W. Raith and M. Weber

Fakultät für Physik, Universität Bielefeld, D-33501 Bielefeld, Germany

We report the first measurement of doubly-differential ionization cross sections for positron impact on argon atoms. Energy- and angle-resolved measurements of ejected electrons in time correlation with the produced and detected ions have been performed. Corresponding measurements with incident electrons were made for comparison. With positrons and electrons as primary particles of 100 eV energy and ejected electrons of 15 eV, our measurements were extended over electron-emission angles from 0° to 90°. Lacking theoretical predictions for the doubly-differential ionization of argon, we compare our measured data with the theoretical doubly-differential ionization cross sections, calculated for positron and electron impact on hydrogen by Klar and Berakdar (Freiburg) [1]. The angular dependence of positron and electron cross sections for argon agrees well with the theory for hydrogen. In particular, we found that for small angles of electron ejection the cross section for positron impact ionization exceeds that for electron impact by an order of magnitude in accordance with the predictions of Klar and Berakdar.

1. Introduction

One reason why scattering experiments with low-energy positrons are performed, is to support the development of a theory of electron *and* positron interactions with atoms and molecules, in order to improve understanding of the *electron*–atom interaction [2]. A theory which describes both the positron and electron interaction with atoms and molecules, will give a better description of what is happening during an electron–atom interaction than present theories. Especially, the more differential an experiment is, the more detailed information can be obtained from the collected data. We show that doubly-differential ionization cross sections for positron impact on gases (argon) can now be measured, and present the first data available from our experiment.

Positron experiments are almost similar to electron experiments – except for the projectile beam intensities. These are orders of magnitude lower than those of corresponding electron measurements. Because of this, enhancements to the experimental techniques are essential – for example to improve the signal to noise ratio. The present state of the art of experiments on positron-impact ionization of atoms can be summarized as follows [3]: Most measurements on single outer-shell ionization yield the so-called "total" ionization cross section, σ^+, which is an integral signal of scattering events over all angles $d\Omega_+$ and $d\Omega_-$ of the outgoing positron and electron and over all partitions of their energy distribution E_+ and E_- within the frame of $E_+ + E_- = E_0 - E_{ion}$ (E_0 = primary energy, E_{ion} = ionization energy). Of the three singly-differential cross sections $d\sigma^+/d\Omega_+$, $d\sigma^+/d\Omega_-$ and $d\sigma^+/dE_\pm$, only the first one has been determined for one target and only for forward angles [4]. Doubly-differential cross sections can be written as $d^2\sigma^+/d\Omega_+ \, d\Omega_-$ and $d^2\sigma^+/d\Omega_\pm \, dE_\pm$, where $d\Omega_\pm$ in the second expression refers to the solid angle of either the scattered positron or the ejected electron. We demonstrate here that the latter doubly-differential cross section can now be measured. The most complete *triply-differential cross section* measurement, $d^3\sigma^+/d\Omega_+ \, d\Omega_- \, dE_\pm$, is not yet accessible experimentally. Positronium (Ps) formation provides an additional channel for ion formation in the case of positron impact. The ionization cross section by definition does not include ionization with Ps formation. In order to distinguish the "normal" (break-up) ionization from ionization with Ps formation we detect the ejected electron together with the produced ion; in Ps formation the electron from the atom combines with the positron to form the Ps atom and subsequently annihilates with the positron.

2. Experimental set-up

Our experimental set-up, shown in fig. 1, is based upon a previous crossed beam experiment, designed for the determination of absolute differential elastic cross sections of positrons scattered from argon Floeder et al. [5]. Positrons from a 100 mCi ^{22}Na source are moderated in a tungsten-mesh (or foil) moderator. For the electron measurements, secondary electrons ejected from the moderator are utilized. The projectile particles are extracted electrostatically from the moderator and focused into a 90°-spherical spectrometer by a five-element electrostatic zoom lens system. The spectrometer reduces background associated with high energy positrons from the source and ensures that the positron and electron beams are comparable in energy distribution (from the broad energy distribution of the secondary electrons, only a fraction of the electrons is *cut out* to make the positron and electron spectra comparable – the moderated positrons have a reasonable small energy distribution of 2 eV and pass the spectrometer with minimal loss of flux). From this spectrometer the beam is transported to the scattering region by another five-element electrostatic lens system. In the scattering region the projectile beam intersects an argon atom beam at a right angle. The atomic beam emerges from a multicapillary-array orifice and beyond the interaction region it is dumped onto the baffle of a cryopump. The flow of the atomic beam is kept constant by a flow controller. Scattered projectiles or ejected electrons from the ionization process pass through a turnable spectrometer with an energy resolution of 2.8% of the spectrometer transmission energy and are registered by a channel electron multiplier (CEM). The detector can be adjusted from −30° to 120° and has an angular accep-

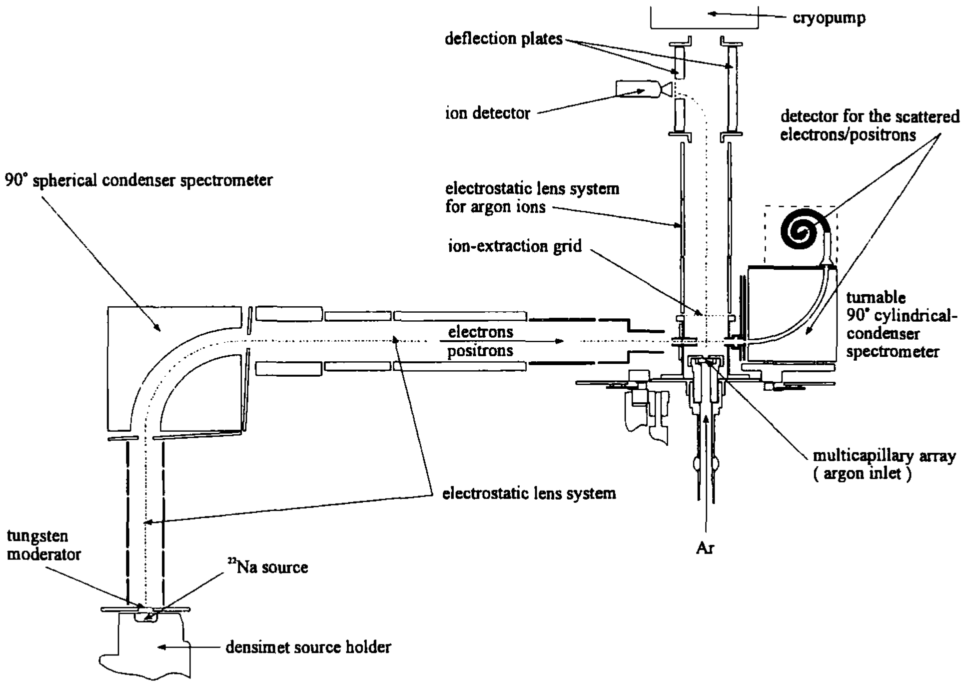


Fig. 1. Experimental set-up.

tance of ±6°. Because it can be moved through 0°, it can also be used for projectile beam analysis. The angular profile of the positron and electron beams can be mapped out, to confirm that both beams have a comparable overlap with the atomic beam. Fig. 2 shows that electron measurements can be used to establish an absolute scale for our positron data. The reason for the displacement of the positron beam on the energy axis is the different work function of tungsten for positrons and electrons. This was taken into account in the measurements.

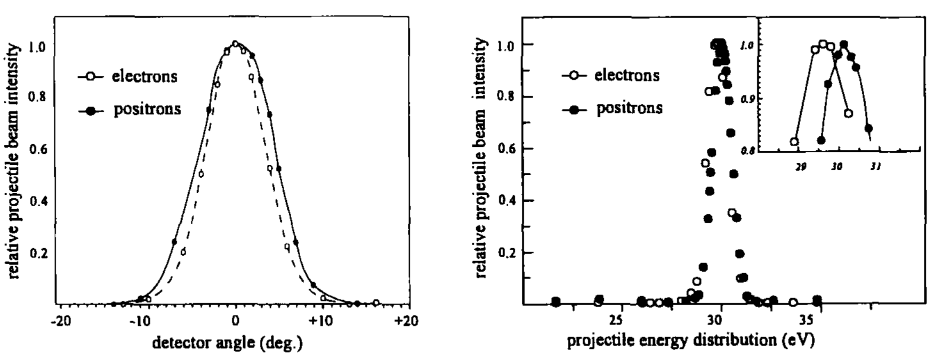
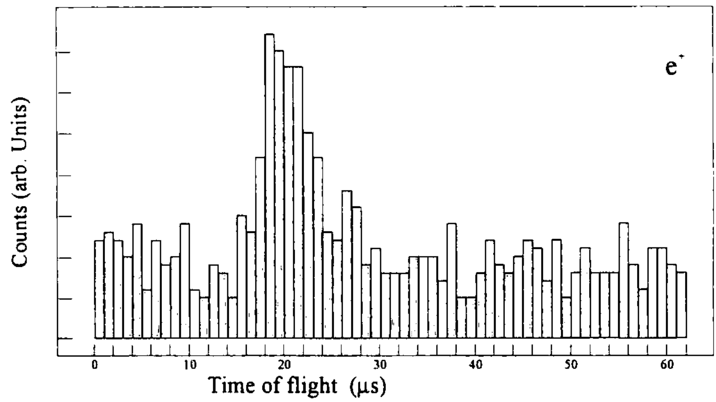


Fig. 2. Angular profile (left) and energy distribution (right) of positron and electron projectile beam.

For the measurement of doubly-differential ionization cross sections we added ion extraction and detection to the experimental set-up, also shown in fig. 1. The detected positrons or electrons provide a time mark for the start of a time-to-amplitude converter (TAC). The produced ions are extracted from the interaction region, and separated from the argon atoms (which fly in the same direction) by a weak electric field. The ions are detected by a second CEM that provides the TAC stop signal. A multi-channel analyzer (MCA) compiles the time-correlation spectra. All time-correlation spectra exhibit a distinct peak, which occurs about 20 μs after the electron/positron detection and represents events where electron/positron and ion stem from the same collision. Only these peak events, corrected for background, were evaluated. Typical time-correlation spectra for positron and electron impact are shown in fig. 3. The flat background on either side of the ion



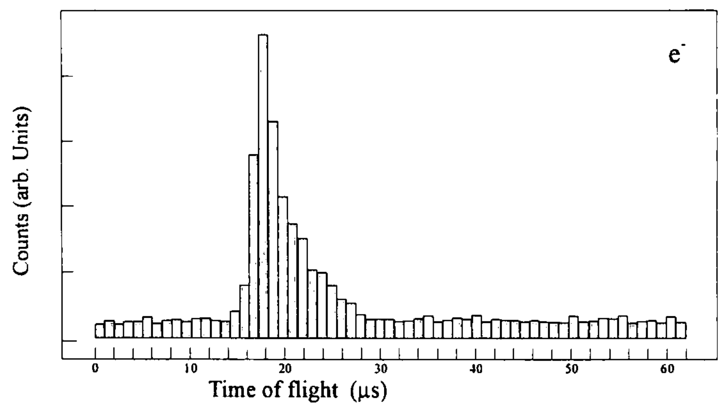


Fig. 3. Ion-correlation spectrum: for positron impact (upper) and for electron impact (lower). In both cases the TAC was started by the detection of the ejected electron and stopped by the ion detection. The data accumulation time was 1.4×10^5 and 8.0×10^3 for the upper and lower spectrum, respectively.

peak is only a small portion of the total background because numerous electron-detection events are *not* followed by an ion-detection event within the TAC time range of 100 μs and are therefore discarded.

Our apparatus permits us

– to select the ejected electron of energy E_b, emitted at an angle Θ_b with respect to the primary beam axis ranging from 0° to 90° with an uncertainty on angular position of ±1° and an angular acceptance of ±6° (alternatively the scattered positron can be observed),

– to check the angular shape and energy distribution of the projectile beam,

– to analyze the kinetic energy of the selected particle with an energy resolution of $\Delta E \approx 0.5$ eV in these measurements,

– to detect the time correlation of the selected particle with the ion produced simultaneously, and to perform corresponding measurements with incident electrons to put the positron data on an absolute scale.

The uncertainty in the projectile energy is about ±2 eV due to the potential gradient in the interaction region. The latter could be reduced by pulsing the ion extraction. This is planned for future measurements.

The method of *detecting the ionizing positron in time correlation with the produced ion* has been developed to discriminate against positronium formation in "total" positron ionization cross-section measurements [6]. In a differential positron-impact ionization experiment the detection of an ejected electron or the detection of the scattered positron with the a kinetic energy $\leqslant (E - E_{\text{ion}})$, should by itself provide a unique signature for break-up ionization, even without detection of the time-correlated ion. However, we found that severe background problems, which (more or less) beset all differential scattering experiments, are greatly reduced by this scheme.

3. Theoretical work for comparison

Our apparatus permits the detection of either the (fast) scattered positron or the (slow) ejected electron. After performing test-measurements of the first, we concentrated on the latter because Klar and Berakdar (Freiburg) provided us with theoretical guidance [7] based on numerical integrations [1] of their calculated triply-differential cross sections for positron and electron impact [8]:

$$\mathrm{DDCS}(E_b, \Omega_b, E_i) = \int \frac{\mathrm{d}^3\sigma}{\mathrm{d}\Omega_a\,\mathrm{d}\Omega_b\,E_b}\,\mathrm{d}\Omega_a\,.$$

Although these calculations were made for H, whereas we measure on Ar, we feel that a comparison is worthwhile. The large differences in positron and electron doubly-differential cross sections (DDCS) originate in the infinite extent of the Coulomb potential. The first Born approximation does not take this into account and, therefore, fails. For hydrogen and argon in the ground state the asymptotic shapes of their wavefunctions are very similar. Thus, Klar and Berakdar expect [7] that the H theory is also a good approximation for Ar.

4. Experimental data for comparison

Searching for experimental data for comparison with our electron data, we unfortunately found no date of electron–argon doubly-differential cross sections, except for work by Opal et al. [9] at 500 eV incident electron energy.

At 100 eV incident projectile energy, measurements of doubly-differential cross sections have been performed by Shyn for hydrogen [10] and by Shyn and Sharp for helium [11], by Müller-Fiedler et al. [12] for helium and by Opal et al. [9] for helium, nitrogen and oxygen. At angles above 50° the experimental data for e^-–H ionization of Shyn [10] agree well with Klar and Berakdar's theoretical predictions [1], but at smaller angles the experimental data lie far above the theoretical results. We have included Shyn's data points in fig. 5. The fact that Shyn's data points are close to our positron measurements and the calculations for positron impact may be accidental. From refs. [9,11,12], summarized in fig. 4, one can see that the e^-–He values of Shyn and Sharp [11] – taken with the same experimental setup as in ref. [10] – are significantly higher than those of Müller-Fiedler et al. [12] and Opal et al. [9]. Only the latter is in reasonable agreement with our e^-–Ar data and the calculations of Klar and Berakdar for e^-–H [1]. Apparently, Shyn overestimates cross sections at angles below 50°. All of these experiments are crossed-beam experiments, but none of them use ion detection in time correlation with the scattered / ejected electron.

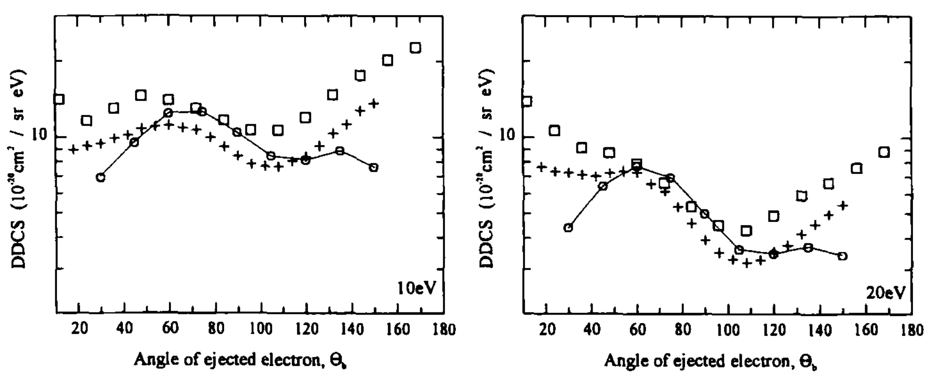


Fig. 4. Comparison of doubly-differential electron–He measurements for 10 (left) and 20 eV (right) secondary electrons. Open squares Shyn [11], open circles Opal [9] et al. and crosses Müller-Fiedler et al. [12]. (The data points of Opal et al. are connected by a solid line for optical guidance.)

Table 1
Normalized doubly-differential ionization cross sections and statistical errors for positron (right) and electron (left) impact on argon.

Angle (deg.)	e^-–Ar DDCS (10^{-20}/sr eV)	Δe^-–Ar DDCS	e^+–Ar DDCS (10^{-20}/sr eV)	Δe^+–Ar DDCS
0.00	2.25	2.14	–	–
10.00	2.16	1.55	–	–
20.00	3.78	1.98	50.40	28.60
30.00	3.60	2.70	59.40	28.80
40.00	6.57	3.24	–	–
50.00	–	–	34.20	18.00
70.00	9.90	3.60	–	–
90.00	6.30	3.06	21.60	16.20

The unsatisfactory discrepancy between Klar and Berakdar's e^-–H theory and Shyn's e^-–H measurement is a good example of open questions in electron–atom scattering. These might be answered by studying positron–atom scattering, predicted by the same theory.

5. Results

We measured relative values of the doubly-differential positron and electron cross sections and made a *best fit of only our electron data for argon* to Klar and

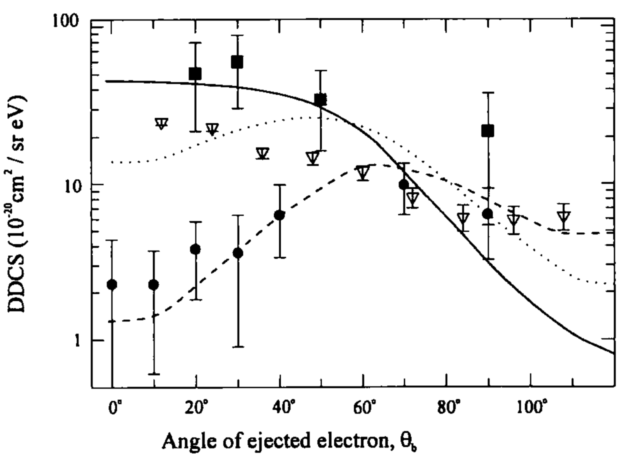


Fig. 5. $d^2\sigma/d\Omega\, dE$ (DDCS) for ejected electrons as function of the emission angle Θ_b at constant energies of $E_0 = 100$ eV and $E_b = 15$ eV. The doubly-differential argon cross sections for positron impact (full squares) and electron impact (full circles) determined in this experiment are compared with Klar and Berakdar's theoretical hydrogen cross sections for positron impact (fat line) and electron impact (dashed line), as well as their first Born approximation calculation (dotted line) [7]. The measured electron-impact cross sections of Shyn for hydrogen [10] are indicated by open triangles.

Berakdar's electron prediction *for hydrogen*. By using the same normalization factor we obtained absolute values for our positron–Ar data. Table 1 and fig. 5 show our normalized values. The agreement of our positron data with the theoretical prediction for positron H collisions is good. In particular, the prediction that $d^2\sigma^+/d\Omega_-\, dE_\pm >> d^2\sigma^-/d\Omega_-\, dE_\pm$ is confirmed by our values of (50.4 ± 28.6) and $(3.8 \pm 2.0) \times 10^{-20}$ $cm^2\ sr^{-1}\ eV^{-1}$ at $\Theta_b = 20°$ for positron and electron impact, respectively.

Acknowledgement

The authors gratefully acknowledge stimulating discussions with H. Klar and J. Berakdar. This research has been supported by the Deutsche Forschungsgemeinschaft and the University of Bielefeld.

References

[1] H. Klar and J. Berakdar, Structure in triply and doubly-differential ionisation cross sections of atomic hydrogen, submitted.
[2] W. Raith and G. Sinapius, Comments At. Mol. Phys. 22 (1989) 199.
[3] W. Raith, Hyp. Int. 73 (1992) 3.
[4] R.L. Chaplin, L.M. Diana and D.L. Brooks, Mater. Sci. Forum 105–120 (1992) 525.
[5] K. Floeder, P. Höner, W. Raith, A. Schwab, G. Sinapius and G. Spicher, Phys. Rev. Lett. 60 (1988) 2363.
[6] D. Fromme, G. Kruse, W. Raith and G. Sinapius, Phys. Rev. Lett. 57 (1986) 3031.
[7] H. Klar and J. Berakdar, private communication (1992).
[8] M. Brauner, J.S. Briggs and H. Klar, J. Phys. B 22 (1989) 2265.
[9] C.B. Opal, E.C. Beaty and W.K. Peterson, At. Data 4 (1972) 209.
[10] T.W. Shyn, Phys. Rev. A 45 (1992) 2951.
[11] T.W. Shyn and W.E. Sharp, Phys. Rev. A 19 (1979) 557.
[12] R. Müller-Fiedler, K. Jung and H. Ehrhardt, J. Phys. B 19 (1986) 1211.