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Positron-atom doubly differential ionization cross sections

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Doubly differential ionization cross sections for positron impact on argon atoms were determined by energy- and angle-resolved measurements of ejected electrons in time correlation with the produced ions. Corresponding measurements with incident electrons were made for comparison. With primary particles (positrons or electrons) of 100 eV and ejected electrons of 15 eV, measurements were extended over electron-emission angles from 0° to 90°. Lacking theoretical predictions for the ionization of argon we compared our data with the doubly differential ionization cross sections of Klar and Berakdar computed for positron and electron impact on hydrogen. The measured angular dependence of positron and electron cross sections for Ar agrees well with the theory for H. In particular, we find that at small angles of electron ejection the cross section for positron impact exceeds that for electron impact by an order of magnitude in accordance with the calculations of Klar and Berakdar (unpublished).

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One major goal of scattering experiments with low-energy *positrons* is the comparison with corresponding electron scattering data and with scattering theory in order to improve the understanding of the *electron*-atom interaction [1]. The assumption is that a future theory of electron *and* positron interactions with atoms, developed in accordance with experimental results for electron as well as positron impact, will give a better description of electron scattering than the present theory.

Because of severe intensity limitations, experiments on positron-atom scattering are far behind corresponding electron experiments. The present state of the art of positron-impact ionization of atoms can be summarized as follows [2]: Thus far, most measurements on single outer-shell ionization have yielded the so-called "total" ionization cross section σ^+, which results from integrating over all angles $d\Omega_+$ and $d\Omega_-$ of the outgoing positron and electron and over all partitions of their energy $dE_\pm$ within the frame of $E_+ + E_- = E_0 - E_{\rm ion}$ (E_0 is the primary energy; $E_{\rm ion}$ is the 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 [3]. The 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 either to the solid angle of the scattered positron or the ejected electron. We demonstrate here that the latter doubly differential cross section can now be measured. The most specific *triply differential cross section*, $d^3\sigma^+/d\Omega_+ d\Omega_- dE_\pm$, is not yet experimentally accessible. For positron impact the formation of positronium (Ps) provides an additional channel, which also leads to ion formation. Note that the cross sections introduced above do not include ionization by Ps formation. In order to distinguish the "normal" (breakup) ionization from ionization by Ps formation, we detect the ejected electron as well as the produced ion; in Ps formation the electron removed from the atom vanishes in the subsequent annihilation.

Our apparatus permits us (i) to select either the scattered positron of energy E_a at the angle θ_a or, as in the measurements described here, 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 in angular position of $\pm 1°$ and an angular acceptance of $\pm 6°$; (ii) to analyze the kinetic energy of the selected particle with an energy resolution of $\Delta E \approx 0.5$ eV; (iii) to detect the selected particle in time correlation with the simultaneously produced ion; (iv) and to perform corresponding measurements with incident electrons. Related experiments by other groups are (1) the deduction of an absolute singly differential ionization cross section for forward angles from positron time-of-flight measurements with helium [3] and (2) the measurement of the energy distribution of the electrons from e^+-Ar ionization ejected in the forward direction in order to study electron capture into continuum states of positronium [4].

Our experimental setup (Fig. 1) is based on the differential scattering experiment of Floeder *et al.* [5]. The low-energy positrons are produced by a ^{22}Na source and a tungsten-mesh (or foil) moderator. For electron measurements the secondary electrons emitted from the moderator are utilized. The positrons (electrons) are accelerated to 70 eV and electrostatically deflected through 90° in order to reduce background due to high-energy positrons and γ rays from the source. The energy width ΔE of the moderated positrons is about 1 eV, the much larger width of the secondary electrons is narrowed to 2–3 eV in the 90° deflector. After acceleration to the interaction energy—here 100 eV—the positron (electron) beam intersects an argon atomic beam at right angles. The argon beam emerges from a multicapillary orifice. The flow is kept constant by a flow controller. Beyond the interaction region the argon beam is dumped onto the baffle of a cryopump. The angular profile and energy distribution of the positron beam as well as the electron beam were mapped out and optimized for comparable overlap with the argon beam.

The turnable particle detector accepts the ejected electrons which are energy analyzed in a 90° cylindrical electrostatic spectrometer before they impinge onto a channel electron multiplier (CEM), providing time marks for the start of a time-to-amplitude converter (TAC). The ions produced are extracted from the interaction region, separated from the argon atoms (which go into the same direction) by an electric field, and detected by another CEM providing the TAC stop signals. A multichannel analyzer accumulates the time-correlation spectra. They exhibit a distinct ion peak which occurs about 20 μs after the electron detection. Only these peak events, corrected for background, were evaluated. The uncertainty of the projectile energy is about ± 2 eV, due to electron or positron work-function differences and due to the potential gradient in the interaction region. The latter could be reduced by pulsing the extraction. This is planned for future measurements.

The method of *detecting the ionizing positron in time correlation with the produced ion* has been developed for the discrimination against positronium formation in "total" positron-impact 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 an energy $\leq (E - E_{\text{ion}})$ should by itself provide a unique signature for breakup ionization, even without detection of the time-correlated ion. However, we found that the severe background problems, which (more or less) beset all differential scattering experiments, are strongly reduced by this ion detection. This is equally true for electron-impact measurements.

Typical time-correlation spectra for positron and electron impact are shown in Fig. 2. The flat background on either side of the ion peak is only a small portion of the whole background because numerous electron-detection

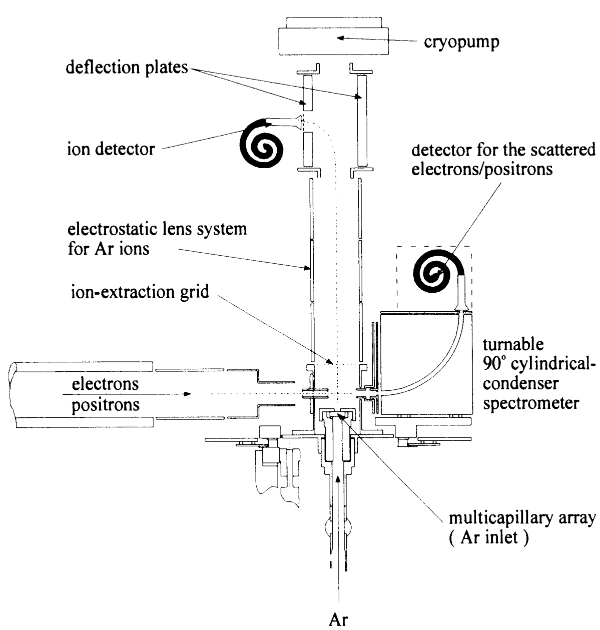

FIG. 1. Experimental arrangement.

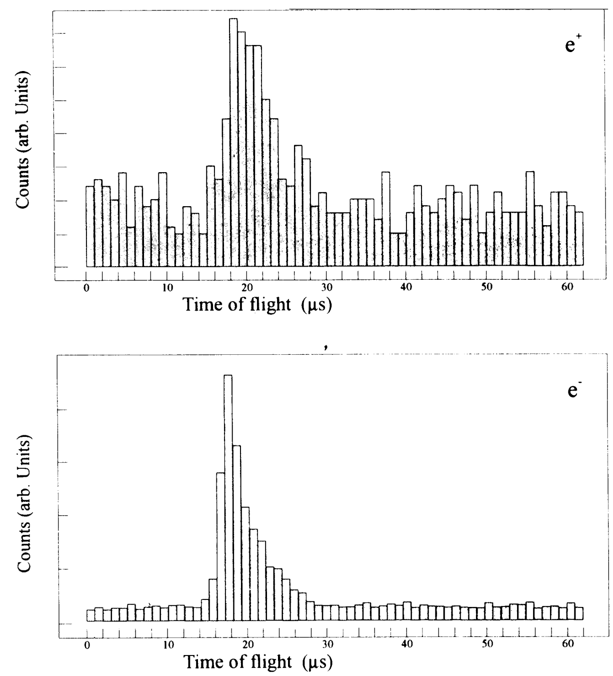

FIG. 2. Ion-correlation spectrum: for positron impact (above) and for electron impact (below). In both cases the TAC was started by the detection of the ejected electron and stopped by the ion detection. The data accumulation time was 1.4×10^5 and 8.0×10^3 s for the upper and lower spectra, respectively.

events are *not* followed by an ion-detection event within the TAC time range of 65 μs and are therefore not displayed in the figure.

The apparatus permits the detection of either the (fast) scattered positron or the (slow) ejected electron. We concentrated on the latter because Klar and Berakdar provided us with theoretical guidance [7], based on numerical integrations [8] of previously calculated triply differential cross sections for positron and electron impact [9]. Although these calculations were made for H, whereas we measure with Ar as the target, we feel that a comparison is worthwhile. The large differences in positron and electron doubly differential cross sections (DDCS's) originate in the infinite range 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 wave functions are very similar. Thus, Klar and Berakdar expect that their theory for H is also a good approximation for Ar.

Unfortunately, we found no experimental data of electron-argon doubly differential cross sections, except those of Opal, Beaty, and Peterson [10] for 500 eV incident electron energy. At 100 eV incident projectile energy, measurements of doubly differential cross sections have been performed by Shyn for hydrogen [11] and by Shyn and Sharp for helium [12], by Müller-Fiedler, Jung, and Ehrhardt [13] for helium, and by Opal, Beaty, and Peterson [10] for helium, nitrogen, and oxygen. At an-

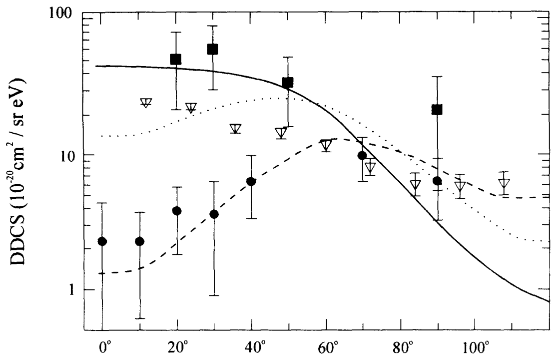

FIG. 3. $d^2\sigma^{\pm}/d\Omega_{-}dE_{\pm}$ (DDCS) for ejected electrons as a function of the emission angle θ_0 at constant energies of $E_0=100$ eV and $E_b=15$ eV. The doubly differential argon cross sections for positron impact (full squares) and electron impact (full circles) determined in this 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) [8]. The measured electron-impact cross sections of Shyn for hydrogen [11] are indicated by open triangles.

gles below 50° Klar and Berakdar's theoretical results [8] for the doubly differential e^--H cross section do not agree with the experimental e^--H results of Shyn [11]. As shown in Fig. 3, the *electron* theory gives much lower values at these angles. The fact that Shyn's *electron* data points come close to the *positron* theory, we regard as fortuitous. The e^-He values of Shyn and Sharp [12] are significantly higher than those of Müller-Fiedler, Jung, and Ehrhardt [13] and Opal, Beaty, and Peterson [10]. The latter are in good agreement with our e^--Ar data and the calculations of Klar and Berakdar for e^--H [8].

The reason for the discrepancy between Klar and Berakdar's e^--H theory and Shyn's e^--H measurement is an open question in electron-atom scattering. Additional information can be obtained by measuring positron-atom scattering, predicted by the same theory.

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 Berakdar's electron prediction *for hydrogen. By* using the same standardization factor we obtained absolute values for our positron-Ar data. The agreement of our positron data with the theoretical positron prediction for H is good. In particular, the prediction that $d^2\sigma^+/d\Omega_{-}dE_{\pm} \gg d^2\sigma^-/d\Omega_{-}dE_{\pm}$ is borne out 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 impacts, respectively.

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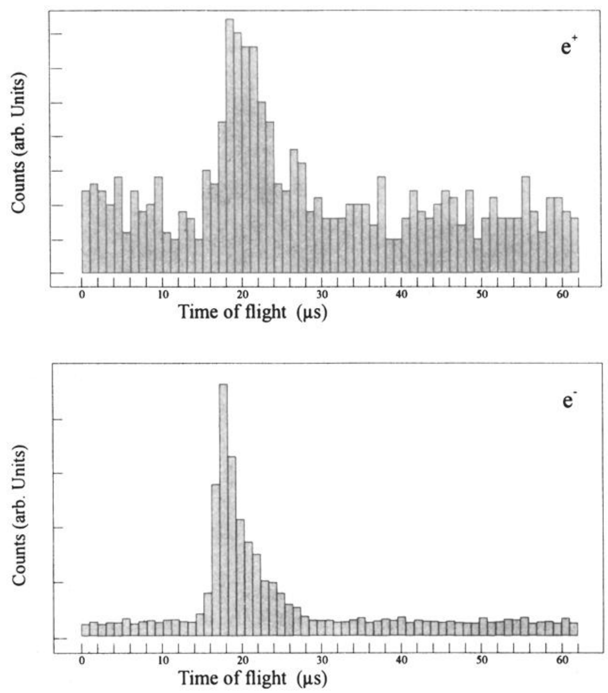

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