Ionization of Atomic Hydrogen by Positron Impact

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In a crossed-beam experiment the angle-integrated ionization cross section for both positron and electron impact on atomic hydrogen (excluding positronium formation) has been measured in the energy region of 17.5 to 600 eV. Below 450 eV the positron cross section is larger than the electron one, at 50 eV by about a factor of 2. Absolute cross sections are obtained by comparing the electron data with literature values. At energies above 30 eV all theoretical predictions lie below our measured cross sections for positron-impact ionization.

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Of all positron-atom scattering problems the e^+-H interaction can be calculated with the highest accuracy and experimental tests are, therefore, of fundamental importance. The positron case is an ideal testing field for the "scattering of electrons without exchange," but on the other hand, the theoretical description of the positronium formation is difficult. In this experiment on e^+-H scattering we have restricted ourselves to the process of impact ionization. Experimentally it is more feasible to measure impact ionization than elastic scattering. For theorists it is the other way around and, therefore, there have been only a few theoretical papers on e^+-H impact ionization thus far.[1-4] In addition to its theoretical significance, the e^+-H interaction is of great astrophysical interest because of the 511-keV γ radiation observed in the direction of the galactic center.[5]

Historically, the laboratory experiments on positron-atom scattering began with simple gas-target transmission experiments and only recently progressed to crossed-beam experiments with noble gases;[6,7] this is the first positron experiment with a crossed beam of atomic hydrogen. By detecting ion and positron in time correlation we measure the relative impact-ionization cross section; the positronium (Ps) formation (in which the positron vanishes) is excluded. Figure 1 shows schematically the experimental arrangement. Fast positrons from a 170-MBq ^{22}Na radioactive source are moderated by two annealed tungsten meshes. The low-energy positrons are accelerated, pass a 90° deflector, and are electrostatically transported into the scattering region. The channel electron multiplier (CEM) No. 1 detects the unscattered positrons and those scattered into a forward cone of 30° apex half angle. The hydrogen atoms emerge from a Slevin-type rf-discharge source.[8] Ions produced by positron impact are extracted from the interaction region by a weak electric field. They move along the atomic beam into the detector region where they are electrostatically bent toward the CEM No. 2. Typical counting rates for CEM No. 1 and No. 2 are 3000 and 10 s^{-1}, respectively. With reversed beam-transport potentials the secondary electrons from the moderator are used for the respective electron measurements. With "inverted timing" we measure the time between an ion count of CEM No. 2 and the delayed positron (electron) count of CEM No. 1. Atomic and molecular ions can be distinguished by their different flight times. The H_2 is a part of the incompletely dissociated hydrogen beam and the main component of the residual gas in the scattering chamber. Only about 0.1% of the CEM No. 2 counts are time correlated to e^+ (e^-) detection. The main portion of this count rate was due to I_α photons and charged particles from the hydrogen source.

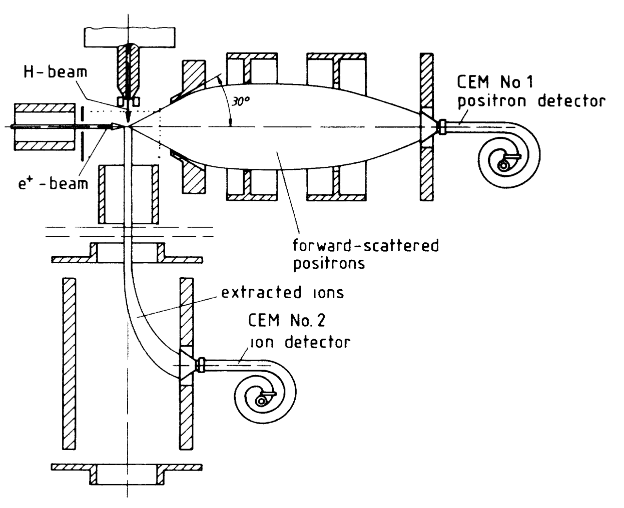

FIG. 1. Layout of the experiment.

Table I lists the relevant ionization processes, the cross-section symbols, and the respective threshold energies. Since we detect correlated $e^{+/-}$-H^+ and $e^{+/-}$-H_2^+ pairs, we measure both $\sigma_{\rm ion}(H)$ and $\sigma_{\rm ion}(H_2)$ for positron (electron) impact simultaneously. The Ps-formation processes with cross sections $\sigma_{\rm Ps}(H)$, $\sigma_{\rm Ps}(H_2)$, and $\sigma_{\rm Ps,diss}(H_2)$ lead to uncorrelated ions which are not measured here. The dissociative cross section $\sigma_{\rm diss}(H_2)$ contributes, in principle, a correlated H^+ ion. However, in tests with 100-eV electrons or positrons and a pure H_2

TABLE I. The relevant processes for the positron-impact ionization of atomic and molecular hydrogen.

Process	Cross section	Threshold (eV)
$e^+ + H \rightarrow Ps + H^+$	$\sigma_{Ps}(H)$	6.8
$e^+ + H \rightarrow e^+ + e^- + H^+$	$\sigma_{ion}^{+}(H)$	13.6
$e^+ + H_2 \rightarrow Ps + H_2^+$	$\sigma_{Ps}(H_2)$	8.6
$e^+ + H_2 \rightarrow e^+ + e^- + H_2^+$	$\sigma_{ion}^{+}(H_2)$	15.4
$e^+ + H_2 \rightarrow Ps + H_1 + H_1^+$	$\sigma_{Ps,diss}(H_2)$	11.1
$e^+ + H_2 \rightarrow e^+ + e^- + H_1 + H_1^+$	$\sigma_{diss}^{+}(H_2)$	17.9

beam (discharge turned off) we could not detect any H^+ ions. Apparently, most dissociative-ionization events proceed via highly excited states and yield ions of high kinetic energy which we collect with low efficiency. For electrons at 100 eV their contribution to our H^+ signal is less than 1% although the cross section $\sigma_{diss}^{-}(H_2)$ amounts to 7% of $\sigma_{ion}^{-}(H_2)$.[9]

The most serious disadvantage of our experimental arrangement is the limitation of the positron (electron) detection to scattering angles of less than 30°. A data correction for the undetected large-angle events would require detailed knowledge of the differential ionization cross section which describes the angular distribution of the outgoing positron (the outgoing electron with higher energy). This information is not available. From studies of differential electron-impact ionization, however, it is known that most ionization events are associated with small momentum transfers and correspondingly small scattering angles of the primary electrons.[10] This behavior is typical for higher energies but does not apply to ionization near threshold. By taking electron data as a function of the energy and comparing them with literature values it is possible to find out how the restriction to small angles affects our measurements. For low energies we expect that our measured electron cross sections fall below the literature values because of the systematic error made by not detecting the large-angle events. This systematic error can, in principle, be different for positron ionization because of a different angular dependence. Here we assume that this difference is negligible at energies for which our measured electron cross sections agree with the literature values within the error margin. In order to get a theoretical estimate we employed the full-range first Born approximation which does not distinguish between positive and negative charges of the ionizing particle and does not account for exchange. Our computations indicate that for energies $E \geq 100$ eV more than 90% of the impact-ionization events lead to scattering angles $\theta \leq 30°$.

Since the detection probabilities for the correlated positron(electron)-ion pairs, the overlap volume of projectile and target beam, and the densities of H and H_2 in the interaction region are unknown we can only determine relative ion-formation probabilities. To obtain $\sigma_{ion}^{-}(H)$ and $\sigma_{ion}^{-}(H_2)$ the ion-formation probabilities are normalized to already known absolute electron-impact-ionization cross sections[11-15] in the energy range from 200 to 600 eV. For H we used the values of Fite and Brackmann[12] and those of Shah, Elliot, and Gilbody[15] with equal weight, and for H_2, the values of Rapp and Englander-Golden.[16] The same normalization factors are used for the normalization of the positron data on H and H_2. Fortunately, we can check this procedure by comparing our e^+-H_2 results with those obtained earlier

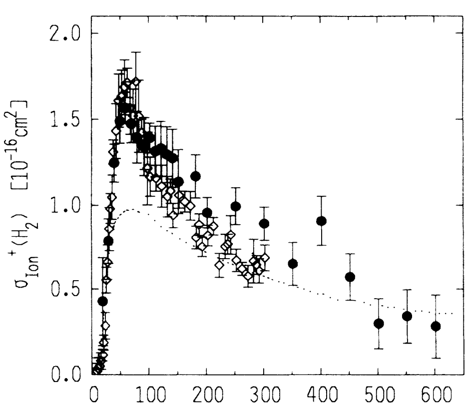

FIG. 2. Positron-impact-ionization cross sections of molecular hydrogen: ●, present results normalized by fitting our e^--H_2 data to the literature values. ◇, results of Fromme *et al.* (Ref. 17) obtained in an entirely different experiment at Bielefeld. ····, *electron* data of Rapp and Englander-Golden (Ref. 16), for comparison.

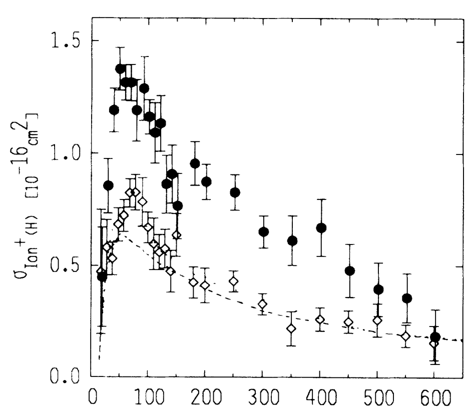

FIG. 3. Positron- and electron-impact-ionization cross sections of atomic hydrogen. Present results: ●, $\sigma_{ion}^{+}(H)$; ◇, $\sigma_{ion}^{-}(H)$. Literature values of $\sigma_{ion}^{-}(H)$: ---, results of Shah, Elliot, and Gilbody (Ref 15); ····, results of Fite and Brackmann (Ref. 12). For normalization a best fit of our electron data points between 200 and 600 eV to the average of the two literature curves was made.

in a different apparatus[17] (Fig. 2).

In Fig. 3 the first measurements on the ionization of atomic hydrogen by positron impact are shown; for comparison our measured electron data and literature values are also shown. The good agreement of our electron data with the literature values over the whole range of measurement indicates that we detect nearly all the electrons scattered in the ionization processes. Below 400 eV the e^+-H impact-ionization cross sections (Fig. 3) are significantly higher than the respective electron cross sections. The cross sections σ_{ion}^+ and σ_{ion}^- should merge at sufficiently high energy: The polarization interaction is only important at very low energies; the influence of exchange effects in electron scattering and Ps formation in positron scattering decreases with increasing energy and, ultimately, the first Born approximation (FBA) should become valid for both. It is of great interest to test experimentally at what energy the merging occurs. Our data are consistent with equal positron- and electron-impact-ionization cross sections above 500 eV.

Qualitatively, the positron cross section shows the shape predicted by the theoretical estimates of Ghosh, Mazumdar, and Basu,[1] Mukherjee, Singh, and Mazumdar,[2] Ohsaki *et al.*,[3] and Wetmore and Olson[4] (Fig. 4). Ghosh, Mazumdar, and Basu[1] calculated the total impact-ionization cross section up to 58 eV by using a distorted-wave polarized-orbital method. They found a strong dependence on the choice of the final-channel wave function. Their results obtained with a plane wave for the scattered positron, which are very close to their FBA results given in the same paper, are shown in Fig. 4. At maximum they are about 20% too low. The predictions of Mukherjee, Singh, and Mazumdar[2] lie lower. We plotted their model with the highest cross-section

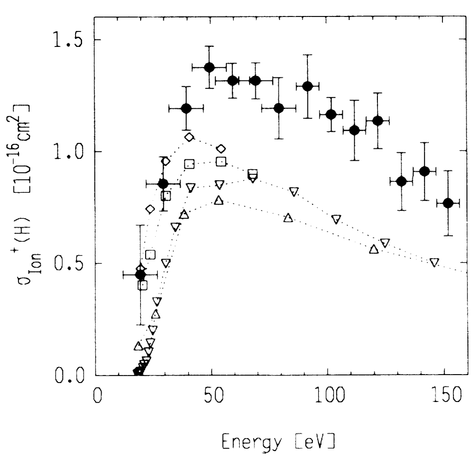

FIG. 4. Comparison of measured positron-impact-ionization cross section of atomic hydrogen with theoretical predictions. ●, present results; ◇, Ghosh, Mazumdar, and Basu (Ref. 1); □, Mukherjee, Singh, and Mazumdar (Ref. 2); △, Ohsaki *et al.* (Ref. 3); ▽, Wetmore and Olson (Ref. 4).

maximum which is called DCPE, referring to distortion (of the outgoing waves), Coulomb wave (for the outgoing electron), plane wave (for the outgoing positron), and energy integral (fuel evaluation of). These authors implemented some corrections which were used by Campeanu, McEachran, and Stauffer[18] for positron-impact ionization of helium and gave good agreement with the experimental results of Fromme *et al.*[19] The Monte Carlo results of Ohsaki *et al.*[3] and Wetmore and Olson[4] lie definitely outside the error margin of our measurements.

The work on e^+-H scattering reported here has been limited by the very low signal rate of less than 0.01 s^{-1}, which prohibited more ambitious measurements. In the near future this experiment will be moved to the high-current positron source of the Brookhaven National Laboratory[20] and in a collaboration we will perform further e^+-H measurements.

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