Measurement of Positronium Formation in Positron Collisions with Hydrogen Atoms

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The positronium-formation cross section was measured for positron collisions with atomic hydrogen in a crossed-beam experiment. Measurements were made in the energy range of 13 eV $\leq E \leq$ 205 eV. At $E = 15 \pm 2.8$ eV we observed a maximum cross section of $(4.3 \pm 0.8) \times 10^{-16}$ cm^2; because of averaging over an energy-resolution function of 6.5 eV FWHM, the observed maximum is a lower limit of the true maximum. For $E \geq 75$ eV the cross section is zero within our error margin of 0.3×10^{-16} cm^2. No other measurements but numerous theoretical predictions are available for comparison.

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The system $e^+e^-p^+$ is a fundamental three-particle system of great theoretical interest. It contains three distinguishable particles and has two two-particle bound states, $\mathrm{H}=(p^+e^-)$ and positronium $\mathrm{Ps}=(e^+e^-)$, related by the *charge-transfer* or *rearrangement reaction*

$$e^+ + \mathrm{H} \to \mathrm{Ps} + p^+ . \tag{1}$$

The understanding of this most fundamental process has provided a formidable theoretical challenge. Starting in 1954 with the pioneering work of Massey and Mohr [1], this process has been the topic of numerous theoretical papers. For the early work and the historical perspective we refer to reviews [2,3]; some of the more recent work [4–21] will be discussed later.

Aside from being a fundamental process, this reaction is also significant in two other respects. First, the observation of the 511-keV radiation from the galactic center [22] leads to the conclusion that huge quantities of positrons, about 10^{43} per s^{-1}, somehow originate very close to the center and subsequently slow down and annihilate with electrons from the surrounding matter, presumably consisting of hydrogen atoms. When positrons annihilate either directly with a free electron or after having formed Ps($1\,^1S$), two 511-keV photons are emitted; the photons emitted in the 3γ decay of Ps($1\,^3S$) have a broad energy distribution extending up to 511 keV. From the intensity of the observed 511-keV line relative to that of its low-energy tail, a large Ps fraction has been inferred [23]. Second, one of the methods pursued for creating antihydrogen atoms is positron transfer from positronium to antiprotons [24]. The cross section for antihydrogen ($\bar{\mathrm{H}}$) formation in Ps-antiproton scattering, $\sigma_{\bar{\mathrm{H}}}$, is related to the cross section for Ps formation in positron-hydrogen scattering, σ_{Ps}, by charge-conjugation and time-reversal invariance; the ratio of these cross sections is a simple state-dependent kinematic factor [25].

Experimentally, low-energy positron-atom collisions can be studied with good energy resolution by means of moderated positrons which emerge from a solid-state moderator with a small energy spread; the intensity of typical positron beams, however, lies many orders of magnitude below that of typical electron beams and makes positron scattering experiments challenging. In recent years methods were developed for measuring the partial cross sections of impact ionization and positronium formation in gas-cell targets [26], and the intensities of moderated-positron beams increased sufficiently to allow the use of atomic-beam targets in positron-atom crossed-beam experiments [27].

The first experiment on e^+H scattering was that of Spicher *et al.* [28] (Bielefeld) which provided measured cross sections for the reaction

$$e^+ + \mathrm{H} \to p^+ + e^- + e^+ ; \tag{2}$$

a similar experiment is under way at University College London [29]. Reaction (2) is called positron-impact ionization, in analogy to the corresponding electron collision, or *breakup reaction,* in order to distinguish it from reaction (1) which also leads to ionization.

The Bielefeld experiment was severely limited by very low beam intensity, background due to Lyman-α from the hydrogen source, and lack of a mass spectrometer separating $\mathrm{H_1}^+$ and $\mathrm{H_2}^+$ ions. For performing more advanced e^+H experiments, the scattering apparatus used by Spicher *et al.* [28] was moved to the High-Intensity Positron Beam Facility at the High Flux Beam Reactor of Brookhaven National Laboratory [30]. For the measurements reported here, we employed the high-intensity positron beam from a low-temperature solid-neon moderator [31].

Figure 1 shows the experimental arrangement. Hydrogen atoms, along with hydrogen molecules, emerge from a Slevin-type rf-discharge source [32]; the operating parameters of the source were held constant over many days of around-the-clock data taking. The degree of dissociation is $>90\%$ for the beam emerging from the nozzle of the discharge tube and $\approx 55\%$ for the mixture of beam and residual gas in the scattering region. The hydrogen beam intersects with the positron beam at right angles. A channel electron multiplier (CEM) detects the positrons

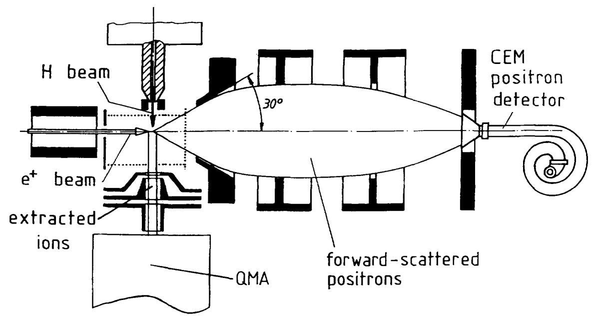

FIG. 1. The layout of the hydrogen scattering experiment: The ion rate of the quadrupole mass analyzer (QMA) is measured. In addition, the ion detector of the QMA provides the "start pulse" for the time-correlation measurement, while the time-delayed positron-detection signal from the channel electron multiplier (CEM) provides the "stop pulse."

scattered into a forward cone with a 30° half-apex angle (as well as the unscattered positrons). Ions are extracted from the scattering region by an electric field of 8 V/cm and mass analyzed by the quadrupole mass analyzer (QMA). Only ions with mass 1 are counted.

The QMA-mass-1 ion rate, corrected for background measured with positron beam off, is proportional to the sum of impact-ionization and Ps-formation cross sections $\sigma_{\text{ion}}^{+}+\sigma_{\text{Ps}}$. In order to distinguish between ions from Ps formation and impact ionization, we not only measure the QMA ion-detection rate but also take positron-ion time-correlation spectra. Such a spectrum is obtained by starting each time measurement with the detection of an $\text{H}_1{}^{+}$ ion and stopping it by the time-delayed positron-detection signal. The rate of correlated events, obtained from the background-corrected peak of the time-correlation spectrum at each energy, is proportional to the impact-ionization cross section, $\sigma_{\text{ion}}^{+}(E)$, alone. The background of the spectrum is flat and typically about 25% of the peak; it results from QMA pulses due to Ps-formation ions or γ radiation followed by an uncorrelated positron within the 4-μs time interval covered by the spectrum.

Three different systematic errors must be considered.

Dissociative processes.—The identification of the measured signals with the cross sections for *atomic hydrogen* is based on the assumption that *dissociative* ionization of H_2, with and without Ps formation, can be neglected. In a test at 40 eV, we found that the influence of these processes on our Ps-formation cross-section measurement is less than 3%.

Ps detection by the CEM.—This positron detector could also count some of the Ps-formation events by responding either to annihilation radiation or to Ps impinging onto the detector; such Ps-formation events would wrongly be interpreted as breakup ionization. At 30 eV this count rate is only about 2% of the correlated-event rate and, therefore, it is negligible here.

Wide-angle scattering of the ionizing positron.—From studies of electron-impact ionization it can be inferred [33] that positron-impact ionization *at high energies* leads predominantly to forward-scattered positrons which can be detected by the CEM. At low energies, however, a portion of the impact-ionization ("breakup") events lead to positrons scattered through angles of more than 30° which would not be detected by the CEM. Such breakup events would wrongly be interpreted as Ps formation. With decreasing energy the percentage of the wide-angle ionization events increases, but its effect on the determination of σ_{Ps} is mitigated by the simultaneous decrease of σ_{ion}^{+} and the increase of σ_{Ps}. In order to correct for this effect without knowing the angular distribution of positron-impact ionization, we employed the differential impact-ionization cross section obtained with the first Born approximation (FBA) for computing the percentage of ionizing positrons scattered through angles $>30°$. The FBA depends only on the square of the projectile's charge. Since the FBA disregards exchange, it is a better approximation for positrons than for electrons. This assumption is supported by the fact that the angle-integrated ("total") impact-ionization cross section for helium, $\sigma_{\text{ion}}(\text{He})$, calculated by Basu, Mazumdar, and Ghosh [34] in FBA agrees much better with the positron cross section, $\sigma_{\text{ion}}^{+}(\text{He})$, measured by Fromme *et al.* [35] than with data for the electron cross section, $\sigma_{\text{ion}}^{-}(\text{He})$. The result of our FBA correction is a lowering of the measured σ_{Ps} by factors of 0.96, 0.90, 0.92, 0.83, 0.81, 0.80, and 0.84 for $E=15$, 20, 25, 35, 45, 55, and 65 eV, respectively.

As is typical for capture processes [1], the Ps-formation cross section is expected to peak and then to fall off at lower energies than the impact-ionization cross section. From the observation that the ratio of the QMA signal to the correlation signal remains constant at $E \geq 75$ eV within the accuracy of our experiment, we concluded that σ_{Ps} is zero at these higher energies. Thus both signals, the rate of QMA ions and the rate of time-correlation events, are proportional to σ_{ion}^{+} at these energies. We used our measurements at 75, 85, and 205 eV to determine the relative efficiencies of the two signals. At any energy below 75 eV, the rate of correlated events, representing a relative measure of σ_{ion}^{+}, is subtracted from the calibrated QMA ion rate for determining σ_{Ps} in the same units as σ_{ion}^{+}. In order to determine absolute cross-section values without knowing the H-atom target thickness and the detector efficiencies, we compare all the relative σ_{ion}^{+} data obtained in this work with the earlier positron and electron measurements at Bielefeld [28] where both σ_{ion}^{+} and σ_{ion}^{-} had been determined under identical target and detector conditions. Finally, the relative σ_{ion} data of the Bielefeld experiment were normalized by fitting the data points in the energy range of 50 to 600 eV to the absolute measurements of Shah, Elliot, and Gilbody [36]. The scaling uncertainty, affecting all our measured cross-section values, was determined by quadratic addition of all calibration and normalization errors and amounts to 18%.

Both the true zero point of the energy scale and the energy spread of the beam were determined in a separate retarding-potential measurement with the neon-moderated positron beam. The energy distribution, combined with the effect of the potential gradient in the scattering region, leads to an experimental energy-resolution function of 6.5 eV FWHM approximately described by a Gaussian of ± 2.8 eV standard deviation. The retarding-potential measurement also showed that the mean energy of the incident positrons is given by $E=e(U+5\ \mathrm{V})$ where U is the voltage applied between positron moderator and scattering region.

The observed maximum cross section at 15 eV is $(4.3\pm 0.8)\times 10^{-16}\ \mathrm{cm}^2$; the stated error mainly stems from the 18% scaling uncertainty. Because of averaging over the energy-resolution function of 6.5 eV FWHM, the observed cross-section maximum is a lower limit for the true maximum and its energy location is uncertain by ± 2.8 eV. On the low-energy side of the maximum, reliable measurements are not yet possible because of insufficient energy resolution and signal rate.

In Fig. 2 our measured Ps-formation cross sections, corrected for wide-angle scattering of ionizing positrons as described above, are compared with several theoretical predictions. Only a few theories yield cross-section maxima consistent with our measurement. This is most surprisingly true for the FBA results of Massey and Mohr [1] (dashed curve), which is the simplest approach possible and not believed to be very accurate for this rearrangement process. It is also true for the first-order exchange approximation of Mandal and Guha [4] and the distorted-wave approximation of Mandal, Guha, and Sil [5] (neither shown in Fig. 2) as well as for the result of the rather sophisticated Fock-Tani computation of Straton [15] (open circles) who improved the field-theoretical

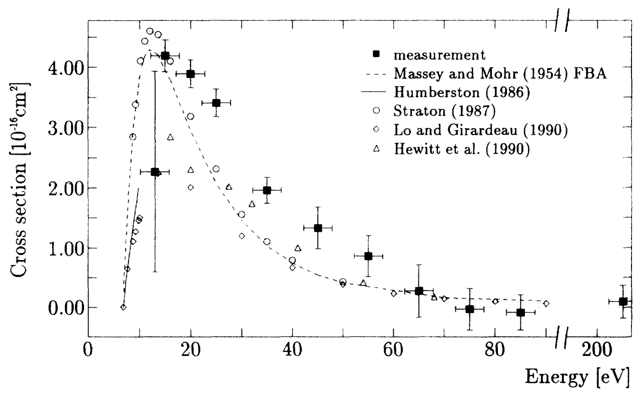

FIG. 2. Measured Ps-formation cross sections (solid squares with error bars); the vertical bar represents the statistical error of the data point, and the horizontal bar, the energy uncertainty. Also plotted are several theoretical predictions explained in the text.

work of Varracchio and Girardeau [7] (not shown). However, a different extension of that work by Lo and Girardeau [19] (open diamonds) led to a maximum which is distinctly too low. Similarly low are the maxima predicted by the distorted-wave FBA of Shakeshaft and Wadehra [6], the R-matrix calculation of Higgins and Burke [21], and the classical Monte Carlo trajectory computations of Ohsaki *et al.* [13] as well as Wetmore and Olson [14] (none of them plotted). The curve with open triangles, which also has a lower maximum, will be discussed later.

The theories which do predict a sufficiently high maximum (cf. dashed curve and open circles in Fig. 2) seem to indicate that it lies at a slightly lower energy than the observed one, while the lower maxima predicted by other theories lie energetically closer to the observed one.

The low-energy region above 10.2 eV, where additional inelastic channels open up, is rather difficult for the Ps-formation theory. Much more trustworthy results can be obtained between 6.8 and 10.2 eV, where Ps formation is the only inelastic channel open [9–11,18]. The most elaborate of those near-threshold theories is the Kohn variational calculation of Humberston [3,9,11] (solid curve) which predicts that the cross section rises from threshold more slowly than the FBA curve; an extrapolation of Humberston's result could easily be consistent with size and energy location of the observed maximum.

Since our experiment does not distinguish between different final states of the formed Ps, *the measured cross-section values include Ps formation in excited states.* Only a few of the theoretical groups take this into account, at least partially, by also computing the formation cross sections for Ps(2S) and Ps(2P) which give substantial additions to the total cross section. We plotted the close-coupling result of Hewitt, Noble, and Bransden [20] (open triangles) as a typical example. The other approaches, namely, the distorted-wave polarized-orbital approximation of Khan and co-workers [8,12] the second Born approximation of Basu and Ghosh [16], and the Glauber eikonal approximation of Tripathi, Sinha, and Sil [17], give similar results. All predict cross sections which are significantly lower than our results near the maximum. For 30 eV $< E <$ 60 eV their predictions, as well as the Monte Carlo results [13,14], lie slightly below the data points plotted in Fig. 2; but they are consistent with them because of the 18% scaling error, not covered by the error bars in Fig. 2. Above 60 eV all theories are close to zero, consistent with our measurements.

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