Partial–Cross-Section Measurements for Ionization of Helium by Positron Impact

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Positrons ionize helium atoms either by impact ionization, resulting in three outgoing particles, or by positronium formation. We determined cross sections for both processes for incident-positron energies ranging from the respective thresholds to 1000 eV. The cross section for impact ionization by positrons ($\sigma_{\rm ion}^{+}$) exceeds the corresponding electron cross section ($\sigma_{\rm ion}^{-}$) below 500 eV. On the high-energy side of its maximum, the positronium-formation cross section ($\sigma_{\rm Ps}$) lies above all theoretical predictions.

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For the comparison of positron and electron scattering by atoms and molecules several groups have measured total cross sections for a variety of target gases. At low energies the electron and positron cross sections are distinctly different. In order to investigate the differences in detail, partitioning of the total cross section into its separate contributions is desirable. Above its threshold, ionization is the most significant open channel. In the case of positron scattering two ionization processes are possible. One is impact ionization (cross section $\sigma_{\rm ion}^{+}$, threshold energy $E_{\rm ion}=24.6$ eV),

$$\mathrm{He}+e^{+}\rightarrow\mathrm{He}^{+}+e^{-}+e^{+},$$

which is analogous to electron-impact ionization ($\sigma_{\rm ion}^{-}$). The other one is positronium formation ($\sigma_{\rm Ps}$, $E_{\rm Ps}=17.8$ eV),

$$\mathrm{He}+e^{+}\rightarrow\mathrm{He}^{+}+\mathrm{Ps},$$

which is followed by positronium decay with 2γ or 3γ emission.

In this Letter we report measurements for both cross sections, $\sigma_{\rm ion}^{+}$ and $\sigma_{\rm Ps}$, from threshold to 1000 eV. Our experimental arrangement differs significantly from those employed by other groups in earlier measurements.[1-5] Here an ion is detected in time correlation with the positron that produced it. The apparatus allows simultaneous determination of the relative values for the sum $\sigma_{\rm Ps}+\sigma_{\rm ion}^{+}$ and for $\sigma_{\rm ion}^{+}$ separately. These relative values can be normalized to literature values[6] of $\sigma_{\rm ion}^{-}$ at sufficiently high energies where $\sigma_{\rm ion}^{+}$ and $\sigma_{\rm ion}^{-}$ merge and no positronium is formed. Reports on preliminary results have already been given.[7]

In our experimental arrangement (Fig. 1) the interaction region is a differentially pumped gas target. The target gas is supplied through holes in the middle of the scattering tube which is pumped at both ends. For background measurements the gas flow is directed to the ends through by-pass pipelines. The scattering tube consists of a long glass tube (length 50 cm, inside diameter 1.1 cm) whose inside wall is lined with a helix of tungsten wire. The helix (Fig. 1, enlargement) provides a wall of well-defined electric potential. By the drawing of a current through the tungsten wire a longitudinal electric field of 20 V/m is generated for the extraction of the ions. The whole apparatus is surrounded by coils providing a longitudinal magnetic guiding field for the positrons as well as for the ions produced in the scattering tube. The field strength is about 35 mT in the scattering tube and lower elsewhere.

A ^{22}Na positron source (about 70 MBq activity) is located off axis so that there is no line of sight to the microchannel-plate detectors. Some of the high-energy positrons from the source are moderated by an annealed tungsten plate mounted at an angle of 45° with respect to the optical axis. The energy of the slow positron beam is varied by the potential applied to the moderator. The tube entrance aperture of 4-mm diameter ensures that the ions are produced close to the axis. The scattered positrons are radially confined by the magnetic field. The applied potentials ensure that at all energies they leave the scattering tube together with the unscattered ones—except for the very few elastically scattered backwards. Those positrons which form positronium vanish.

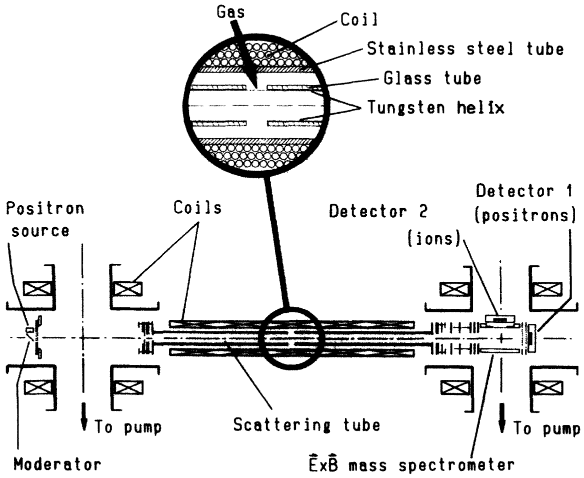

FIG. 1. Experimental arrangement.

The target thickness was set at about 5×10^{14} cm^{-2}, keeping the chance of double scattering below 1%.

Beyond the scattering tube the positrons are accelerated and traverse the region of a crossed electric and magnetic field ($\mathbf{E}\times\mathbf{B}$) mass separator.[8] For positrons the $\mathbf{E}\times\mathbf{B}$ field causes only a small deflection. The positron counting rate of detector 1 is about 1000 s^{-1}. The ions leaving the scattering tube are accelerated and then deflected in the $\mathbf{E}\times\mathbf{B}$ mass separator toward detector 2. The ion counting rate is 10 s^{-1} or less.

The counting rates R_1 and R_2 of detectors 1 and 2 are recorded simultaneously. One measurement cycle consists of four different measurements. The target gas is alternately directed into the scattering tube and through the by-pass, and in both cases counting rates are recorded with the positron beam switched on and off. From these measurements we obtain the rate of primary positrons R_{e^+} and the production rate of helium ions R_{He^+}, both corrected for background. The ratio $R_{\mathrm{He}^+}/R_{e^+}$ is a relative measure of $\sigma_{\mathrm{Ps}}+\sigma_{\mathrm{ion}}^+$.

Each event registered by detector 1 starts a time-to-amplitude converter, which is stopped by a subsequent signal from detector 2. The time-to-amplitude converter pulses are recorded by a multichannel pulse-height analyzer. The resulting distribution is a time-correlation spectrum with a distinct peak at about 33 μs. This is—for given extraction and acceleration voltages—the difference between the flight times of a helium ion and a positron from the center of the scattering tube to their respective detectors. Thus the peak of the spectrum originates from helium ions which were produced by impact ionization resulting in three outgoing particles. The peak sits on top of a flat background which mainly results from ions whose correlated positrons disappeared by forming positronium. The width of the peak on top of the background is about 8 μs FWHM, its height is about 5 times higher than the background level, and the integral number of counts in the peak between 26 and 41 μs (which was used in our data evaluation) exceeds that of the background, for example, by a factor of 2.6 at $E=80$ eV. The counting rate of events in the peak, $R_{\mathrm{He}^+(\mathrm{corr})}$, represents ions produced by impact ionization; $R_{\mathrm{He}^+(\mathrm{corr})}$ divided by the rate of positrons starting the time-to-amplitude converter is a relative measure of σ_{ion}^+. In principle, a relative measure of σ_{Ps} could be obtained from the background of the time-correlation spectrum, provided that contributions not related to Ps formation (e.g., due to gamma detection and detector-noise pulses) were separately measured and deducted. For better accuracy, however, we chose to determine σ_{Ps} from the measurements of $\sigma_{\mathrm{Ps}}+\sigma_{\mathrm{ion}}^+$ and σ_{ion}^+.

For measurement of the energy dependence of the cross sections, the energy of the primary positrons is varied by changing of the potentials of the moderator and the first grid. The other potentials and the magnetic field are kept constant. Tests indicated that the magnetic guiding field of 35 mT is not strong enough for complete radial confinement and that the ion-extraction efficiency decreases with increasing positron energy. However, this does not affect the ratio of our relative values for $(\sigma_{\mathrm{Ps}}+\sigma_{\mathrm{ion}}^+)/\sigma_{\mathrm{ion}}^+$. From the energy dependence of this ratio we conclude[9] that σ_{Ps} is negligible above 300 eV within the uncertainty of our measurement.

In a separate measurement we counted the ions produced by secondary electrons from the moderator. On the assumption that the electron intensity is proportional to the intensity of the positron beam at all energies,[10] the ratio of ion counting rates produced by electrons and positrons is a relative measure of $(\sigma_{\mathrm{Ps}}+\sigma_{\mathrm{ion}}^+)/\sigma_{\mathrm{ion}}^-$, converging to $\sigma_{\mathrm{ion}}^+/\sigma_{\mathrm{ion}}^-$ at energies above 300 eV. Our data show that this ratio approaches a constant value above 600 eV, indicating convergence of σ_{ion}^+ and σ_{ion}^-.[11] We use our data at energies above 750 eV for normalizing our relative values of $\sigma_{\mathrm{Ps}}+\sigma_{\mathrm{ion}}^+$ and σ_{ion}^+ to σ_{ion}^- from the literature.[6] From our fitting procedure and the uncertainties of the literature values we estimated a systematic error, common to all our data points, of ±8%. The energy width of our data points is about 4 eV FWHM as estimated from the width of the helium-ion peak in the time-correlation spectrum and the potential gradient in the target.

Our results are displayed in Figs. 2 and 3 together

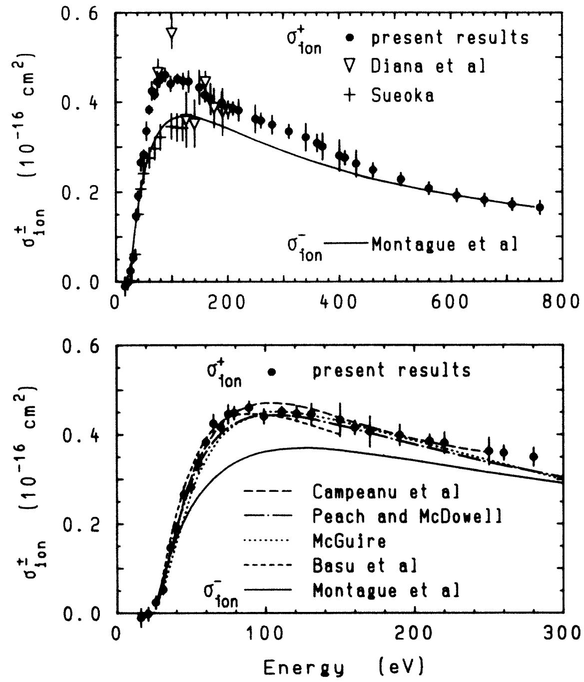

FIG. 2. Cross section for positron-impact ionization of helium, σ_{ion}^+. Top: comparison with other experimental results (Refs. 1 and 2). Bottom: comparison with theoretical results (Refs. 12–15). The electron-impact–ionization cross section σ_{ion}^- (Ref. 6) is also shown.

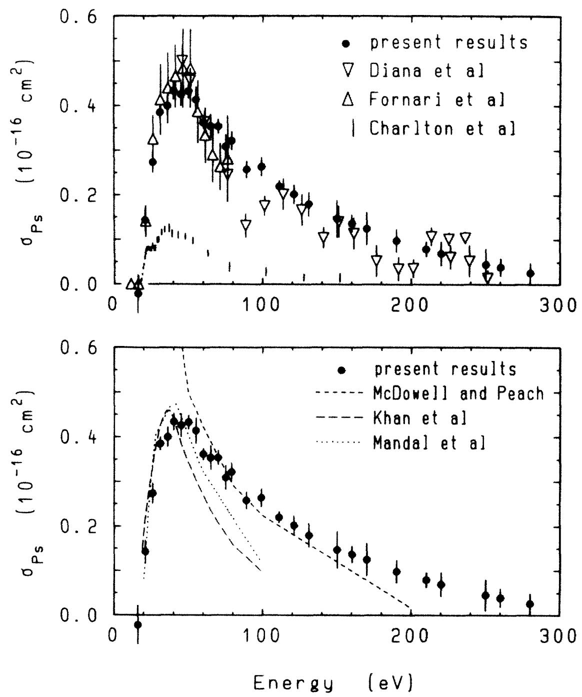

FIG. 3. Positronium-formation cross section of helium, $\sigma_{\rm Ps}$. Top: comparison with other experimental results (Refs. 3–5). Bottom: comparison with theoretical results (Refs. 16–18).

with other experimental and theoretical results. For comparison, $\sigma_{\rm ion}^{-}$ is also shown in Fig. 2. The error bars of our data points represent statistical 1-standard-deviation errors. Our data on $\sigma_{\rm ion}^{+}$ (Fig. 2, top) show clearly that $\sigma_{\rm ion}^{+}$ exceeds $\sigma_{\rm ion}^{-}$ at low energies, contradicting the experimental results of Sueoka[1] and only partially agreeing with the measurements of Diana *et al.*[2] All available theoretical results,[12–15] obtained with rather different methods, are in remarkably good agreement with each other and with our data (Fig. 2, bottom). The results of McGuire[13] and of Peach and McDowell[14] were computed for "electron ionization without the exchange interaction." Their good description of positron ionization indicates that exchange is the main reason for the difference between $\sigma_{\rm ion}^{+}$ and $\sigma_{\rm ion}^{-}$. The most recent and most elaborate calculations of Campeanu, McEachran, and Stauffer[15] show the best agreement with our measurements.

Our results for $\sigma_{\rm Ps}$ deviate from previous measurements (Fig. 3, top); they significantly exceed those of Charlton *et al.*[3] throughout their energy range and do not show the structure exhibited by the data of Diana *et al.* on the high-energy side of the maximum.[5] The measurements include formation of positronium in excited bound states. So far, theoretical work on positronium formation either considers the ground state only[16] or includes selected excited states.[17–19] On the high-energy side of the maximum all theoretical results fall off more rapidly than ours (Fig. 3, bottom). It is doubtful whether this discrepancy can be attributed to neglect or incomplete consideration of positronium formation in excited states. While the inclusion of more excited-state formation would certainly increase the theoretical cross-section values, a more adequate treatment of polarization effects would tend to decrease them.[16,20] Thus the generally good agreement of the theories with our results on the low-energy side of the maximum might be fortuitous.

A comparison of $\sigma_{\rm Ps}$ with the cross section for charge transfer in proton-helium collisions,[21] $\sigma_{\rm H}$, at equal velocities may prove instructive. For example, at $v = 3.9$ a.u. (the corresponding energies of positron and proton are 210 eV and 386 keV, respectively) the ratio $\sigma_{\rm Ps}/\sigma_{\rm H}$ is about 25. This is consistent with recent calculations of McGuire, Sil, and Deb[22] who found that $\sigma_{\rm Ps}/\sigma_{\rm H}$ is significantly greater than unity for $v < 10$ a.u., and increases rapidly with decreasing v in the velocity range considered here.

In 1981 Kauppila *et al.*[23] measured electron and positron *total* cross sections on helium and observed merging already at 200 eV whereas calculations of angle-integrated *elastic* cross sections showed that electron scattering exceeds positron scattering significantly at 200 eV and even well above.[24] Our measurements indicate that compensation is provided by $\sigma_{\rm ion}^{+} > \sigma_{\rm ion}^{-}$ and especially by $\sigma_{\rm Ps} > 0$ in this energy region. This might explain the early convergence of the total cross sections.

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the cross-section ratio above 300 eV indicates that σ_{Ps} is negligible.

[10] This assumption holds except for slightly different energy-dependent focusing in the magnetic field between moderator and scattering tube, caused by the different emission characteristics. This was studied separately and taken into account.

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