Production and scattering of a positronium beam

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Abstract

Progress in the field of positronium beam-production and scattering is reviewed. A useful beam of positronium is obtained in the energy range 10–250 eV by scattering positrons from H₂ and N₂. With such a beam, total positronium – atom/molecule scattering cross-sections and integrated and differential fragmentation cross-sections have been measured. Results are presented and compared with recent theoretical determinations. First results for the absolute differential positronium formation cross-sections are also presented.

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1. Introduction

Positronium (Ps) is the bound state of an electron (e⁻) and its antimatter counterpart the positron (e⁺) and is of interest in many diverse areas of science, from atomic and molecular collision physics to material characterization and astrophysics [1–5]. In Ps, the centers of charge and mass coincide, leading to a zero-static interaction thus enhancing the effects of electron-exchange [6]. Ps may be formed in either a triplet (ortho-) or singlet (para-) state depending on the spin orientation of the constituent particles. These two spin states are characterized by lifetimes, differing by three orders of magnitude (142 ns and 125 ps respectively for o-Ps and p-Ps in their ground state) and decay modes (predominantly 3-γ and 2-γ respectively).

Information on Ps momentum-transfer cross-sections near thermal energies can be obtained experimentally using indirect methods such as Angular Correlation of Annihilation Radiation (ACAR) [7,8] and Doppler broadening [9]. At higher energies, cross-sections are being measured directly using a Ps beam, produced through neutralizing a e⁺ beam in a gaseous target [10–12].

In the next sections, we outline the experimental method used to produce a beam of Ps atoms and
review scattering experiments performed. These include Ps total cross-sections determined for simple atoms and molecules and the cross-section for its fragmentation in collision with He atoms. First results for the absolute differential Ps formation cross-sections, extracted from measurements of the Ps beam production- and detection-efficiencies are also presented.

2. Experimental arrangement

Fig. 1 shows a schematic diagram of the Ps beam-line at University College London. A radioisotope of sodium (\(^{22}\)Na) provides the source of \(\beta^+\) particles, which are moderated by a solid argon film [13] and accelerated to the required beam energy. The slow \(e^+\) are then guided by the magnetic field produced by eleven Helmholtz coils. A Wien filter is used to separate the slow \(e^+\) beam from the flux of fast particles from the source. Ps is generated through charge-exchange of the incident \(e^+\) beam in the first gas cell [10–12]. Due to the finite lifetime of Ps, the beam is composed of \(\sigma\)-Ps atoms, the singlet state being untransportable at atomic velocities. Providing that Ps formation is not accompanied by another inelastic process, the energy of the Ps beam is given by

\[
E_{Ps} = E_{\beta^+} - I + B,
\]

where \(E_{\beta^+}\) is the incident \(e^+\) beam kinetic energy, \(I\) is the target gas ionization energy and \(B\) is the Ps binding energy (6.8 eV/\(n^2\), where \(n\) is the principal quantum number). A grid arrangement after the first gas cell serves to remove transmitted \(e^+\) from the beam. The second gas cell contains the gas under investigation for Ps scattering studies. Two coincidence-detection systems are employed in the Ps beam-line in order, among other things, to improve signal-to-background levels. In the first, a remoderator is placed in close proximity to a pair of annular channel-electron-multiplier-arrays (CEMA1). In this way, \(e^+\) transmitted through the annulus are incident upon the remoderator, releasing secondary electrons which are detected by CEMA1. The remoderated \(e^+\) are then accelerated to the required energy by biasing the remoderator positively. The delayed coincidences between the pulses from CEMA1 and those from CEMA2, placed at the end of the beam-line, generate time-of-flight spectra for \(e^+\) or Ps. These measurements are particularly important for the latter in order to determine its energy and quantum state [14,15]. Fig. 2 compares characteristic energy-spectra for the Ps beam formed through \(e^+\) impact on molecular hydrogen (under the high-pressure conditions necessary for beam generation) [11,12,15]. Shown in the figure are the energies corresponding to Ps formed in the ground and first excited state. As can be seen, the Ps beam formed from \(H_2\) is consistent with Eq. (1) and formation in the ground state. The second detection system employs CEMA2 in coincidence with a \(\gamma\)-ray detector (either a NaI or CsI crystal detector) also placed at the end of the beam. This system, which allows the full intensity of the incident \(e^+\) beam to be used, is employed only after characterization of the Ps beam energy and quantum state via the time-of-flight method.
3. Beam-production efficiency

The Ps beam-production efficiency, $\varepsilon_{\text{Ps}}$, is defined as the number of Ps atoms produced per detection solid angle, per incident $e^+$ in accordance with

$$\varepsilon_{\text{Ps}} = \frac{N_{\text{Ps}}}{\Omega N_+} D,$$

(2)

where $N_{\text{Ps}}/N_+$ are the Ps atom/incident $e^+$ beam count rates respectively, $D$ corrects for the in-flight decay of Ps and $\Omega$ is the detection solid angle. Fig. 3 shows 3-D Plots of $\varepsilon_{\text{Ps}}$ versus Ps kinetic energy for $e^+$ incident upon $N_2$ and $H_2$ at various pressures [16,17]. As can be seen from the figure, $H_2$ is the better ($e^+$ to Ps) converter at energies up to 100 eV, whereby $N_2$ becomes more efficient allowing a useable Ps beam to be formed up to 250 eV.

The pressure variation of $\varepsilon_{\text{Ps}}$ depends on the differential Ps formation cross-section, $d\sigma_{\text{Ps}}/d\Omega$, and the total cross-sections, $\sigma_T$, for both $e^+$ and Ps scattering (corresponding subscripts + and Ps respectively) according to the following expression:

$$\varepsilon_{\text{Ps}} \propto \left\{ 1 - \exp\left(-\rho l_{+}\sigma_{T+}\right) \right\} \times \left\{ \frac{1}{\sigma_{T+}} \int_0^{\theta_0} \frac{d\sigma_{\text{Ps}}}{d\Omega} \sin \theta d\theta \right\} \exp\left(-\rho l_{\text{Ps}}\sigma_{T_{\text{Ps}}}\right).$$

(3)

Here the first term corresponds to the fraction of scattered $e^+$ through the gas cell of length $l_+$, the second to the probability of forming Ps within the angular range $0-\theta_0$ and the third to the transmission probability of Ps through a gas of number density $\rho$ and length $l_{\text{Ps}}$ (note that this length is different from $l_+$ as Ps atoms are formed within the cell). In practice, $l_{\text{Ps}}$ is approximately half $l_+$. Therefore, as the production gas pressure increases, the Ps atoms produced are attenuated within the production gas itself, causing $\varepsilon_{\text{Ps}}$ values

Fig. 2. Energy distribution of 35 eV Ps beam formed from high pressure $H_2$; hollow circles – Armitage and Laricchia [15] and full circles – Garner et al. [12].

Fig. 3. Ps beam-production efficiency from $N_2$ [16] and $H_2$ [11,12] versus Ps kinetic energy and pressure of neutralizing gas.
to saturate with increasing pressure. A comparison of the pressures at which saturation occurs for each gas suggests e.g. that the total cross-section for Ps scattering from N\textsubscript{2} is greater than that for H\textsubscript{2} at 30 eV.

4. Ps-atom/molecule total cross-sections

The total cross-section, \(\sigma_T\), for Ps scattering have been determined \([11,12,17]\) through measurements of the Ps beam transmitted through the second gas cell containing the gas under investigation, according to the Beer–Lambert law

\[
\sigma_T = \frac{kT}{pL} \ln \left( \frac{I_0}{I} \right), \tag{4}
\]

where \(I_0(I)\) is the net incident (transmitted) flux, \(k\) is the Boltzmann constant, \(p\) the target pressure and \(T\) is its temperature. The effective length of the second gas cell, \(L\), is determined for each target gas by measuring corresponding e\textsuperscript{+} total cross-sections and normalizing them to known values \([18–20]\). The Ps total cross-sections for He and H\textsubscript{2} are shown in Fig. 4, where they are compared with the total cross-sections determined for equivelocity positrons and electrons. As can be seen in the figure, for these targets, the Ps cross-sections fall between those for e\textsuperscript{−} and e\textsuperscript{+} at the lowest velocities. With increasing velocity, they tend towards those for e\textsuperscript{−} and rise above these data from 1.5 a.u. onwards.

5. Ps fragmentation in collision with helium

The absolute cross-section for the fragmentation of Ps in collision with He, \(\sigma_f\), has been determined by detecting the ejected e\textsuperscript{+} \([21]\) according to

![Fig. 5. Fragmentation cross-section of Ps in collision with helium: full line – close-coupling approximation \([23]\); long dashed line – First Born approximation \([25]\); CTMC \([26]\) and short dashed line – Coulomb–Born approximation \([24]\). Experimental data from Armitage et al. \([21]\).](image)

![Fig. 4. Total cross-sections for Ps scattering from He and H\textsubscript{2} \([11,12,17]\) compared with corresponding e\textsuperscript{−} (full line) and e\textsuperscript{+} (dashed line) data \([18–20]\).](image)
\[ \sigma_t(E) = \frac{N_+}{(N_{Ps})_{\text{scatt}}} \sigma_T(E) S G \left( \frac{E_{Ps}}{E} \right), \]  

where \( N_+ \) is the number of \( e^+ \) from Ps fragmentation, \( (N_{Ps})_{\text{scatt}} \) is the number of scattered Ps atoms, \( \sigma_T(E) \) is the corresponding total cross-section, \( S \) and \( G \) are corrections respectively for in-flight annihilation of Ps and the ratio of the solid angles for detection of the ejected \( e^+ \) and Ps. The numbers of ejected \( e^+ \) and Ps atoms are corrected for the ratio \( (e^+ / e^+)_{Ps} \) of their respective detection efficiencies. These have been measured explicitly in a separate study [22]. The results for \( \sigma_t \) in Ps–He collisions are shown in Fig. 5, where they are compared with available theories. The three experimental determinations shown in the figure arise from the systematic uncertainty in the determination of the \( e^+ \) and Ps-detection efficiencies [22]. As can be seen from the figure, the measurements are in good agreement with a close coupling calculation [23] and at 33 eV about 25% greater than a Coulomb–Born approximation [24]. However, calculations using a First Born approximation [25] and a classical-trajectory-Monte-Carlo (CTMC) methods [26] are shown.

Fig. 6. Longitudinal energy distributions of \( e^+ \) released from fragmentation of Ps in collision with He atoms. Experimental points [21]: Line – CTMC [26].
greater than the measurements by around a factor of two across the energy range.

The longitudinal energy distributions of the ejected \( e^+ \) from Ps fragmentation have been obtained using the time-of-flight method. These spectra are shown in Fig. 6. Here it can be seen that, at all incident Ps energies, a peak is observed just below half of the ejected \( e^+ \) energy indicating the occurrence of electron-loss-to-the-continuum [27]. The shift in the peak of the energy distributions from half of the residual energy is consistent with the ejected \( e^+ \) being released within an angular range \( \theta \leq 20^\circ \), significantly larger than for heavier projectile impact e.g. [28]. Also shown in the figure are the energy distributions calculated using CTMC [26]. Here a good agreement is found at all incident Ps energies with the shape of the experimental data although, as mentioned above, a considerable discrepancy exists between the corresponding integrated cross-sections. The asymmetry between the ejected \( e^+ \) and \( e^- \) energy distributions predicted by the same theory [26] is currently under investigation with the Ps beam.

6. Absolute differential Ps formation cross-section

The determination of the detection efficiency of the CEMA2 for \( e^+ \) and Ps atom impact [22] has enabled the absolute differential Ps formation cross-section to be extracted [29] from Ps beam-production efficiency measurements [11,12]. Available measurements of \( \sigma_T \) [11,12,17] have enabled this analysis to be carried out at all the pressures investigated thus resulting in high precision. The results for the absolute differential Ps formation cross-section for \( e^+ \) scattering from \( H_2 \) thus obtained are shown in Fig. 7 where they are compared with available theoretical determinations [30,31]. An additional uncertainty of +8% to −(20–30)% is associated with the absolute scale of the experimental data due to the systematic uncertainties in the determination of the Ps detection efficiency [22]. As can be seen from the figure, the experimental data appears to agree better with the trend of a second order Born approximation [30] rather than that of a first order Born theory [31].

7. Outlook

In order to aid the understanding of the Ps atom/molecule collision systems, the measurements of total cross-sections are being expanded to larger molecules such as \( O_2, N_2 \) and \( H_2O \). The study into the fragmentation of Ps in collision with helium is being extended to the measurement of the longitudinal energy distributions of the ejected \( e^- \). This should shed light on the predicted asymmetry between the energy sharing between the ejected particles and, through the subtraction of the corresponding \( e^+ \) fragmentation cross-section, ascertain the extent of target ionization. The analysis of the absolute differential Ps formation cross-section is being performed for other targets where, especially in the case of more complex targets, significant challenges for theories are expected.

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Fig. 7. Absolute differential Ps formation cross-sections for \( e^+ \)-\( H_2 \) scattering. Circle – experiment [29]; Dashed line – second order Born approximation [30]; Full line – first order Born approximation [31].
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