Energy dependence of the positronium formation cross-section in argon

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Abstract. The positronium (Ps) formation cross-section, Q_{Ps} for positron-argon interactions has been measured for incident positron energies from threshold to 60 eV, in an attempt to resolve the apparent discrepancy between earlier experimental results. Q_{Ps} was found to vary smoothly with positron energy between 15 and 30 eV, in qualitative agreement with earlier results using methods involving the measurement of positron neutralization (as in the current experiment) and in disagreement with the double-peak energy dependence reported by Laricchia et al (2002), who used a positron-ion coincidence detection method. Possible reasons for this discrepancy, including Ps fragmentation and excited-state Ps formation, are discussed.

PACS: 34.80.Uv, 36.10.Dr

1. Introduction

For the last three decades there has been fundamental interest in measuring and calculating the cross section for the unique process of positronium (Ps) formation, Q_{Ps} [1].

There is reasonably good agreement between recent measurements and calculations of Q_{Ps} for helium; measurements for for neon, argon, krypton and xenon show general agreement to within ~ 25%, and calculations for these four gases exhibit broadly similar energy dependences but often differ from experiment by a factor of ~ 2 in magnitude [1]. However, in argon there is a significant discrepancy in the energy dependence of Q_{Ps} in the region 15-30 eV between three recent experimental results [2-4]. The Q_{Ps} reported by Marler et al [3] and Jones et al (2009) [4] rise to a peak at about 10 eV above threshold (8.9 eV) and then fall smoothly with increasing positron energy. In contrast the results of Laricchia et al [2] exhibit a double-peaked structure, with broad peaks at ~ 18 and 30 eV separated by a dip at ~ 21eV, an observation explained by the authors as most probably associated with the observation of the formation of excited-state Ps. If this double-peak behaviour is real then it is unclear why a similar structure would not be seen in refs 3 and 4. There is, however, a significant difference in the experimental methods used in refs 3 and 4 and that in ref 2. In the former two experiments Ps formation is recorded when an argon ion is formed and detected without the coincident detection of a positron; in the last experiment Ps formation is recorded when a positron is lost from the beam (this being the only channel, except the negligible process of direct annihilation, which removes a positron from the beam). Argon is the only gas for which a double-peak structure has been observed and for which there is a significant difference between results from different laboratories; shoulder-like structures are seen in krypton and xenon in refs 2 and 3.

The current experiment uses the positron loss method for measuring Q_{Ps}, this having been used successfully by the authors in the past (eg [5,6]). A brief overview of the experimental method will be followed by results for Q_T and Q_{Ps} in helium (to check the procedure) and argon, and a discussion of these results in light of the earlier discrepancy.

2. Experimental apparatus

Figure 1 shows a schematic diagram of the apparatus used, which was based on the system used by Jay and Coleman to study threshold effects in positron-noble gas scattering [7]. A 17MBq ^{22}Na source was positioned behind an annealed double 50%-transmission tungsten mesh moderator [8] to produce a 4mm diameter beam of c. 2000 positrons sec^{-1} of mean energy 1.5eV with an approximately Gaussian energy distribution of FWHM 1.5eV. The moderated positrons were then accelerated to the final desired mean energy by applying a potential V_M.

To narrow the energy distribution a 92%-transmission tungsten mesh was held immediately in front of the moderator at a potential of (V_M + 1.5) V. The energy spread of the beam was reduced to ~ 800meV, peaking at ~ (V_M + 2) eV, with a consequent reduction in useable beam intensity of about 50%. This mesh also serves as an efficient reflector of positrons scattered back towards the source.

The collimated beam then traverses a 30cm-long flight path along an evacuated tube under the guidance of an approximately uniform axial magnetic field of ~ 100G. It first passes through a gas cell with an exit aperture 12.5 mm in diameter and 35 mm long which ensures maintenance of an appropriate pressure differential; a vacuum of ~ 10^{-7} mbar was maintained throughout the rest of the apparatus using a turbo-molecular pump. A needle valve controlled the gas flow into the cell, and the gas pressure was chosen so that no more than 15% of positrons entering the cell were scattered, with typical attenuations of 3-10%; this constitutes a reasonable compromise between statistically acceptable measurements of beam attenuation and the minimisation of multiple scattering effects, and is comparable to the situation in other recent measurements.

The positrons then passed through a retarding field analyser (RFA), a copper tube held at either 0V or (V_M + 1.35)V, depending on the measurement being made (see later). The tube was 50 mm long and 20 mm in diameter to ensure that fringe (field penetration) effects did not reduce the potential in the centre of the tube.

The positron beam finally reaches the channel electron multiplier (CEM) which generates pulses for each particle detected after entering its 10mm-diameter cone. These pulses were amplified, shaped and recorded by a multi-channel scaler (MCS) after discriminating against small electrical noise pulses. A potential of -2 kV was applied to the cone of the CEM to repel as many electrons as possible; these are secondary electrons ejected from the source/moderator assembly by beta positron bombardment, and those transported by the magnetic field can have energies from ~ 1 to 10^3 eV. A fine mesh was held across the cone, also at -2 kV, to prevent electrons from the cone being sucked from the CEM.

It is important for these measurements that essentially all scattered positrons could be guided to the CEM by the magnetic field. The beam radius is 2 mm and the CEM cone radius is 5mm; in the extreme worst-case scenario for the apparatus described here, a 60eV positron at the edge of the beam scattered away from the axis through 90º is has a Larmor radius of 2.6 mm, and so will be detected.

3. Experimental procedure

3.1. Total cross sections

The total scattering cross section Q_T is deduced using the Beer-Lambert law $I = I_0 \exp(-nlQ_T)$, where, I_0 and I are the incident and transmitted positron intensities, and n and l are the atomic number density of and path length through the target gas atoms, respectively. In this experiment I and I_0 are measured and the product nl obtained using the Q_T values of Caradonna et al for helium [9] and of Jones et al for argon [4]. This effectively is a procedure which normalises the current Q_T values to those of recent measurements by the ANU group (which are generally in agreement with earlier values – see figure 2 below).

In order to measure I and I_0 four count rate measurements were required – essentially total and background rates with and without gas in the gas cell. The RFA was held at (V_M + 1.35)V for Q_T measurements, an experimentally-determined value which ensured that essentially all scattered positrons were prevented from passing through the RFA tube. The runs were controlled using the MCS, measuring count rates as the moderator potential V_M was ramped from 5 to 58eV in 1eV steps. The MCS was set to perform repeated short scans to minimise the influence of any fluctuations in the measurement conditions; the count rate was measured for 10 s at each energy and 150 ramps were performed, so that the measurement time at each energy was 1500s – resulting in total counts of ~1.5×10^6 and a resultant statistical uncertainty of ~0.1%.

Total (signal + background) rates were measured with the cut-off mesh (in front of the moderator) at (V_M+1.5)V. Background rates were measured in the same way, but with the cut-off mesh at a potential of (V_M + 5)V, so that all slow positrons were prevented from entering the gas cell and only those particles (mostly fast positrons and electrons) contributing to the background count would be detected. The background rates were measured at each value of V_M with and without gas in the cell – they depend on V_M and gas density, because the background consists of energetic positrons and electrons.

The intensities I and I_0 were then used to find Q_T as described above. The mean energy of the positron beam was measured to be (V_M + 1.5) eV, after a small adjustment was made for contact potential differences (after multiple measurements of Q_T) in order to replicate the rapid rise in the cross sections above the Ps threshold.

3.2. Ps formation cross sections

Q_{Ps} was obtained from the thin-target result $Q_{Ps} = (A_{Ps}/A_T)Q_T$, where A_{Ps} and A_T refer to the measured positron attenuations due to Ps formation only and to all scattering channels, respectively. Using the terminology of the previous section, $A = (I_0 - I)/I_0$. The measurement of A_T is described above in section 3.1. A_{Ps} was measured by following identical procedures, but with the RFA potential set to 0 V. As Ps is a neutral particle it is not constrained by the magnetic field and will, therefore, never reach the detector - instead decaying by annihilation in the gas, vacuum, or upon collision with the apparatus wall. All other scattering channels, which the positrons survive, do not contribute to the attenuation as the RFA no longer prevents the scattered positrons from reaching the CEM detector. The same gas pressures were used for these runs as was used for the measurement of Q_T.

4. Results

The experimental procedure was first tested using helium gas, where there is reasonable agreement between earlier measurements of Q_T and Q_{Ps} [5,9-15].

The results for Q_T for helium are shown in figure 2(a), along with previous results. Although these results were obtained using a normalisation procedure the good agreement seen between the energy dependence of the current results with earlier measurements is gratifying.

Figure 2(b) shows Q_{Ps} for helium, along with a selection of earlier measurements. Satisfactory agreement is again seen between measurements, giving confidence in the technique. The statistical uncertainties in these, as well as all other cross sections reported herein, are reflected in the scatter of the points, and thus for helium are ± (0.03-0.04) x 10^{-20} m^2.

For argon the results for Q_T and Q_{Ps} are shown in figures 3(a) and (b). Statistical uncertainties are here of the same order as the symbol size; they are considerably smaller than those for the helium results because the latter were intended only to check the reliability of the system and thus the measurements were not repeated as many times. The energy dependence of Q_T for argon, as for helium, agrees well with earlier results. Q_{Ps}, however, shows good agreement up to ~15eV, and then diverges from all recent results as the positron energy increases. This result was reproduced many times.

5. Discussion

The aim of this experiment was to investigate the energy dependence of Q_{Ps} at positron energies around 30eV. While the absolute values of the measured cross sections results can suffer from errors due to non-measurement of small-angle elastic scattering, any corrections are (a) likely to be small, as elastic scattering makes a relatively small contribution to Q_T in the energy range of interest, and (b) are very unlikely to influence the broad shape of Q_T and Q_{Ps} at these energies. It is also true that the 0.8eV energy width of the beam used here is not wide enough to mask the dip feature seen in the results of Laricchia et al [2].

The present results for Q_{Ps} in argon (figure 3(b)) do not exhibit a double-peak structure, but do show a rather flat-topped energy dependence between ~ 18-30 eV. They are quantitatively higher than recent measurements at higher energies but, interestingly, agree well with earlier measurements. To investigate the possibility that these higher values could be caused by an increasing inability to confine all surviving scattered positrons in the beam to the detector, a set of measurements were taken with the magnetic field decreased to 70G; there was a resultant increase in Q_{Ps} at 60eV, but this was much smaller than the observed difference between the results shown.

The results of the San Diego and Australian groups [3,4] show similar energy dependence but differ in absolute magnitude, probably as a result of different measurements of the gas cell product *nl*. They both employ the positron loss method used in the current experiment; in contrast, Laricchia et al detected argon ions with no coincident positron [1,2]. It is thus tempting to link the observed difference between the energy dependences of Q_{Ps} reported in refs. 2-4 simply with measurement technique; however, the reasoning behind such a correlation is not easy to formulate.

It was suggested by Murtagh et al [17] that the second peak at ~ 30eV may result from observation of Ps formation in exited states. For this not to be seen in positron-loss experiments the longer-lived Ps* would presumably have to break up in a second collision, releasing the positron which would then be detected and Ps* formation would not be registered. There are reasons why this explanation may not be correct: (a) similar beam attenuations (ie *nl* values) were used in both methods, so that Ps* break-up could occur in both measurements, (b) neutral Ps* drifts from the beam axis and so the detection of all the positrons released from the break-up of essentially all the Ps* formed in the gas cell has to be considered highly unlikely, especially with the 10mm-diameter detector used in the present experiment, and (c) the first measurements of cross sections for Ps* formation in the n = 2 state [17] are considerably smaller than the second peak would suggest, and so contributions from Ps* formation in higher n states would need to be considerable. Q_{Ps*} (n = 2) from ref [17] is plotted in figure 3(b). To investigate the possible consequences of multiple scattering an experiment was performed with higher gas pressure – so that the maximum attenuation was ~30%. No significant change from the results presented in figure 3(b) was observed. Measurements with lower gas pressures were not performed, as the maximum value of the attenuation due only to Ps formation, A_{Ps}, was ~ 6%, and smaller attenuations were impractical.

The second possibility is that, rather than a second peak being missing from Q_{Ps} in measurements based on positron loss, a broad dip is present in the results of Laricchia et al [2] at around 20eV. This could also be explained by Ps dissociation collisions – that Ps formed at 6.8eV or more above threshold (ie at positron energies above the ionization energy of 15.7eV) can break up on a second collision, leading the ion detection method to register the scattering as direct ionization rather than Ps formation. Fragmentation cross sections measured by Brawley and Laricchia [18] for Ps-He and Ps-Xe collisions suggest that the probability of Ps break-up is significant at a few eV above threshold; the losses due to fragmentation would need to decrease between 20 and 30eV rather more rapidly than the measured cross sections of ref [18] suggest – this may happen if the more energetic Ps escapes the gas region or reach a region out of sight of the positron detector.

Clearly the relative likelihood of these different scenarios is difficult to judge, being critically dependent on the geometries of the gas cell/region and the size of the positron detectors used in particular experiments.

None of the theoretical calculations for Q_{Ps} in argon [19-21] – not shown in Fig 3 for the sake of clarity (the reader is referred to [1]) – exhibits a significant second peak at 30eV, being more broadly similar in energy-dependence (but not in magnitude) to the results of refs 3 and 4. A small shoulder a few eV above the first peak is seen in the results of Gilmore et al [20], who included the formation of Ps* and of Ps from inner *ns* shells of argon. Dunlop and Gribakin [21] argue that inclusion of Q_{Ps} from the 3s shell of argon may produce a second peak similar to that seen in ref [2], having a threshold at 22.5eV - which the authors claim is a more realistic explanation than Ps* formation, whose threshold they consider to be too low.

6. Conclusion

Although one can attribute the observed differences between $Q_{Ps}(E)$ in the 20-30eV region solely to the two different measurement techniques used, an explanation as to why this should be is not straightforward as both techniques should in principle be able to measure Q_{Ps} satisfactorily. Indeed, one might symmetrically argue that second collisions could lead both to a dip in Q_{Ps} measured by ion detection or a missing peak in Q_{Ps} measured by positron loss. The results of the present measurement do not offer conclusive support to either explanation, but do add to the number of results which do not possess a second peak (or dip) and, after the failure of attempts to induce such a feature in the results by varying experimental conditions, the authors are led to favour the existence of at most a modest shoulder in Q_{Ps} associated with Ps* formation or Ps formation from inner shells, but not of a double-peaked structure.

Acknowledgments

Thanks are due to Mr H E Bone for technical support.

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Figure 1

Schematic diagram of the experimental apparatus. RFA - Retarding Field Analyser, CEM - Channel Electron Multiplier. The distance between source and CEM is ~ 300 mm.

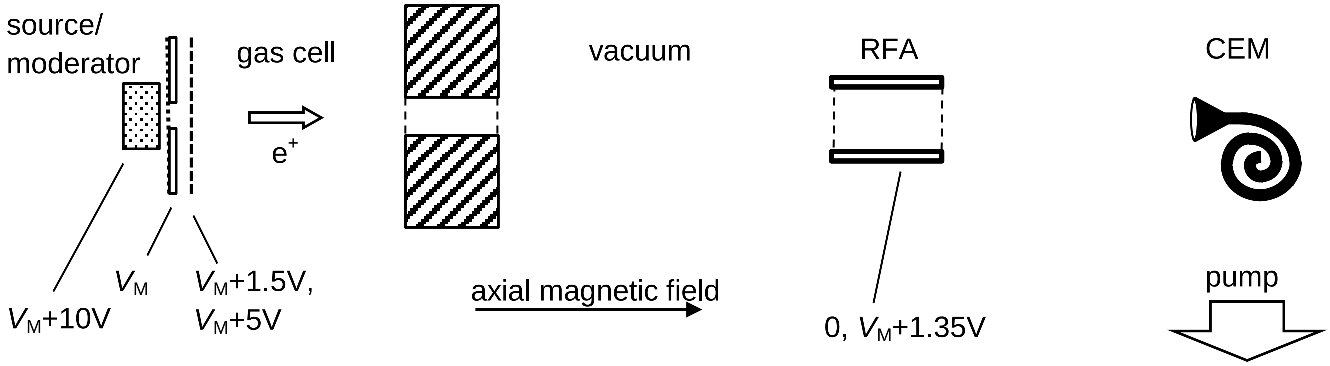

Figure 2

Experimentally-determined total and Ps formation cross sections for helium. Upper points are Q_T, lower points Q_{Ps}. ● – current measurements: ○ – Q_T and Q_{Ps}, Caradonna et al [9]: □ – Q_T from Kauppila et al [10], lower limit of Q_{Ps} from Stein et al [11]: ◇ - Q_T, Brenton et al [12]; ▽ - Q_T from Griffith et al [13], Q_{Ps} from Murtagh et al [14]; △ - Q_{Ps}, Fornari et al [5]: ☆− Q_{Ps}, Fromme et al [15].

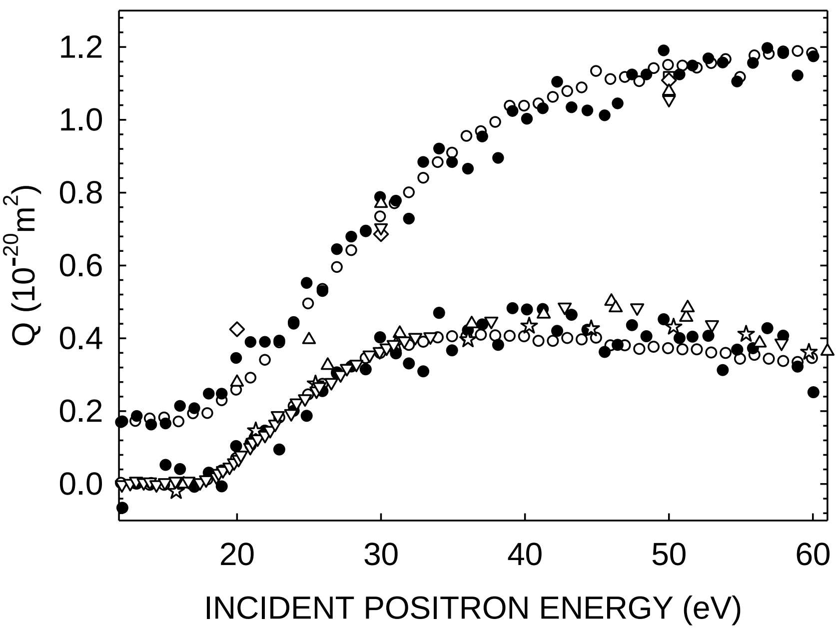

Figure 3

(a) Experimentally-determined total cross sections Q_T for argon. ● – current measurements: △ – Jones et al [4]: ▽ - Kauppila et al [10]: □ - Griffith et al [13]: ◇ - Tsai et al [16].

(b) Positronium formation cross sections Q_{Ps} for argon. ● – current measurements: △ – Jones et al [4]: ▽ - lower limit results of Stein et al [11]: □ - Laricchia et al [2]: ◇ - Fornari et al [5]: ○ – Marler et al [3]: ✕ - $n = 2$ Ps, Murtagh et al [17].