Positronium-Argon Scattering

N. Zafar, G. Laricchia, M. Charlton, and A. Garner
Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, United Kingdom
(Received 6 June 1995)

The total cross section σ_T for orthopositronium (o-Ps) scattering from argon gas has been measured directly for the first time using a variable energy o-Ps beam in the range 16–95 eV. The cross section is found to rise from a value of approximately 9×10^{-20} to 15×10^{-20} m^2 in the 16–30 eV range and thereafter decline slowly to 11×10^{-20} m^2 at the highest energy investigated. Comparison with theory suggests that the increase in σ_T is probably due to inelastic processes.

PACS numbers: 36.10.Dr, 34.50.–s

Over the last two decades there have been numerous experimental studies of the interactions of low energy positrons (e^+) with gaseous atoms and molecules. These have encompassed investigations of various total and partial cross sections and, more recently, some differential in the angle and energy of the scattered e^+ [1]. It was apparent from early measurements [1] that Ps formation, by the reaction $e^+ + A \rightarrow \mathrm{Ps} + A^+$ of a positron with an atom A was a significant channel at intermediate energies. Theoretical studies for H and He targets [2,3] found that the differential cross section for this process was relatively large at small angles to the incident e^+ beam, suggesting that useful beams of Ps atoms could be produced by neutralizing positrons in gaseous targets. This was experimentally confirmed, independently, by Brown [4] and Laricchia and co-workers [5,6]. These and other methods for fast Ps production have been recently reviewed in some detail [7,8]. Briefly, Brown [4] was the first to obtain experimental evidence in support of the energy tunability of Ps formed in e^+-gas reactions by employing a high resolution γ-ray detector to monitor the annihilation (in the same medium in which it was formed) of the short-lived p-Ps, the $S = 0$ state which decays by 2γ emission in vacuum with a characteristic lifetime of $\sim$125 ps. In contrast, the London group [5,6] generated a beam of the long-lived o-Ps ($S = 1$, 3γ, $\sim$142 ns) atoms and measured its overall efficiency for production, collimation, transport, and detection away from the production region. In the study of Laricchia *et al.* [6], it was estimated that up to 4% of the scattered e^+ could be detected as o-Ps within a cone of $\pm 6°$ around the incident e^+ direction. With the inclusion of a beam timing method [9], this work was extended with detailed studies [10] of the Ps beam produced from He and Ar gases, including its energy width, quantification of the component in excited states, and preliminary, and indirect, estimates of Ps scattering cross sections. In this Letter we report the first direct measurement of Ps-Ar total scattering cross sections using a double gas cell arrangement in which Ps formation can be optimized and controlled in one cell while collision conditions are independently varied in the other.

Very little is known about Ps scattering, other than from annihilation studies of processes occurring at, or near, thermal energies (see, e.g., [11]). There has been only sporadic theoretical activity [12] in the area of energetic Ps collisions since the pioneering study of Massey and Mohr [13]. Collisions of the neutral Ps with other atoms (and molecules) have a number of novel features. The coincidence of the centers of charge and mass in the Ps atom removes the mean static interaction which is present between two heavier neutrals, thereby enhancing the importance of the exchange interaction. In addition, the small Ps mass, and concomitant long de Broglie wavelength, has led to the suggestion [14] that theories of Ps scattering will more closely resemble those for positrons and electrons than those applied to other (heavier) neutral systems. Aside from this intrinsic interest, however, a knowledge of the cross sections for various processes may be of benefit in a number of areas, e.g., e^+ slowing down in certain media where repeated Ps formation and breakup cycles may be important (while the former can be adequately treated, little is known about the latter); in studies of Ps diffraction from surfaces [15]; in modeling interactions of Ps injected into a plasma [16]; and in gaining a better understanding of the role of the buffer gas commonly used in precision studies of Ps properties [17–19]. The measurements reported herein represent a first step in filling the gaps in our knowledge and understanding of the atomic interactions of energetic Ps.

The double gas-cell arrangement used in the experiment is illustrated in Fig. 1. A primary e^+ beam of $\sim 10^5$ s^{-1}, guided by a 50–100 G axial magnetic field, is delivered by the positron gun [20]. After passing through an 8 mm collimator, it enters from the left at an energy of around 350 eV. The e^+ pass through a hole in the center of the channel electron multiplier array (CEMA 1) and strike a remoderator $(M2)$ [9]. This is fabricated from four overlapped annealed tungsten meshes from which $\sim$12% of the e^+ are re-emitted with a maximum energy of $\sim$3 eV. The combined timing and remoderation efficiency is $\sim$5%, and the energy of the remoderated e^+ can be varied by changing the potential applied to $M2$. These e^+, and some of the transmitted primary beam, pass through gas cell 1,

 © 1996 The American Physical Society

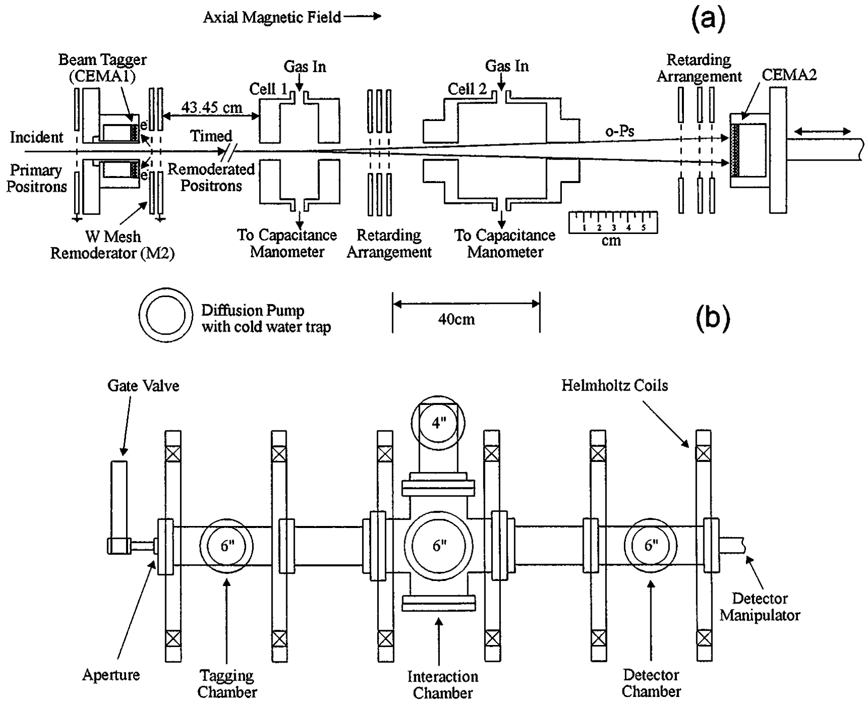

FIG. 1. Schematic diagram of the experimental arrangement (a). The system is differentially pumped. The relative pressures in the neutralizing cell, adjacent grid region, and moderating region are approximately 1:10^{-2}:10^{-4}. The location of the diffusion pumps and their size are indicated in (b).

which is 20 mm long with an internal diameter of 30 mm and has 8 mm diameter, 10 mm long, apertures at each end. For all measurements except that at 80 eV, this cell was maintained at a constant Ar gas pressure of 0.93 Pa (7 μm Hg) as measured by a capacitance manometer, having previously found these conditions to be optimum for Ps beam production [10]. The beam at 80 eV was generated using, as the neutralizer, molecular hydrogen. This has recently been found to be more efficient than Ar for the production of collimated Ps [8,21,22].

Following optimization of the primary and remoderated e^+ beams at CEMA2, the latter was prevented from reaching gas cell 2 by the application of appropriate voltages to the system of grids and apertures shown in Fig. 1. Under these conditions a timed beam of Ps atoms, originating from gas cell 1, could be observed by arranging a standard delayed coincidence circuit between the outputs of the two detectors. The resulting time-of-flight (TOF) spectra were recorded on a PC-based multichannel analyzer for further analysis. Two TOF spectra taken with mean remoderated e^+ kinetic energies T_e of 39.6 and 63.5 eV without gas in cell 2 (hollow circles) are shown in Fig. 2. To a first approximation, the Ps kinetic energy T_{Ps} is related to that of the e^+ by $T_{\mathrm{Ps}} = T_e - E_I + E_B$, where E_I is the ionization energy of the target (15.76 eV for Ar) and $E_B = 6.8/n^2$ (eV) for Ps in a state of principal quantum number n. The intrinsic timing resolution of the system was found by operating the remoderated beam at high kinetic energies, to be around 10 ns. Additional time spread may be introduced by the intrinsic energy spread of the e^+ and Ps beams and some jitter caused by the different points of creation of the Ps along gas cell 1. Under the conditions employed for these measurements, no substantial component from $n \geq 2$ Ps was detected in the beam. This may be due to the relatively high Ar pressure, and consequent scattering of the excited Ps, used in gas cell 1 to maximize the ground state flux. Each TOF spectra with gas cell 2 evacuated is accompanied, in Fig. 2, by a spectrum of equal run duration taken with Ar gas admitted (filled circles). The attenuation of the Ps beam by the gas is evident. The pressures were 0.28 and 0.44 Pa for the runs at Ps energies of 30.6 and 54.5 eV, respectively.

In order to determine σ_T the Ps beam intensities with (I) and without (I_0) Ar gas in cell 2 were used in the usual

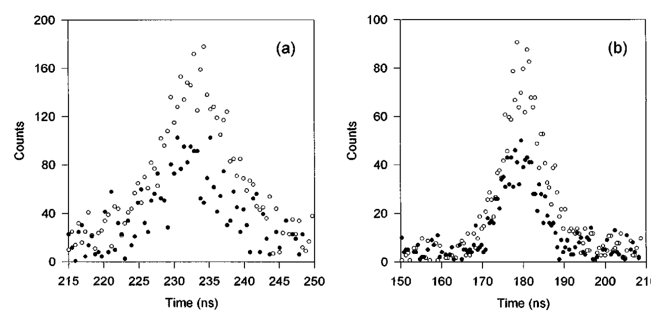

FIG. 2. Positronium time-of-flight spectra taken at (a) 39.6 eV and (b) 63.5 eV incident positron energies. The hollow circles refer to the Ps beam incident onto an Ar target. The filled symbols represent the Ps beam intensity transmitted through the target. Target pressures are given in the text.

Beer-Lambert relation,

$$I = I_0 \exp(-\rho \sigma_T L), \quad (1)$$

where the target density-length product ρL was found to be of the form $\rho_0 l_0/k$. Here, ρ_0 is the gas density determined from measurements of the pressure at the center of the cell using a dedicated capacitance manometer and the ambient temperature and l_0 is the geometric length of the cell (40 mm). The constant k was determined by normalization to known cross sections for e^+-Ar scattering [23] and found to be 0.81 $\pm$ 0.02 over the range of pressures employed in the Ps scattering experiments.

Various systematic checks were performed at certain Ps energies: (i) the Ps attenuation ($= I_0/I$) was measured at different gas pressures in the range 0.13–0.67 Pa with no statistically significant deviation from Eq. (1) observed. Typical one standard deviations on a *single* run were $\pm 25\%$, a typical datum for extracting σ_T consisting of five or more runs; (ii) I/I_0 was measured at different positions of CEMA2 in order to vary the flight path of the Ps after scattering and, to some extent, the angular acceptance of the detector (usually 4° and 7°) and no statistically significant effect was noted; (iii) the possibility of I_0/I varying across the TOF spread of the Ps was investigated and variations of up to 20% were found with I/I_0 being in general smaller, if the whole Ps peak was used, in comparison to the results obtained by using a 5 eV region on the high energy side of the Ps peak. This might be due to contributions from excited states [implying that the Ps-Ar total cross section for Ps($n > 1$) is smaller than for Ps($n = 1$), in conflict with our earlier hypothesis], and/or reflect the natural variation of σ_T with projectile energy (although the variation with energy is rather weak above ~30 eV). It could also be related to the probability of scattering at angles $\leq 4°$, the minimum angular acceptance of the detector. In view of the added uncertainties which would be introduced by deducing the cross sections from the whole Ps peak, the 5 eV region on the high energy side of the Ps peak was used in the final evaluations of I_0/I.

Our values of σ_T for (o-Ps)-Ar scattering in the energy range 16–95 eV are presented in Fig. 3. The cross section can be seen to rise from 8.6×10^{-20} m^2 to around twice that value in the energy range 26–40 eV. Thereafter σ_T appears to fall gradually over the remaining energy range investigated. Comparison with theoretical calculations performed on other Ps-atom systems [21,24] suggests that the rise in σ_T at intermediate energies is the result of increasing inelastic scattering with, particularly, projectile breakup being the dominant scattering channel in some cases. Also shown in Fig. 3 is the mean value for the Ps-Ar elastic scattering cross section [11] in the energy range 0–6.8 eV derived from studies of the angular correlation of the annihilation radiation emitted by Ps thermalizing by elastic collisions with this gas.

In conclusion, the first direct measurements of the total cross section of orthopositronium atoms scattering from Ar gas at incident energies in the range 16–95 eV have

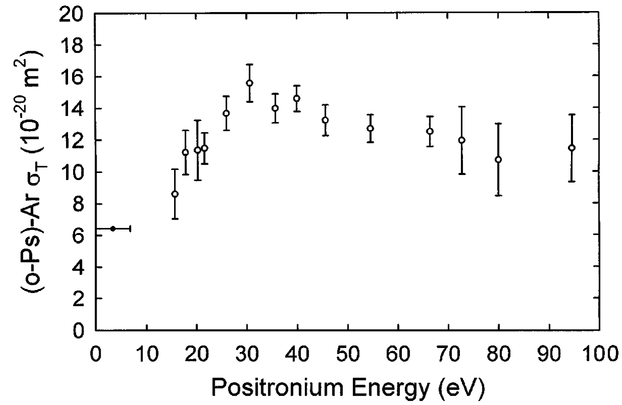

FIG. 3. Orthopositronium-argon total cross section: Hollow symbols represent present results; the filled symbol represents the mean elastic scattering cross section between 0 and 6.8 eV [11].

been reported. It is expected that these measurements, in addition to their intrinsic interest, will provide new testing ground for collision theories and aid the understanding of a variety of studies involving positronic probes.

The authors are grateful to the Engineering and Physics Sciences Research Council for supporting this work under Grants No. GR/44948 and No. GR/K5633. G L. would also like to thank the Nuffield Foundation for the award of a Science Research Fellowship.

[1] E.g., M. Charlton and G. Laricchia, J. Phys. B **23**, 1045–1078 (1990); G. Laricchia and M. Charlton, Mater. Sci. Forum **105–110**, 349–358 (1992); *Positron Interactions with Atoms, Molecules and Clusters*, edited by W. Raith and R. P. McEachran (Baltzer, Switzerland, 1994).

[2] C. J. Brown and J. W. Humberston, J. Phys. B **18**, L401–406 (1985).

[3] P. Mandal, S. Guha, and N. C. Sil, J. Phys. B **12**, 2913–2924 (1979).

[4] B. L. Brown, Bull. Am. Phys. Soc. **30**, 614 (1985); *Positron Annihilation*, edited by R. M. Singru and P. C. Jain (World Scientific, Singapore, 1985), pp. 328–329.

[5] G. Laricchia *et al.*, *Positron (Electron)-Gas Scattering*, edited by W. E. Kauppila, T. S. Stein, and J. M. Wadehra (World Scientific, Singapore, 1986), pp. 303–306.

[6] G. Laricchia *et al.*, J. Phys. B **20**, L99–105 (1987).

[7] G. Laricchia and N. Zafar, *Positrons at Metallic Surfaces*, edited by A. Ishii (Trans. Tech. Publications, Switzerland, 1992), pp. 347–364.

[8] G. Laricchia, in *Positron Spectroscopy of Solids*, Proceedings of the International School of Physics "Enrico Fermi," Course CXXV, edited by A. Dupasquier and A. P. Mills (IOS Press, Amsterdam, 1995), pp. 401–418.

[9] G. Laricchia *et al.*, *Atomic Physics with Positrons*, edited by J. W. Humberston and E. A. G. Armour (Plenum Press, New York, 1987), pp. 223–231; J. Phys. E **21**, 886–888 (1988).

[10] N. Zafar *et al.*, J. Phys. B **24**, 4661–4670 (1991); G. Laricchia *et al.*, Hyperfine Interact. **73**, 133–145 (1992).
[11] P. G. Coleman *et al.*, J. Phys. B **27**, 981–991 (1994).
[12] M. Charlton and G. Laricchia, Comments At. Mol. Phys. **26**, 253–267 (1991), contains a compilation.
[13] H. S. W. Massey and C. B. O. Mohr, Proc. Phys. Soc. London **67**, 695–704 (1954).
[14] R. J. Drachman, *Atomic Physics with Positrons*, edited by J. W. Humberston and E. A. G. Armour (Plenum Press, New York, 1987), pp. 203–214.
[15] K. F. Canter, *Positron Scattering in Gases*, edited by J. W. Humberston and M. R. C. McDowell (Plenum, New York, 1984), pp. 219–225; M. H. Weber *et al.*, Phys. Rev. Lett. **61**, 2542–2545 (1988).
[16] C. M. Surko and T. J. Murphy, Phys. Fluids B **2**, 1372–1375 (1990).
[17] C. I. Westbrook *et al.*, Phys. Rev. A **40**, 5489–5499 (1989).
[18] A. H. Al-Ramadhan and D. W. Gidley, Phys. Rev. Lett. **72**, 1632–1635 (1994).
[19] G. H. Bearman and A. P. Mills, Jr., Phys. Lett. **56A**, 350–352 (1976).
[20] N. Zafar *et al.*, Hyperfine Interact. **73**, 1632–1635 (1992).
[21] S. Tang and C. Surko, Phys. Rev. A **47**, 743 (1993).
[22] A. Garner and G. Laricchia (to be published).
[23] W. E. Kauppila *et al.*, Phys. Rev. A **24**, 725–742 (1981).
[24] G. Peach (private communication); H. R. J. Walters (private communication).