Positronium Formation in Collisions of Positrons with He, Ar, and H_2

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Absolute cross sections for the formation of positronium in positron collisions with He, Ar, and H_2 have been measured for incident positron energies up to 76.3 eV. The results are markedly different, in magnitude and energy dependence, from those of Charlton *et al.* The measurements in He and H_2 agree well with distorted-wave and charge-exchange calculations.

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Apart from the intrinsic importance of Ps formation as the only scattering channel peculiar to the positron, knowledge of the cross sections for the process (Q_{Ps}) is essential (a) in the interpretation of observations of annihilation radiation from the direction of the galactic center,[1] (b) in the partitioning of the total cross section (Q_{tot}) for positrons into the various elastic and inelastic channels,[2] (c) to the understanding of measurements of Ps formation fractions in high-density gases,[3] and (d) in the comparison of electron and positron total cross sections at intermediate energies as a test of the validity of the Born approximation, when one should strictly compare $(Q_{tot} - Q_{Ps})_{e^+}$ with $(Q_{tot})_{e^-}$.[4]

Charlton *et al.*[5] have published direct measurements of the energy dependence of Q_{Ps} for He, Ar, H_2, and CH_4 and have recently reported new results for a number of gases.[6] Estimates of Q_{Ps} for incident positron energies between the thresholds for Ps formation and atomic excitation or ionization (E_{Ps}, E_{ex}, and E_{ion}, respectively) have been made from measurements of the fraction of positrons forming Ps in high-density gases[7,8] and by subtraction of the smoothly extrapolated elastic scattering cross section Q_{el} from Q_{tot}.[9]

The new measurements of Q_{Ps} reported in this Letter were performed with an experimental technique complementary to that of Charlton *et al.* Rather than detect Ps formed in a gas cell we detect all the positrons which leave the gas cell without forming Ps. After encouraging measurements with an earlier system,[10] the apparatus was completely redesigned to incorporate several improvements; the new system is illustrated in Fig. 1. The beam of slow positrons ($\overline{E} = 1.3 \pm 1.0$ eV), of intensity 150 sec^{-1} and diameter 5 mm, is produced by bombarding an annealed tungsten mesh with positrons from a 150-μCi ^{22}Na source. The mean beam energy is increased by an accelerating potential V_W applied to the tungsten mesh. The positrons pass down a 2.3-m-long flight tube to a channel electron multiplier (CEM). A uniform axial magnetic field of 100 G is provided by a solenoid which surrounds the tube, and the entire system is shielded from Earth's magnetic field. Simple positron optics aid in extracting and collimating the beam at the source end, and at the detector end allow the placement of the magnetic-field–sensitive CEM in a region of lower field strength. The 92%-transmission reflector mesh, a few millimeters in front of the source mesh, is held at V_W; the incident beam passes through this mesh, but essentially all positrons scattered into the backward hemisphere in the gas cell are reflected back toward the CEM.

Gas is leaked into the system continuously at the source end of the flight tube and pressure measured by ionization gauges at both ends of the tube. Because of the low gas densities required ($\approx 10^{-4}$ Torr at the source end) and the pressure gradient along the flight tube (both being due to the 2.3 m length of the tube), the gas pressures

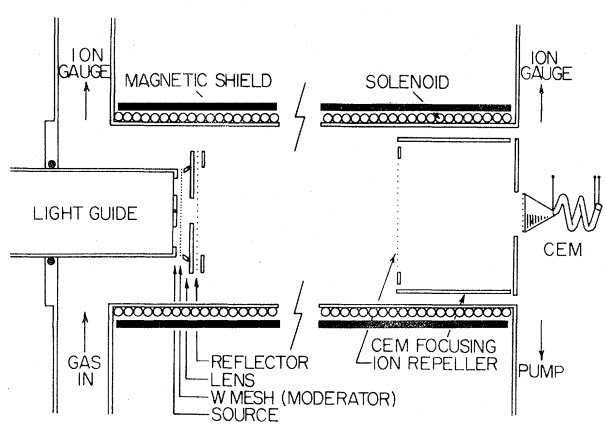

FIG. 1. Experimental apparatus. Distance from source to detector is 2.3 m.

at the CEM end are always low enough to allow low-noise operation of the detector without the need for differential pumping baffles which might trap scattered positrons.

CEM counts and time-of-flight (TOF) spectra are recorded simultaneously, with and without gas in the flight tube. The TOF technique used is described by Coleman *et al.*[11] The fraction of the incident beam which undergoes any form of scattering, F, is obtained from the attenuation of the peaked TOF spectra. At positron energies above 35 eV allowance is made for the presence of a few small-angle elastically scattered positrons in the attenuated TOF spectra by following the approach of Coleman *et al.*,[12] which works well for energies below 100 eV. The fraction of the incident beam which forms Ps, f, is the fractional decrease in the CEM signal count rate; essentially all positrons which do not form Ps are constrained to paths which end at the CEM detector. The background CEM count rate, determined by applying a stopping potential of $V_W + 13$ V to the reflector mesh, is subtracted from the total rate to yield the signal count rate. To avoid problems associated with systematic drifts during each 2 520-sec run, total and background CEM rates are accumulated in alternate 60-sec intervals.

The total Ps formation cross section is simply fQ_{tot}/F, and the results for He, Ar, and H_2 are presented in Table I. The values used for Q_{tot} are those from Refs. 13 (He and Ar) and 14 (H_2). The experimental uncertainties are the sums of the statistical standard deviations, quoted uncertainties in the Q_{tot} values, and the estimated uncertainties associated with the systematic corrections discussed below.

In order to ensure that the Q_{Ps} values were not being underestimated because of the detection of positive ions created by the incident beam, Q_{Ps} was remeasured in H_2 at selected energies with the "ion repeller" mesh, shown in Fig. 1, installed. With +1.3 V applied to this mesh no thermal-energy ions can reach the CEM. Under these conditions no systematic increase in the measured cross sections was observed. This null result is attributed to the smaller detection efficiencies of the ions[15] compared with positrons. He^+ and Ar^+ ions have even lower detection efficiencies than H_2^+.

Measurements of Q_{Ps} were made at selected energies in each gas with different magnetic field strengths to ensure that the field used was more than adequate to transport all the surviving positrons to the CEM.

TABLE I. Positronium formation cross sections in He, Ar, and H_2 (uncertainties in parentheses).

Positron energy (eV)	He	Q_{Ps} (πa_0^2) Ar	H_2
5.3	···	−0.02(0.10)	···
6.3	···	0.13(0.06)	···
7.3	···	0.33(0.18)	···
8.3	···	0.27(0.13)	···
9.3	···	1.34(0.12)	0.01(0.05)
11.3	0.00(0.01)	2.65(0.21)	···
12.3	···	···	1.83(0.44)
16.3	0.00(0.02)	3.64(0.59)	3.11(0.38)
19.8	···	···	2.93(0.37)
21.3	0.16(0.04)	3.89(0.17)	···
26.3	0.37(0.06)	3.80(0.51)	2.87(0.39)
31.3	0.47(0.09)	3.78(0.59)	2.23(0.20)
36.3	0.50(0.09)	3.48(0.15)	2.10(0.34)
41.3	0.53(0.08)	3.12(0.41)	1.38(0.24)
46.3	0.55(0.10)	2.84(0.35)	1.29(0.26)
51.3	0.55(0.10)	2.64(0.31)	1.15(0.18)
56.3	0.44(0.08)	2.48(0.32)	0.96(0.20)
61.3	0.38(0.07)	2.35(0.32)	0.90(0.09)
66.3	0.33(0.07)	2.11(0.31)	0.64(0.08)
71.3	0.30(0.06)	2.22(0.32)	0.57(0.07)
76.3	0.32(0.11)	2.14(0.30)	0.49(0.06)

A number of Q_{Ps} measurements were also made with different gas densities and, once again, the changes in the cross-section values were no larger than the uncertainties listed in Table I. This test demonstrates that the probability of scattering sequences in which Ps is formed in the second or subsequent collisions is small. F was kept to about 10% in order to achieve this condition. Estimates for double-scattering corrections have been made and applied to the Q_{Ps} values in Table I by assuming reasonable total and differential elastic cross sections for He and Ar (extrapolating reliable phase shifts[16,17] to higher energies). The angular distributions $I(\theta)$ for H_2 were assumed to be similar to those for He. At energies above $E_{Ps}+E_{ex}$, where the sequence inelastic scattering–Ps formation can occur, it was assumed that $I(\theta)_{inel} \approx I(\theta)_{el}$. These calculations led to corrections to Q_{Ps} of between 5% and 12%. Note that these corrections decrease as the positron energy increases and $I(\theta)$ becomes more forward peaked. At energies below E_{Ps}, at which its value is ideally zero, f was found to exhibit the same linear dependence on gas density in each gas, increasing to about 2% at the highest densities used. Attributing this to a dependence of the CEM detection efficiency upon gas density, we

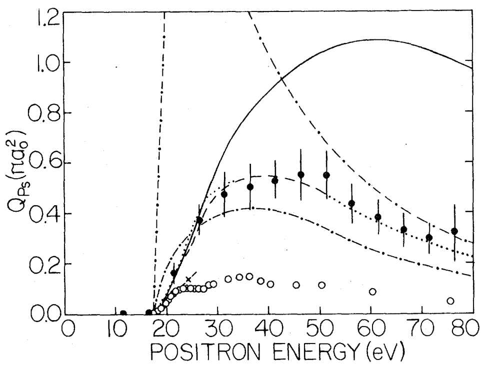

FIG. 2. Ps formation cross sections in He. Solid circles with error bars, present results; open circles, Ref. 6; solid line, Q_{inel} (see text); dashed line, $Q_{inel} - Q_{ex+ion}$ (see text); dash-crossed line, from lifetime data (Ref. 7); double-dash–dotted line, Born approximation (Ref. 18); dotted line, distorted wave (Ref. 19); dash-dotted line, polarized orbital (Ref. 20).

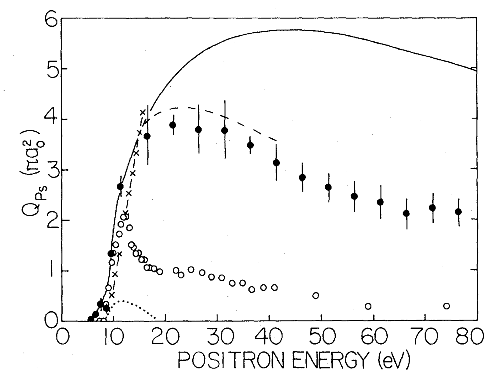

FIG. 3. Ps formation cross sections in Ar. Solid circles with error bars, present results; open circles, Ref. 6; solid line, Q_{inel} (see text); dashed line, $Q_{inel} - Q_{ex+ion}$ (see text); dash-crossed line, from lifetime data (Ref. 8); dotted line, distorted wave (Ref. 21).

mode corrections to both f and F, reducing Q_{Ps} typically by less than 5%.

The present cross sections are compared with other experimental and theoretical results in Figs. 2–4. The most striking feature in the plots is the disagreement between the two direct measurements of Q_{Ps}, both in magnitude and energy dependence. The rapid rise in our Q_{Ps} above E_{Ps} is in close agreement with $Q_{tot} - Q_{el}$ for each gas.[13,14] At higher energies the cross sections are high enough to indicate that they should not be ignored when comparing Q_{tot} values for positrons and electrons at intermediate energies.[4]

On each figure are drawn total inelastic cross sections, estimated by subtracting from the measured Q_{tot} values [13,14] constant Q_{el} values extrapolated from below E_{Ps} [(0.22, 2.70, and 0.89) $\times \pi a_0^2$ for He, Ar, and H_2, respectively]. For He and Ar, subtraction of Q_{ex+ion}, the cross section for excitation plus ionization of Coleman *et al.*,[23] leaves a residual which in both cases agrees well with the present measurements. This implies the following: (a) The scattering associated with positron impact excitation and ionization is predominantly into the forward hemisphere—i.e., the Q_{ex+ion} of Ref. 23 approximately equals the total Q_{ex+ion}. (This is consistent with the calculation of McEachran, Parcell, and Stauffer[24] for He 1S-2S excitation.) (b) Q_{ex} is a small contributor to Q_{tot}—consistent with the conclusion of Griffith *et al.*[2] that ionization is the dominant inelastic process at intermediate energies. (c) There are striking similarities between Q_{ion} for electrons[25] and positrons, both in He and Ar—consistent with the recent measurements by Sueoka.[26] (d) The dominance of Q_{Ps} over Q_{ex} in the "Ore gap" region ($E_{Ps} < E < E_{ion}$) predicts Ps formation fractions close to the upper limit predicted by the Ore model. In the light of reported measurements[7,8] it would appear that for He and Ar one has to modify the initial positron energy distribution used to calculate the Ore value or to assume that the process which considerably reduces the measured Ps fractions in Kr and Xe is occurring, to a lesser extent, in the lighter noble gases.[3]

The energy dependence of Q_{Ps} in He from two recent calculations[19,20] is very similar to that of our results. The only calculation of Q_{Ps} for Ar[21] is much smaller than the present results. For H_2 our results agree well with the charge-ex-

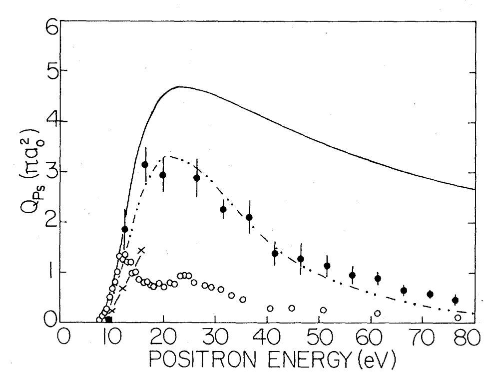

FIG. 4. Ps formation cross sections in H_2. Solid circles with error bars, present results; open circles, Ref. 6; solid line, Q_{inel} (see text); dash–double-dotted line, charge exchange (Ref. 22); dash-crossed line, from lifetime data (Ref. 8).

change cross section used by Bussard, Ramaty, and Drachman.[22]

In the near future the measurements will be extended to higher energies and will be made in a number of other atomic and molecular gases.

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[1]R. J. Drachman, in *Positron Annihilation*, edited by P. G. Coleman, S. C. Sharma, and L. M. Diana (North-Holland, Amsterdam, 1982), p. 37.

[2]T. C. Griffith, G. R. Heyland, K. S. Lines, and T. R. Twomey, J. Phys. B. 12, L747 (1979).

[3]D. M. Schrader and R. E. Svetic, Can. J. Phys. 60, 517 (1982).

[4]Suggested by W. Raith, private communication.

[5]M. Charlton, T. C. Griffith, G. R. Heyland, K. S. Lines, and G. L. Wright, J. Phys. B 13, L757 (1980).

[6]M. Charlton, G. Clark, T. C. Griffith, and G. R. Heyland, J. Phys. B 16, L465 (1983), and in Proceedings of the NATO Advanced Research Workshop on Positron Scattering in Gases, 1983 (Plenum, New York, to be published).

[7]P. G. Coleman, T. C. Griffith, G. R. Heyland, and T. L. Killeen, J. Phys. B 8, L185 (1975).

[8]M. Charlton, T. C. Griffith, G. R. Heyland, and K. S. Lines, J. Phys. B 12, L633 (1979).

[9]W. E. Kauppila and T. S. Stein, Can. J. Phys. 60, 471 (1982).

[10]D. R. Cook, P. G. Coleman, L. M. Diana, and S. C. Sharma, in *Positron Annihilation*, edited by P. G. Coleman, S. C. Sharma, and L. M. Diana (North-Holland, Amsterdam, 1982), p. 87.

[11]P. G. Coleman, J. D. McNutt, J. T. Hutton, L. M. Diana, and J. L. Fry, Rev. Sci. Instrum. 51, 935 (1980).

[12]P. G. Coleman, T. C. Griffith, G. R. Heyland, and T. R. Twomey, Appl. Phys. 11, 321 (1976).

[13]W. E. Kauppila, T. S. Stein, J. H. Smart, M. S. Dababneh, Y. K. Ho, J. P. Downing, and V. Pol, Phys. Rev. A 24, 725 (1981).

[14]A. Deuring, K. Floeder, D. Fromme, W. Raith, A. Schwab, G. Sinapius, P. W. Zitzewitz, and J. Krug, J. Phys. B 16, 1633 (1983).

[15]C. N. Burrous, Albert J. Lieber, and V. T. Zaviantseff, Rev. Sci. Instrum. 38, 1477 (1967).

[16]R. I. Campeanu and J. W. Humberston, J. Phys. B 10, 239 (1977).

[17]D. M. Schrader, Phys. Rev. A 20, 918 (1979).

[18]A. S. Ghosh, N. C. Sil, and P. Mandal, Phys. Rep. 87, 388 (1982).

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

[20]P. Khan and A. S. Ghosh, Phys. Rev. A (to be published).

[21]E. S. Gillespie and D. G. Thompson, J. Phys. B 10, 3543 (1977).

[22]R. W. Bussard, R. Ramaty, and R. J. Drachman, Astrophys. J. 228, 928 (1979).

[23]P. G. Coleman, J. T. Hutton, D. R. Cook, and C. A. Chandler, Can. J. Phys. 60, 584 (1982).

[24]R. P. McEachran, L. A. Parcell, and A. D. Stauffer, in *Positron Annihilation*, edited by P. G. Coleman, S. C. Sharma, and L. M. Diana (North-Holland, Amsterdam, 1982), p. 85.

[25]F. J. DeHeer, R. H. J. Jansen, and W. van der Kaay, J. Phys. B 10, 3741 (1977), and 12, 979 (1979).

[26]O. Sueoka, J. Phys. Soc. Jpn. 51, 3757 (1982).