Coupling between Positron-Atom Scattering Channels above the First Inelastic Threshold

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Experimentally determined cross sections for the elastic scattering of positrons by argon and xenon atoms have been found to exhibit a steplike increase at the first inelastic threshold energy—i.e., that for positronium formation. Rather than supporting the existence of a cusplike behavior predicted theoretically, this feature, which is more pronounced for xenon, suggests the existence of an intermediate virtual positronium state which enhances the elastic interaction probability.

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The possibility that the opening of inelastic channels has an effect on the elastic positron scattering cross section Q_{el} has been a focus of discussion for over 20 yr. In 1985 a broad peak in the Q_{el} was predicted for positrons colliding with hydrogen [1]. The authors extended this prediction to other atoms, predicting a narrow cusplike feature in the value of Q_{el} across the threshold energy E_{Ps} for positronium (Ps) formation, the lowest inelastic threshold for positron-atom scattering. Discontinuities occurring at energy thresholds where particles begin interacting via different channels were first predicted by Wigner in 1948 for the case of nuclear scattering [2] and have been observed in elastic electron-alkali atom scattering at the first excitation threshold in agreement with calculations [3].

In 1987, Campeanu *et al.* [4] attempted to analyze the behavior of the elastic scattering cross section near to E_{Ps} using

$$Q_{el} = Q_{tot} - Q_{Ps}, \tag{1}$$

where Q_{tot} and Q_{Ps} are the total and Ps formation cross sections, respectively, measured by different laboratories using different techniques. They found a pronounced cusplike feature with its peak at E_{Ps} and a minimum at the excitation threshold. While they concluded that the existence of a cusp had been proved, they accepted that the data were not accurate enough to determine its exact shape.

In 1992, Coleman *et al.* explored the region of interest further by measuring total and Ps formation cross sections in the same apparatus [5]. They found that, contrary to the predictions of Campeanu *et al.*, Q_{el} remained essentially constant across E_{Ps}. A series of experimental and theoretical studies at University College London aimed at addressing this problem culminated in the 1997 paper of Laricchia and Meyerhof [6], which addressed channel-coupling effects across the E_{Ps} in terms of the angular momentum quantum number values associated with the initial and final states. The authors explained the absence of a cusp observed in Q_{el} for helium but predicted the presence of progressively more pronounced cusps near E_{Ps} for noble gases of increasing atomic number, for which there is expected to be stronger coupling between scattering channels. In each case the theory predicted a fall in Q_{el} above E_{Ps}.

The aim of the present research was to gain direct evidence of cusps in Q_{el} for the heavier noble gases. The experimental method was based on that of Coleman *et al.* [5], in which monoenergetic positrons are transported through a gas cell by a relatively strong magnetic field, and pass through a planar retarding field analyzer (RFA) before being detected by a channel electron multiplier. Q_{Ps} is determined by measuring the beam attenuation when all surviving positrons, scattered or unscattered, are constrained to paths which end on the detector. Q_{tot} is determined by using the RFA to pass only those positrons which are unscattered in the gas cell. Then, at energies up to the first excitation threshold, $Q_{el} = Q_{tot} - Q_{Ps}$.

A schematic of the apparatus is shown in Fig. 1. A 150 MBq ^{22}Na source capsule is positioned behind two annealed 50%-transmission tungsten meshes with a 4 mm-diameter aperture, which act as the moderator and define the diameter of the incident positron beam. A potential V_M is applied to the moderator to determine the positron beam energy. A double 92% W mesh is placed directly in front of the moderator meshes and held at a potential $(V_M + 2)$ V in order to decrease both the energy spread in the positron beam (to ~0.7 eV FWHM) and its angular divergence. This double mesh also reflects any backward-scattered positrons back towards the detector. The slow positrons proceed through the 7 cm-long differentially pumped gas cell (ending in a 10 mm-diameter hole in a 35 mm-thick plate) under the influence of a 4 mT axial magnetic field.

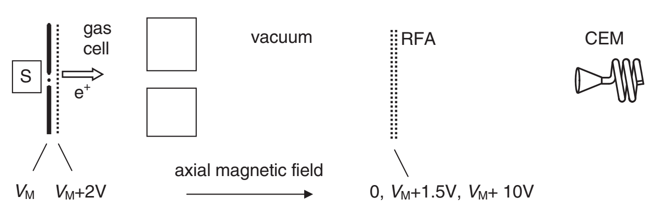

FIG. 1. Schematic diagram of apparatus. S is the source capsule, V_M is the potential applied to the moderator, RFA is the retarding field analyzer. Source-CEM distance ~400 mm.

The beam is then guided a further 25 cm through the evacuated flight tube to the channel electron multiplier (CEM) detector. The RFA is positioned midway between gas cell and CEM; it consists of two 92%-transmission W meshes held 1 mm apart, to which is applied a potential V_R which prevents the passage of positrons which retain axial momenta less than $(2meV_R)^{1/2}$ after deflection and/or energy loss in the gas cell. The entrance cone of CEM is held at -1500 V to reduce the background count rate resulting from the detection of fast secondary electrons from the source or moderator; it is covered by a further fine W mesh to reduce gain loss associated with field penetration effects. CEM pulses are amplified, shaped, and registered by a multichannel scaler (MCS).

The CEM count rate was first measured by the MCS as V_R was ramped from 0 V to above V_M, for a range of V_M, to determine that the value of V_R to be applied to transmit only essentially unscattered positrons was $(V_M + 1.5)$ V. In later measurements the MCS was routinely used to check on stability of count rates.

Measurements of beam attenuation A were made with $V_R = 0$ V and $= (V_M + 1.5)$ V in vacuum and with gas in the cell, for incident positron energies from just below $E_{\rm Ps}$ to just above the excitation threshold for argon and xenon (i.e., 5–15.5 eV for argon and 2–10 eV for xenon). The gas densities were such that A values were no more than $\sim$15%, to reduce the frequency of multiple scattering events. Background count rates were determined using $V_R = (V_M + 10)$ V for every run in both vacuum and gas.

When $V_R = 0$, $A = A_{\rm Ps}$, the attenuation due only to Ps formation. When $V_R = (V_M + 1.5)$ V, $A = A_T$, the total attenuation due to all scattering events, including elastic scattering at angles greater than approximately 10° at 10 eV and 25° at 2 eV.

The total and elastic scattering cross sections, Q_T and $Q_{\rm el}$, were found from

$$Q_T = -\{\ln(1 - A_T)\}/nL$$
$$\text{and} \quad Q_{\rm el} = -\{\ln[(1 - A_T)/(1 - A_{\rm Ps})]\}/nL, \tag{2}$$

where nL is the effective gas density-cell length product. nL was not measured directly, as the present experiment was designed to measure relative, not absolute, Q values. Instead, an average value of nL was found using measured values of A_T and $A_{\rm Ps}$ and previously measured values of Q_T for argon [7] and $Q_{\rm Ps}$ for xenon [8,9].

The results for argon and xenon are shown in Figs. 2(a) and 2(b). The positron energies plotted are correct to within 0.5 eV. For the reasons discussed in the previous paragraph—and, in the case of xenon, because earlier experimental absolute Q_T measurements vary widely—earlier experimentally determined Q values are not shown in Fig. 2. Both argon and xenon exhibit a slowly varying Q_T ($=Q_{\rm el}$) below $E_{\rm Ps}$. Just above threshold in argon a reproducible but small increase in $Q_{\rm el}$ was observed, possibly falling away again until the excitation channel opens at 11.5 eV. This energy dependence could be described as a broad cusp, but centered above and not at $E_{\rm Ps}$, or as a small rounded step. In contrast, in xenon the observation of a significant ($\sim$50%) increase in $Q_{\rm el}$ just above $E_{\rm Ps}$ was reproducibly unequivocal. The negligibly small contribution from atomic excitation just above threshold (11.3 eV) is consistent with earlier results [10].

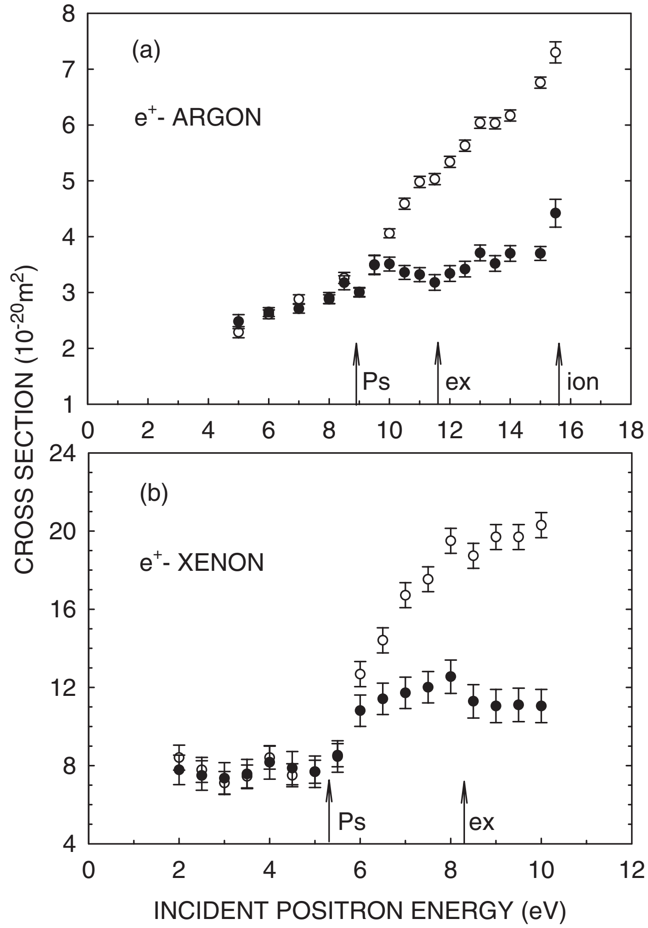

FIG. 2. (a) Total and elastic scattering cross sections for positron collisions with Ar atoms (open and full circles, respectively). Threshold energies for Ps formation, excitation, and ionization are indicated. The error bars are statistical standard deviations. (b) Total and elastic scattering cross sections for positron collisions with Xe atoms (open and full circles, respectively). Threshold energies for Ps formation and excitation are indicated. The error bars are statistical standard deviations.

Various systematic effects leading to the unexpected observations in Fig. 2 have been considered in depth. A sudden change in the differential scattering cross section at $E_{\rm Ps}$ might have some systematic consequences, but such a change is not suggested by the results of Marler *et al.* [11]. The rather flat energy dependence of $Q_{\rm el}$ for Xe below $E_{\rm Ps}$ resembles the calculations of Gianturco *et al.* [12] rather than the later calculations of Ref. [10] and some earlier measurements [13]; while this could indicate problems associated with the measurement of small-angle scattering at very low incident energies, such problems are expected to be very small in the vicinity of E_{Ps} and would in any case not account for a step in the energy dependence of Q_{el} across E_{Ps}.

Detection of an appreciable fraction of ions reaching the CEM from the gas cell would reduce the measured A_{Ps} and thus increase Q_{el} above E_{Ps}. This possibility was experimentally investigated by collecting MCS scans for (a) positron energies at the expected peak of Ps formation (e.g., 12 eV in Xe) and (b) electron energies near the peak of ionization (e.g. 100 eV in Xe). For scan (b) V_M was made negative and secondary electrons from the moderator mesh were used as the projectiles. The ions are expected to have very low residual energies and thus should appear on the scans as a sharp fall in the integral counts at low V_R. While no such feature was discernible in scan (a), a small drop was recorded in scan (b); the number of ions recorded was found to be just under 1% of the total expected from earlier ionization cross section measurements for electron-atom collisions [14]. The number of ions detected following Ps formation interactions is thus within statistical uncertainties, explaining the null result in (a). In summary, detection of 1% of the ions has an effect on the results of Fig. 2 which is smaller than the error bars shown. No other systematic effect in the present method has been identified which would lead to an apparent increase in elastic scattering across E_{Ps}.

One is led to consider possible explanations for the steplike behavior seen in xenon. Existing theories deal principally with sharp resonancelike structures, and predict a fall in Q_{el} just above E_{Ps}, [15] whereas the feature seen in Fig. 2(b) appears to exist over at least several eV—implying a phenomenon not well described as a resonance.

It is probable that the present observation is peculiar to the opening of the Ps formation channel, and an equivalent result could not thus be obtained for the scattering of other particles. It is also made more significant by the strong opening of the Ps formation channel above threshold (i.e., Q_{Ps} rises rapidly from threshold). In the 6.8 eV-wide energy range between E_{Ps} and the direct ionization threshold, a positron is able to leave the scattering site bound to an electron but cannot release a free electron from the atom. It is therefore suggested that, just above E_{Ps}, the positron may enter an intermediate state which then branches into two channels—(Ps + ion) or (positron + atom). Branching into the latter (elastic scattering) channel would be enhanced by this intermediate "virtual Ps" mechanism. This model would also support the increasing importance of this enhancement effect as Z of the target atom increases; the increasing electron density could lead to screening which would reduce the probability of real Ps formation and increase branching into the outgoing elastic channel. A similar correlation has been proposed between Ps formation and direct ionization of atoms by positron impact [16].

It is hoped that the observation of an increase in Q_{el} for positron scattering by the heavy noble gases at E_{Ps} will stimulate further theoretical work in this area.

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