Coupling between positronium formation and elastic positron scattering channels in the rare gases

P.M. Jay and P.G. Coleman

Department of Physics, University of Bath, Bath, BA2 7AY, UK

Abstract

Measurements of elastic scattering cross sections are presented for positron collisions with helium, neon, argon, krypton and xenon around the threshold energy for positronium (Ps) formation. The elastic cross section falls slowly with increasing energy above the Ps formation threshold in helium and neon, whereas in argon, krypton and xenon it exhibits an increase which appears both more prominent and more sustained as the atomic number of the gas increases. It is proposed that this coupling is a result of an intermediate virtual Ps state which enhances branching into the (atom plus positron) final state.

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I. INTRODUCTION

There have been many experimental studies of positron-atom scattering cross sections for collisions involving elastic scattering and the first inelastic process, involving the formation of positronium (Ps), the electron-positron bound state.[1,2] Of particular interest in recent years has been the possibility of coupling between the cross sections for these two processes immediately above the threshold for Ps formation (E_{Ps}, which is 6.8 eV – the ground-state Ps binding energy – below the first ionization potential E_{ion}).

It is difficult to calculate the two cross sections in the energy range from E_{Ps} to E_{ion} and theorists have taken the approach of subtracting experimental Ps formation cross sections (Q_{Ps}) from total cross sections (Q_{tot}), often measured at different times and with different apparatus. Following the early work of Campeanu et al.,[3] Laricchia and co-workers published a series of papers combining theory and experiment in which the elastic cross section Q_{el} exhibited a cusp-like behavior on positron energy around E_{Ps},[4] which generally falls with increasing energy above E_{Ps} – an effect which is very small for He but which increases in magnitude as the atomic number of the scattering gas species increases.

Two experimental studies of positron-helium scattering have suggested that no cusp is observable (in agreement with ref. 4),[5,6] but recently Coleman et al.[7] found a significant upward step in Q_{el} in xenon at E_{Ps}, and a possible smaller effect in argon. This result was attributed to the enhancement of the elastic scattering channel by the existence of an intermediate (positron + atom) state which proceeds either to (ion + Ps) or (positron + atom) final states – the latter being influenced by the former. Their results suggested that in the first 0.5 eV or so above E_{Ps}, most of the increase seen in Q_{tot} for xenon was in fact associated with an increase in Q_{el} rather than with the onset of real Ps formation. The reader is referred to ref. 7 for a fuller discussion of earlier work on this problem.

The aim of the work presented here is to investigate the extent of channel coupling at E_{Ps} for all five stable noble gases, primarily to investigate the dependence of the energy dependence of Q_{el} at E_{Ps} on atomic number. This work was encouraged by preliminary data for neon from Buckman et al.,[8] which suggested that a small change in neon could be seen at E_{Ps} (i.e., lying between the earlier null result for helium and the small result of ref. 7 for argon).

II. EXPERIMENTAL DETAILS

A schematic of the apparatus is shown in Fig. 1. Basic experimental details were given in ref. 7 and so the modified system will only be summarized here. A 115 MBq ^{22}Na source capsule is positioned 1mm from the moderator assembly, comprising two 4mm-diameter well-annealed 50%-transmission tungsten meshes held at a potential V_M, which determines the positron beam energy. (V_M+2) V is applied to a double 92% tungsten mesh placed immediately in front of the moderator meshes to (a) decrease the energy spread (to ~0.5 eV FWHM) and the angular divergence of the positron beam, and (b) to reflect any backward-scattered positrons towards the detector. The slow positrons are guided by a 5mT axial magnetic field through the 7cm-long gas cell and a further 25cm through vacuum, via a cylindrical-geometry retarding field analyzer (RFA) to the channel electron multiplier (CEM) detector, whose output pulses are counted by a multi-channel scaler (MCS). A potential V_R is applied to the RFA, which stops positrons with axial momenta less than $(2meV_R)^{1/2}$ after deflection and/or energy loss in the gas cell. With $V_R = (V_M + 1.5)$ V only essentially unscattered positrons are transmitted through the RFA. The relative sizes of the diameters of the incident beam, holes in the gas cell exit plate and RFA tube were chosen such that essentially all positrons scattered through any angle could be constrained to helical paths which ended on the CEM detector.

The beam attenuation A was measured with V_R = 0 and (V_M + 1.5) V with vacuum and gas in the cell, for incident positron energies from 4eV below to 4eV above E_{Ps} in helium, neon, argon, krypton and xenon. The gas densities were kept low enough so that A was less than ~ 15%, to reduce the probability of multiple scattering in the cell. By increasing V_R to (V_M + 10) V the background count rate could be measured. Signal count rates were recorded by the MCS for each incident positron energy E, which was stepped automatically from (E_{Ps}-4) to (E_{Ps}+4) eV by controlling the moderator potential V_M using the MCS ramp output.

A_{Ps}, the attenuation due only to Ps formation, was measured by comparing signal vacuum and gas count rates with V_R = 0 V, and the total attenuation A_T due to all scattering events, was measured with V_R = (V_M + 1.5) V. Angular discrimination for elastic scattering ranged from approximately 23º at 2eV to 7º at 22eV.

The detection of ions resulting from Ps formation would reduce the measured A_{Ps} and therefore increase the deduced values of Q_{el} above E_{Ps}. Measurements of A_{Ps} were consequently also made with V_R = 0.75V, to stop any ions which may have been otherwise guided to the CEM following Ps formation. It was found that this small positive potential was sufficient to prevent ion detection (the probability of which was found to decrease with the atomic number of the target atoms) and did not significantly affect the results presented. Ion detection can therefore be eliminated as a possible source of systematic error in these experiments.

Q_{el} is then given by $\{\ln[(1-A_T)/(1-A_{Ps})]\}/nL$, where n is the gas density and L the effective length of the gas cell. nL was found using measured values of A_T and A_{Ps} and previously measured values of Q_T and Q_{Ps} for the five gases studied, as the energy dependence of Q_{el}, rather than its absolute value, was the focus of the present work.

III. RESULTS AND DISCUSSION

The results for all five rare gases are shown in Fig.2. Apart from the 2009 Bath results for Ar and Xe [7] the only other experimental results for Q_{el} in these gases are the early work of Coleman et al.[6] and the recent measurements for He of Caradonna et al.[5] Preliminary results for Q_{el} for Ne from the ANU group, as yet unpublished, appear similar to those shown in Fig. 2.[8] Selected earlier absolute measurements of Q_T are shown for He, Ne and Kr [5, 9, 10]; the Ar results are shown alongside those of ref. 7, which were normalized using the Q_T values of Karwasz et al.[11] For Xe the disagreement between published Q_T values is so great that the current measurements were normalized using as a guide the values of ref. 12 below E_{Ps} and the Q_{Ps} values reported in ref. 13 above E_{Ps}.

The results all show a change in Q_{el} at E_{Ps}. In He and Ne this change can be described as a small – but there is an indication in both gases that Q_{el} exhibits a broad peak extending over several eV. In both gases this may be regarded as a reduction above E_{Ps} in the small positive slope in $Q_{el}(E)$, which is more prominent in Ne as there is a more prominent upward trend in Q_{el} below E_{Ps} in this gas. These features are not dissimilar to the cusp-like features at E_{Ps} discussed by Meyerhof and Laricchia,[4] except that the data indicate that the cusp-like feature is peaked at 1eV or so above E_{Ps}, especially in He.

The data for Ar reproduce well our 2009 results near E_{Ps}, with a small but pronounced peak in Q_{el} occurring at ~ 1eV above E_{Ps}. This difference is too large to be explained by incorrect assignment of positron energy, and indicates that, although cusp-like in shape, $Q_{el}(E)$ is does not have the expected maximum at E_{Ps}. The broad peak can instead be thought of as an enhancement of Q_{el} in the energy region between E_{Ps} and the direct ionization threshold E_{ion}, 6.8 eV higher.

This enhancement becomes more pronounced in Kr and Xe. While giving the impression of increasing in a step-wise fashion above E_{Ps}, the increase may also be considered to be an enhancement between E_{Ps} and E_{ion}, especially if the underlying trend in Q_{el} is a slow increase with increasing energy.

While not showing the predicted cusp-like behavior, the increase in the strength of coupling between Q_{el} and Q_{Ps} above E_{Ps} with the atomic number of the target atom is evident. The cusps predicted in refs. 4 and 14 are stronger when Q_{el} increases more prominently with positron energy *below* E_{Ps}, and this happens for the heavier gases. Meyerhof, Laricchia and co-workers[4] studied the coupling in terms of the angular momenta of the initial and final states. Whereas the present measurements do not completely rule out this possibility, there would appear to be a second, stronger coupling which – in the heavier gases at least – which outweighs any cusp-like behavior. We propose that the enhancement of Q_{el} between E_{Ps} and E_{ion} is a result of the existence of an intermediate positron-atom state in this energy region. Here the incident positrons do not have enough energy to eject a free electron from the atom, but can leave in the bound Ps state. The possibility of Ps formation strengthens the positron-atom interaction and consequently increases the possibility of branching into *both* final (positron + atom) or (Ps + ion) states. Thus both Q_{el} and Q_{Ps} increase above E_{Ps}. We suggest that the enhancement of Q_{el} is most marked just above E_{Ps}, and as E increases towards E_{ion} the branching into the two final states progressively favors Ps formation.

It is interesting to note that Weber et al.[14] observed elastic scattering of Ps from a LiF surface when only inelastic scattering was expected; they concluded that the imaginary part of the scattering potential, which mimics the inelastic channel, leads to much more elastic scattering than would be obtained from the real part of the potential by itself – implying that, in the present experiment, the onset of inelastic scattering would enhance the elastic scattering probability.

The question remains as to why the enhancement of Q_{el} becomes more pronounced with atomic number. One possible explanation is that if the intermediate state contains more electrons (rising from 2 for He to 54 for Xe) then the probability of branching into the (Ps + ion) final state is reduced by the increased screening of the positron-electron interaction by the other electrons in the atom. This highly speculative proposal is clearly in need of careful theoretical consideration.

IV. CONCLUSIONS

The present experimental results confirm that there is coupling between elastic scattering and Ps formation above the Ps threshold energy, but that the most significant feature resulting from this coupling – at least in the heavier gases (Ar, Kr and Xe) is not the expected cusp in Q_{el} at E_{Ps}, but instead an increase in Q_{el} from E_{Ps} to about (E_{Ps} +1) eV – above which it falls again or levels out. This enhancement in Q_{el} may result from a strengthening of the positron-atom interaction via a ‘virtual Ps’ intermediate state. The increasing prominence of the enhancement of Q_{el} above E_{Ps} in the heavier gases mimics the behavior predicted for the cusp, but a full understanding would require further theoretical research. It is hoped that these measurements will stimulate further experiments and calculations in the interesting –

and unique – energy range between the first inelastic thresholds for positron scattering.

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Figure captions

Fig.1. Schematic diagram of the apparatus. S = ^{22}Na source capsule, V_M = potential applied to moderator, RFA = tube retarding field analyzer, CEM = channel electron multiplier. Source-CEM distance ~ 400mm.

Fig. 2. Total (white circles) and elastic (black circles) cross sections for positron scattering by He, Ne, Ar, Kr and Xe. Open triangles: earlier absolute total cross sections for He,[5] Ne,[9] Ar[11] and Kr.[10] White squares: Q_{el} for He from ref. 5. Gray circles and squares: 2009 results of Coleman et al. for Q_{el} and Q_T for Ar and Xe.[7]

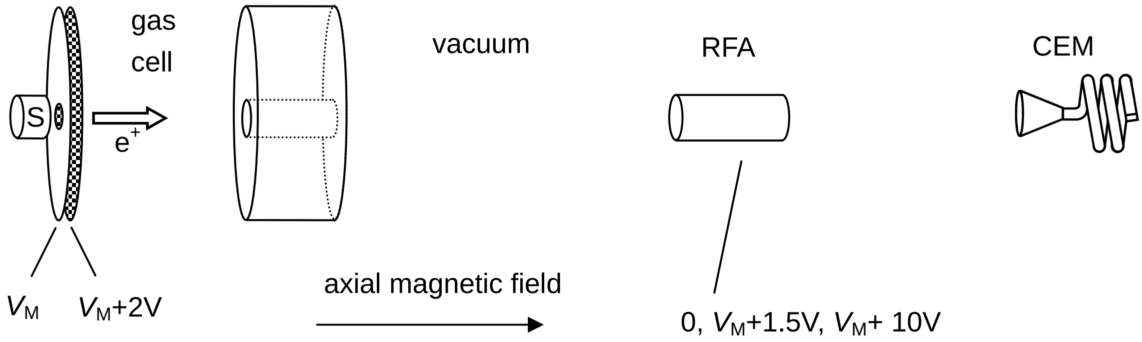
gas
cell
vacuum
RFA
CEM
S
e+
VM
VM+2V
axial magnetic field
0, VM+1.5V, VM+ 10V

Figure 1

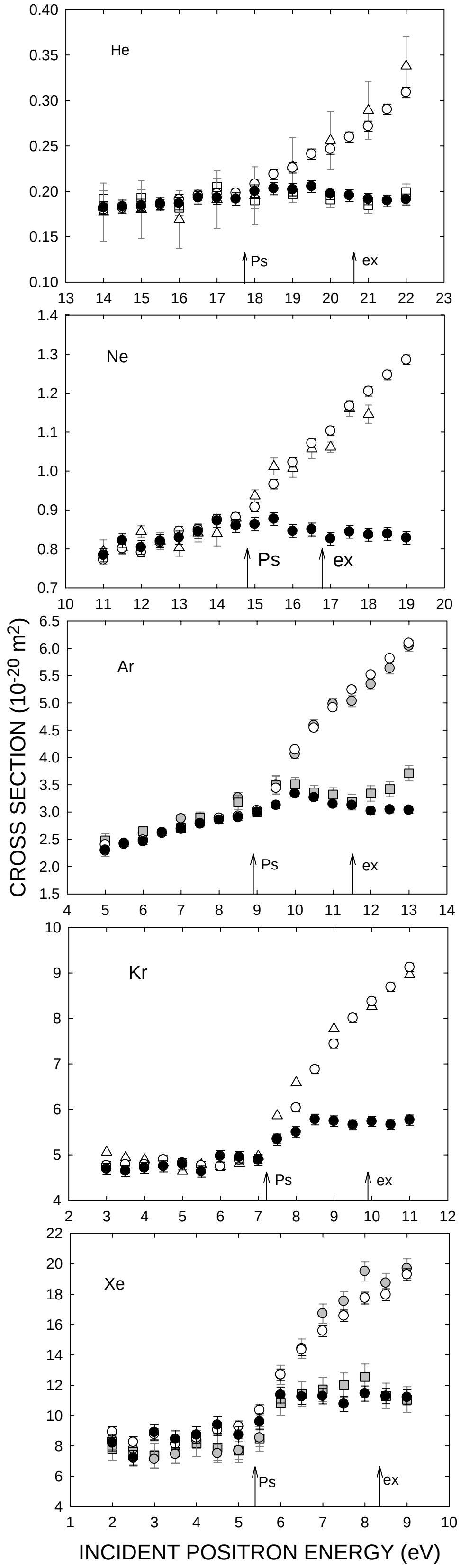
He
Ps
ex
Ne
Ps
ex
Ar
Ps
ex
Kr
Ps
ex
Xe
Ps
ex
CROSS SECTION (10^{-20} m^2)
INCIDENT POSITRON ENERGY (eV)

Figure 2