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## High Resolution Positron Interactions

**A Jones, P Caradonna C Makochekanwa, D Slaughter, D Mueller, J P Sullivan  
and S J Buckman<sup>1</sup>**

ARC Centre for Antimatter-Matter Studies  
Research School of Physics and Engineering  
Australian National University  
Canberra, 0200 ACT, Australia

E-mail: Stephen.buckman@anu.edu.au

**Abstract.** A high-resolution ( $\Delta E \sim 60$  meV FWHM) positron beam apparatus is briefly described and it has been used to measure total scattering, elastic scattering, positronium (Ps) formation, and inelastic scattering cross sections from a number of rare gas atoms. In this paper we present a selection of these results for helium, neon and argon and where possible, compare with previous measurements and contemporary theory. A particular search has been made for resonance and channel coupling effects at, or near, the opening of inelastic channels.

### 1. Introduction

Low energy positron interactions with gases are characterised by a number of significant differences from those of electrons, which are now well studied and understood. While the nature of the static interaction with the atom is different, and positrons do not undergo the exchange interaction, they do however, readily form positronium – an electron-positron pair – which is one of the major pathways to electron-positron annihilation. Positrons are also becoming increasingly used in medicine and technology and their annihilation with their matter counterpart provides the gamma ray signature that is used for a variety of applications, from nano-material design to cancer imaging and therapy.

Electron and positron interactions with atoms, molecules and materials can provide important insights into atomic and molecular structure and reaction mechanisms, and they already underpin a wealth of both realised and potential applications in technology, biomedical science and the environment. At low energies, electron interactions are characterized by, amongst other things, strong scattering resonances involving the temporary trapping of the projectile in the field of the atom or molecule. These resonances often lead to profound effects on the scattering cross sections and, in some cases, they can enhance scattering rates by orders of magnitude.

Measurements of positron interactions, on the other hand, are not so extensive, or advanced, as those for their matter counterpart. Positron scattering experiments have, until recently, generally lacked the specificity and accuracy of electron scattering measurements, mainly as a consequence of low beam intensities and/or relatively poor energy resolution. A significant advance in recent years has been the advent of trap-based positron beams which, when combined with new techniques developed for charged particle scattering in large magnetic fields, have enabled many new measurements. For example, the improved energy resolution and sensitivity offered by these

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<sup>1</sup> To whom any correspondence should be addressed.

techniques have enabled the first absolute scattering measurements for excitation processes in atoms and molecules, including measurements of positronium formation (see [1] for a recent review of positron interactions). These techniques promise much new fundamental information on positron interactions with atoms and molecules, including measurements on biologically important molecules, which may have relevance for a deeper understanding of the interactions that underpin diagnostic techniques such as Positron Emission Tomography (PET).

For both electron and positron scattering, another important rationale for the measurements lies in the comparison with state of the art quantum scattering theory. In order for theory to develop, particularly in the case of complex molecular targets, it is imperative that accurate ‘benchmark’ experimental measurements are available for comparison. For positrons this poses additional problems for theoretical approaches, even for simple targets, in developing a suitable treatment for the positronium channel.

We have commenced a program of studies of positron interactions with atoms, molecules and materials, which is aimed at a better, and more detailed, understanding of positron interactions, and their transport in gases and, ultimately, soft condensed matter. In the following sections we discuss the new experimental initiative in positron physics which has been undertaken. We briefly consider the development of a new positron trap and scattering experiment, and present results that have been obtained with it for positron scattering from the rare gases.

## 2. Experimental considerations

The experimental details have been given before [2] and only a brief account will be given here. At the heart of this experimental program is a ‘Surko trap’ where positrons are accumulated, trapped and cooled through controlled interactions with molecular gases such as  $N_2$  and  $CF_4$ . Positrons from a 30 mCi  $^{22}Na$  source are firstly moderated with a solid neon moderator before entering the first stage of the trap. The principle interactions in this stage trap are near-threshold electronic excitation of the  $N_2$  molecules in which the positrons lose  $\sim 8$  eV of energy and become trapped in the potential well. They are then transferred to the second stage where they cool to room temperature through vibrational and rotational excitations of both the  $N_2$  and the  $CF_4$ . The cold positrons ( $\Delta E \sim 60$  meV FWHM) are then dumped from the trap by modulating the potential of one of the final trap electrodes. A pulsed beam of several microseconds duration is formed and it typically contains 300-1000 positrons, at a repetition rate of 100-300 Hz. Throughout the trapping region the positrons are axially confined with a strong (500 Gauss) magnetic field, and longitudinally confined by tuned electrostatic potentials on the numerous trap elements.

The pulsed positron beam is directed into a scattering cell containing the gas of interest and the transmitted positrons are energy analysed using a retarding potential analyser (RPA), before detection occurs with a microchannel plate assembly coupled to a charge sensitive pre-amplifier and counting electronics. In the presence of the strong magnetic field, almost all scattered positrons are transmitted to the RPA and detector, the exception being those that are scattered through a small angular range about  $90^\circ$  and ultimately annihilate within the apparatus, and those that form positronium and also annihilate. The RPA measures only that component of the positron energy which is parallel to the  $\mathbf{B}$  field, but this information can be interpreted in terms of the positron scattering cross sections. How this is done has been discussed in detail previously [3] and only a brief account is given here.

For the present measurements, the focus has been on the measurement of the grand total, total positronium formation and grand total minus positronium cross sections. Figure 1 is a schematic representation of a typical RPA spectrum of transmitted positrons as a function of retarding voltage, for a positron impact energy of 33 eV in helium. The incident positron beam intensity ( $I_0$ ) is measured at an energy below the Ps threshold of 17.8 eV. The total transmitted intensity, which has lost some portion due to Ps formation ( $I_t$ ), and the transmitted intensity that has lost some portion due to scattering with the target gas ( $I_m$ ) are also measured. The various integral cross sections can then be determined from these experimentally derived quantities using the Beer Lambert Law, equation (1),

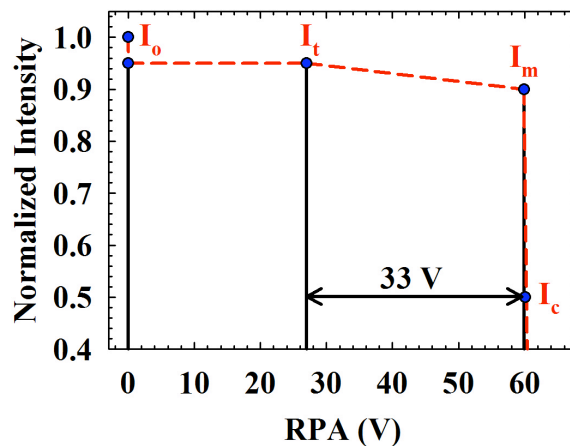
where ( $n$ ) is the gas number density, ( $l$ ) is the path length through the gas, and ( $H$ ) is the appropriate fraction of measured intensities.

$$\sigma = -\frac{1}{nl} \ln(H) \quad (1)$$

For the present experiment, the quantity  $H = I_m/I_o$  in (1), is the scattering fraction needed to experimentally calculate the grand total cross section ( $\sigma_{GT}$ ), whilst  $H = I_t/I_o$  determines the positronium formation cross section ( $\sigma_{Ps}$ ). The partitioning of the Ps formation cross section from the grand total cross section,  $\sigma_{(GT-Ps)}$ , can also be experimentally determined by replacing  $H = (I_m + \Delta I)/I_o$  in (1), where,

$$\Delta I = I_o - I_t. \quad (2)$$

The cross sections that have been measured in this fashion generally have an absolute uncertainty of less than 10%, and in most cases, the error is significantly smaller than this. The main contribution to the experimental uncertainty comes from statistical errors, while uncertainties in number density and path length are typically less than 1%.

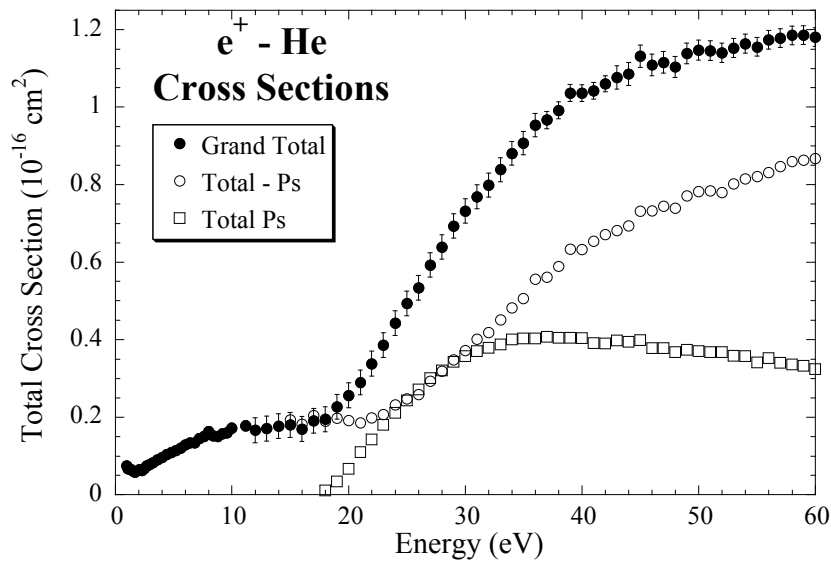


**Figure 1.** Schematic representation of a RPA curve for a 33 eV positron beam scattered by helium .  $I_c = 0.5$  corresponds with the cutoff potential.

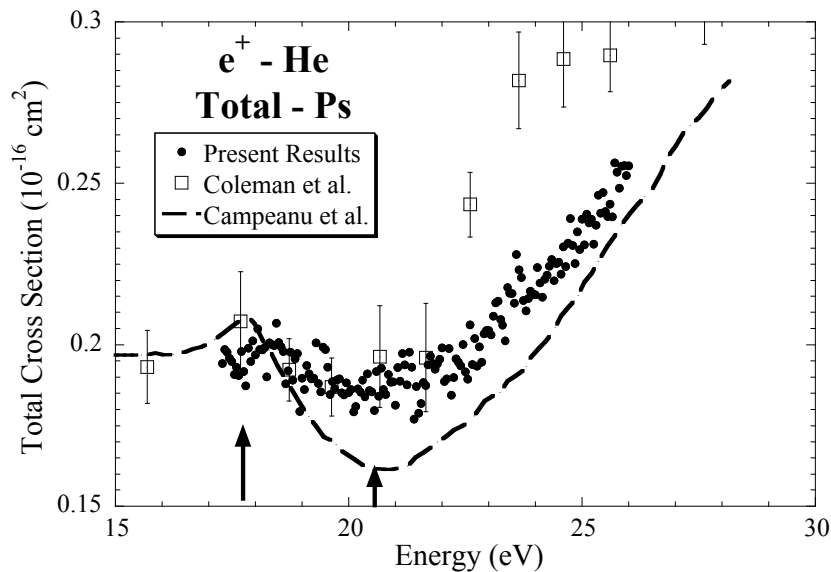
### 3. Results and discussion

#### 3.1. Helium

The grand total, positronium formation, and grand total minus positronium formation cross sections are shown in figure 2 for scattering from helium at energies up to 60 eV. The dominant features of  $\sigma_{GT}$  are the low energy Ramsauer-Townsend minimum at around 1.5 eV and the step increase in the cross section above 18 eV due, principally, to the opening of the positronium formation channel, but also due to other inelastic scattering effects. The partitioning of this increase between positronium formation and other channels can be seen by comparing the Ps cross section with that for ( $\sigma_{GT} - Ps$ ) and up to about 40 eV, most of the increase in  $\sigma_{GT}$  arises from positronium formation.



**Figure 2.** The grand total (solid circles), total positronium formation (open squares) and grand total – positronium formation cross sections (open circles) for helium at energies up to 60 eV.



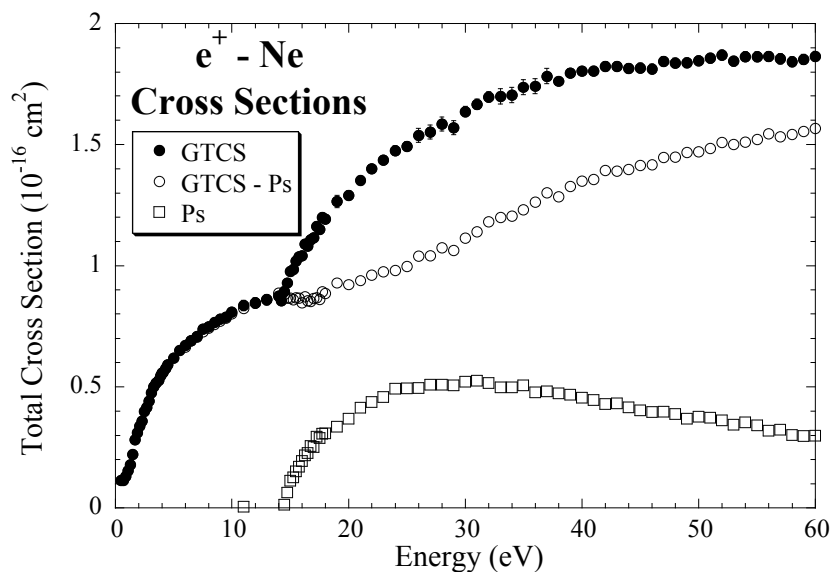
**Figure 3.** The present ( $\sigma_{GT} - Ps$ ) cross section (solid circles) compared to the prediction of [4] (dashed line) and measurements of [5] (open squares)

Space constraints do not enable a detailed comparison of these cross sections with what amounts to quite a large number of other measurements and theory in the literature. In general, however, the agreement at the total cross section level, between experiment and theory is very good. As one of the aims of these experiments, through the use of high-resolution positron beams, was to search for resonances and/or threshold effects, results that we have obtained at and near the threshold for positronium formation and in the Ore gap immediately above this energy, are relevant. The Ore gap is the region between the Ps threshold and the lowest excited state threshold in the atom. In helium this corresponds to the energy region from 17.8 – 20.6 eV, the latter being the threshold for the excitation of the  $2^1S$  state.

In previous work, which resulted from an analysis of grand total and Ps formation cross sections, it was proposed [4] that a strong cusp structure was likely to exist in the  $(\sigma_{GT} - \text{Ps})$  cross section at the Ps threshold. Subsequent measurements [5] of this cross section, which in the Ore gap is equivalent to the total elastic cross section, were suggestive of a structure but not conclusively so. Our measurements of the  $(\sigma_{GT} - \text{Ps})$  cross section are shown in figure 3 where they are compared with the prediction of [4] and measurements of [5]. Our data, taken with an energy resolution of about 55 meV and an energy step of 50 meV, do indicate a down step in the total elastic cross section between the Ps and  $2^1\text{S}$  thresholds, but the observed effect is not as large as predicted by [4].

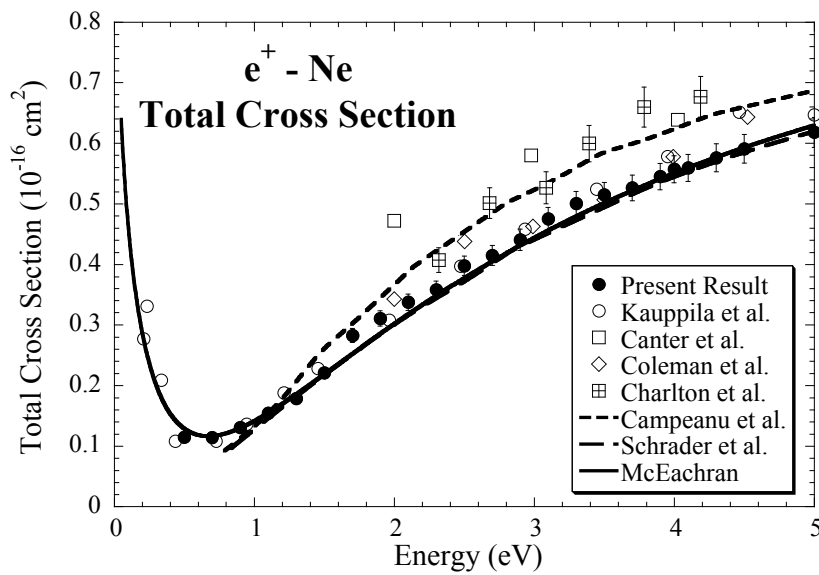
### 3.2. Neon

The preliminary measured cross sections, total scattering, positronium formation, and  $(\sigma_{GT} - \text{Ps})$ , for neon are shown in figure 4 and, once again, the prominent features of the cross section are the Ramsauer-Townsend minimum and the strong influence that the Ps formation cross section has on the overall scattering. As in the case of helium, there are many other measurements and theoretical calculations with which we could compare, but space does not enable us to do justice to all of them here. However, one other point which does emerge from figure 4, and is consistent with the observation in helium above, is the weak ‘structure’ that is observed in the  $(\sigma_{GT} - \text{Ps})$  cross section at the Ps threshold. Once again we see a shallow ‘dip’ in the total elastic cross section in the Ore gap, above the Ps threshold, and this is possibly due to coupling between the elastic and positronium formation cross sections.



**Figure 4.** The grand total (solid circles), total positronium formation (open squares) and grand total – positronium formation cross sections (open circles) for neon at energies up to 60 eV.

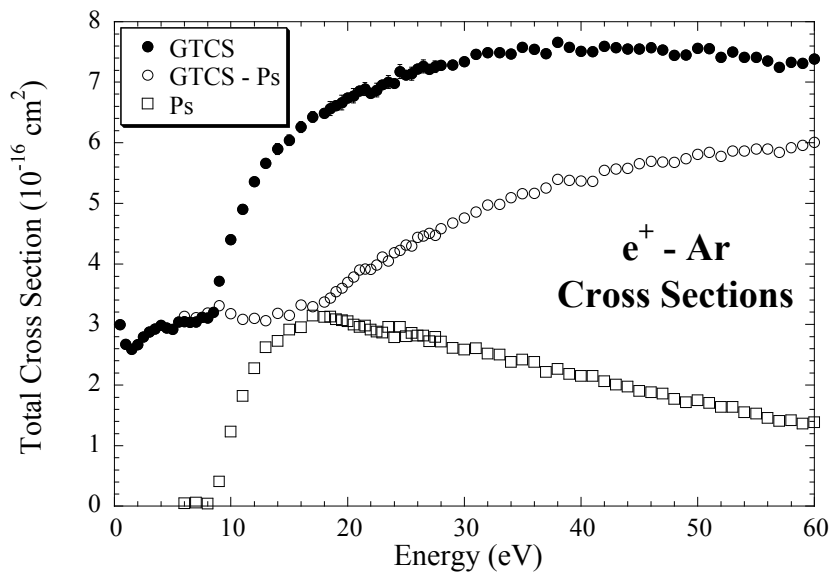
Given that part of the rationale for the present measurements was a focus on comparison with start-of-the-art theory, in figure 5 we show the low energy region of the total scattering cross section for neon, where the present total scattering cross section is compared with other measurements from the literature and theoretical calculations. In general the level of agreement is very good, with most experimental values falling within their mutual uncertainties and the three theories that are illustrated providing an excellent description of the total scattering intensity. This is particularly the case for the polarised orbital calculation of McEachran and colleagues [6].



**Figure 5.** The present grand total (solid circles) compared with a number of previous experiments and theoretical determinations at energies below 10 eV.

### 3.3. Argon

The measured cross sections, total scattering, positronium formation, and  $(\sigma_{GT} - Ps)$ , for argon are shown in figure 6 and, again, the prominent features of the cross section are the Ramsauer-Townsend (R-T) minimum and the strong influence that the Ps formation cross section has on the overall scattering. In fact, the onset of Ps formation in argon is considerably stronger than in either He or Ne. The R-T minimum occurs at around 1 eV, and the cross section is relatively flat between there and the onset of Ps formation at around 8 eV, only increasing by about 20% over this energy range. At an energy of 20 eV, about half of the total scattering cross section is due to positronium formation.



**Figure 6.** The grand total (solid circles), total positronium formation (open squares) and grand total – positronium formation cross sections (open circles) for argon at energies up to 60 eV.

Once again the total elastic cross section reveals some features at the Ps threshold. In the case of Ar, this appears to be a small ‘peak’ followed by the now familiar dip in the cross section in the Ore gap above the Ps formation threshold. This feature appears to be more prominent in Ar than in either He or Ne, and our observation is broadly consistent with the recent observation [7] of structures in the elastic cross section at the Ps formation threshold for Ar, Kr and Xe.

#### 4. Conclusions and Future Directions

This short paper has summarised our recent work in measuring accurate, absolute total scattering, total elastic scattering, total positronium formation, and total minus positronium formation cross sections for the rare gases He, Ne and Ar, with a high resolution positron beam. The general features of the cross sections for all three gases are similar, with a Ramsauer-Townsend minimum evident in each in the energy region 1-2 eV, and strong onset of positronium formation above the Ps threshold. We have also observed ‘features’ – small decreases in the elastic cross section, and the possibility of a small peak at the Ps threshold in the argon case – in each of these gases. Such ‘channel coupling’ effects are perhaps to be expected, given the magnitude and energy dependence of the near-threshold Ps formation cross section in these gases. Such features have been investigated in the past [4,5] and recent work [7] has suggested that they may be due to intermediate virtual positronium formation. Clearly more high resolution studies in this energy region would be beneficial, particularly in the heavier rare gases, and this is planned in the near-term in our laboratory.

#### 5. References

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