Abstract

An electrostatic system has been used to measure Differential Cross-Sections (DCS) in positron-gas collisions. Single DCS were measured using a Retarding Field Analyzer (RFA). Double DCS were measured using a tandem 30° Parallel Plate Analyzer (PPA).

The energy dependencies of the DCS for elastic scattering, positronium formation and direct single ionization in positron-argon collisions at 60° and 30° (not elastic scattering) have been measured in the energy range 40–150eV. Of particular interest was the energy range 55–60eV where Dou et al (Phys. Rev. Lett. 68 (1992) 2913), from the Detroit group, reported a drop in the elastic scattering cross section by a factor of two. This was tentatively attributed to a cross-channel coupling effect with an open inelastic scattering channel. Our measurements showed no structure in any of the cross sections. This agrees with the results of new experiments in which the Detroit group have not been able to reproduce the previously reported structures.

Double differential ionization cross-section measurements were performed at 30° for 60 and 100eV impact energies to investigate the phenomena known as Electron Capture to the Continuum (ECC). ECC cusps have been observed in heavy-ion impact collisions but not in the equivalent positron impact studies, despite the many theoretical calculations predicting their existence. Our measurements showed no evidence of ECC. In addition, at the higher scattered positron energies, results of the Classical Trajectory Monte-Carlo calculations of Sparrow and Olson (J. Phys. B 27 (1994) 2647) exceeds our measurements. This discrepancy was first observed in the equivalent measurements of Köver et al (J. Phys. B 27 (1994) L613) using a RFA. The fact that this discrepancy was observed from two independent experiments, using very different detection instruments, suggests that it is a genuine physical effect and that further work, both experimental and theoretical, is necessary to understand it.
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Acknowledgements

I would like to express my gratitude to those who have supported, encouraged and helped me over the course of my postgraduate work.

For their supervision and tuition I would like to thank Drs Mike Charlton, Nella Laricchia and Ákos Kövér.

For their invaluable technical assistance I must thank Ivan Rangué and Ted Oldfield. Thanks to Catherine Jones for her kindness and to Joe Sanderson for proof reading this work.

The close support of my peer group has been greatly appreciated, in particular the help and friendship of: Andrew, Paul, Jeremy, Vanita, Aysun, David, Karen and Don.

I would like to thank all the members of my family for their support throughout. I must make special mention of my mentor and fellow physicist Amro Gebreel and of Ryan Wolton a loyal friend throughout my formative years.

Finally I must pay special tribute to my brother, Mark.
Chapter 1

Introduction

1.1 Historical Background

The existence of antimatter was first predicted by Dirac\(^1\) who developed a relativistic wave equation describing the motion of free electrons in an electromagnetic field. Solutions of this equation resulted in electrons occupying both positive and negative energy levels. Dirac proposed that these negative energy levels were usually full thereby preventing free electrons from falling into them, due to the Pauli exclusion principle. However, if an electron were excited from a negative to a positive energy level then it would leave a 'hole' which would behave exactly like a positively charged electron. Dirac proposed that a 'hole' was actually a proton, hoping that the Coulomb force between the electrons might explain the different rest masses of the proton and electron. However, Oppenheimer\(^2\) showed that the particle had to have the same mass as an electron and this particle (or anti–electron) became known as the positron. Positrons were first observed experimentally by Anderson\(^3,4,5\) and Blackett and Occhialini\(^6\) using cloud chamber techniques to study cosmic showers. It was suggested by Mohorovicic\(^7\) that the Coulomb interaction between a positron and electron might result in a quasi–stable hydrogenic bound state. This bound state was named positronium (chemical symbol, Ps) by Ruark\(^8\) and its existence was experimentally verified by Deutsch\(^9\) whilst measuring positron lifetimes in gases.

Positrons can be obtained from the decay of certain radionuclides and have become an important probe of many physical phenomena. The possibility of annihilation of a positron with its antiparticle, the electron, has made possible the investigation of such phenomena by a number of experimental techniques which rely on the detection of the annihilation photons. These are discussed in §1.3.1.

Positrons may be formed into nearly monoenergetic beams (§1.3.2) and these have been used, among other things, to study the interaction of positrons with single atoms (and molecules) at well defined energies. Data of this kind are complementary to electron scattering studies in that the masses of both projectiles are equal but the charges are opposite. Comparisons of cross–sections for the scattering of electrons, positrons and other particle/antiparticle pairs may therefore elucidate the roles of projectile charge sign and
mass, exchange effects and electron capture. This chapter presents a brief discussion of the fundamental properties of the positron and Ps and reviews some of the important advances in the production of slow positron beams and the subsequent measurements of positron scattering cross-sections.

1.2 Basic Properties of Positrons and Positronium

The positron is expected to be stable in vacuum, with a lifetime in excess of $2 \times 10^{21}$ years (Bellotti et al. 10). Positron–electron pairs, on the other hand, rapidly annihilate, usually with the emission of photons. Dirac\(^1\) calculated the cross-section for two photon annihilation ($\sigma_{\text{ann}}(e^-)$) of a non-relativistic, free electron–positron pair as

$$
\sigma_{\text{ann}}(e^-) = \frac{\pi r_0^2 c}{v}
$$

(1.1)

where $v$ is the relative velocity of the positron and electron, $c$ is the speed of light and $r_0 = e^2/(4\pi\varepsilon_0 m_0 c^2)$ is the classical electron radius. For positrons in a gas this equation was modified (eg. Heyland \textit{et al.}\(^2\)) to

$$
\sigma_{\text{ann}}(A) = \frac{\pi r_0^2 cZ_{\text{eff}}(v)}{v}
$$

(1.2)

where $Z_{\text{eff}}(v)$ is the effective number of electrons per atom seen by a positron. It may be significantly greater than the atomic number due to long range Coulomb interactions. At the collision velocities typically encountered in positron beam experiments, $\sigma_{\text{ann}}(A)$ is of the order of $10^{-26} m^2$ for $Z_{\text{eff}}=1$, that is, negligible compared to other positron scattering channels, such as Ps formation. The second most probable annihilation mode, that of three photon annihilation, has a cross-section smaller than this by a factor of 378 (Ore and Powell\(^3\)).

Ps can be formed in two ground states, depending on the relative spin orientation of its constituents. If the particles have anti-parallel spins then para-positronium (p–Ps) is
formed; if the spin orientations are parallel, ortho–positronium (o–Ps) results. The total angular momentum \((J=L+S)\) of ground state o–Ps is 1, giving rise to three substates with magnetic quantum numbers \(m=0, \pm 1\), whereas for p–Ps, the total angular momentum is zero and hence \(m=0\). The ratio of the cross–sections for o–Ps to p–Ps formation are therefore 3:1.

Ps has a finite lifetime which is determined by the annihilation mode of the electron–positron pair. For example, the self–annihilation rate for p–Ps \((\lambda_p)\) and o–Ps \((\lambda_o)\) have been calculated to be 7.9852ns\(^{-1}\) (Harris and Brown\(^{14}\)) and 7.0383\(\pm\)0.0007\(\mu\)s\(^{-1}\) (Adkins\(^{15}\)), respectively. The corresponding measurements by Al–Ramadhan and Gidley\(^{16}\) and Asai \textit{et al}\(^{17}\) for \(\lambda_p (=7.9909\pm0.0017\)ns\(^{-1}\)) and \(\lambda_o (=7.0398\pm0.0029\)μs\(^{-1}\)) agree well with theory.

1.3 Experimental Techniques

1.3.1 Early Experiments

The earliest experiments using positrons as projectiles were swarm–type experiments. These involved implanting fast positrons \((\beta^+)\) from the decay of radionuclides directly into the sample under investigation and observing the annihilation photons. For example, in two photon annihilation, in the centre–of–mass frame, the \(\gamma\)–rays are emitted at an angle of 180°, with total energy \(2mc^2 (=1.022\text{MeV})\). In the laboratory frame, because of the finite momentum, \(p\), of the electron–positron pair, the two photons deviate from collinearity by \(\theta\) and their energy is shifted \((\Delta E_{2\gamma})\) according to

\[
\Delta E_{2\gamma} = \frac{v}{c} 511\text{keV}
\]  

The energy shift is measured using \(\gamma\)–ray detectors of high resolution. Since the positron usually thermalizes long before annihilating (e.g Kubica and Stewart\(^{18}\)), the measured momentum distribution is almost entirely attributable to that of the electrons. The angular shift is measured using two detectors placed either side of the sample. One of the detectors is rotated about the sample, in order to measure the coincidence rate between the two
detectors as a function of \( \theta \). In this way an angular correlation annihilation radiation spectrum is acquired. The angular deviation is given by,

\[
\frac{v}{c} = \sin \theta = \theta
\]  (1.4)

Another experimental technique originally developed by Shearer and Deutsch\(^{19}\) permits the study of positron lifetimes in matter by detecting the 1.28MeV photon which accompanies the emission of a \( \beta^+ \) particle from a \( ^{22}\)Na source. This provides a start pulse for a timing sequence which is subsequently stopped on detection of an annihilation photon at a second detector. Many measurements of this kind can be made to build up a lifetime spectrum providing a picture of the annihilation processes occurring in the sample. Over the years, much useful information has been gained from these three types of experiments and among their major achievements are the observation of Ps and the measurement of its lifetime.

1.3.2 The Development of Slow Positron Beams

The techniques described above are ultimately limited by the fact that no control over the impact energy of the incident positrons is possible. A significant advance in the field of experimental positron physics came with the development of tunable, nearly monoenergetic beams of low energy positrons. Such beams are produced by slowing down particles, from a radioactive source, or high energy positrons from pair production, to near thermal energies using a solid moderator. Figure 1.1 shows the energy distribution of \( \beta^+ \) emitted by a \(^{58}\)Co source compared to that of a slow positron beam emerging from a W(110) moderator. The flux of quasi-monoenergetic positrons obtained in the moderation process is several orders of magnitude greater than that which could be attained by velocity selection.

The possibility that positrons with near thermal energies could be obtained by implanting particles from a radioactive source into a solid was first suggested by Madansky and Rasetti\(^{20}\). They estimated that the efficiency of such a moderator would be determined by the ratio between the positron diffusion length and the mean implantation depth of the incident \( \beta^+ \) particles. This they calculated to be of the order of \( 10^{-3} \) for the samples (eg. Pt, glass, mica, etc.) used in their experiment. Unfortunately, Madansky and Rasetti\(^{20}\) were unable to detect any low energy positrons, probably due to the low sensitivity of their
apparatus and defects in their samples.

Figure 1.1: The energy distribution for $\beta^+$ emerging from a $^{58}$Co source compared to that for positrons emitted by a W(110) moderator (Schultz and Lynn$^{21}$).

The first observation of energy-moderated positrons was made by Cherry$^{22}$ using Cr plated mica. The positrons were found to be emitted with energies of less than 10eV when irradiated with $\beta^+$ particles from a $^{64}$Cu source. The ratio between the number of slow positrons to fast $\beta^+$ particles was found to be around $10^{-8}$. Madey$^{23}$ obtained a similar result using a polyethylene moderator and Groce et al$^{24}$ produced positrons of a few eV energy from a Au moderator. The latter work was refined by Costello et al$^{25}$ who measured the flight times of positrons moderated by a 200Å layer of Au deposited on Al, mica and CsBr substrates. Observing a slow positron energy distribution which peaked between 0.75 and 2.90eV, Costello et al$^{25}$ suggested that the kinetic energy of the moderated positrons was due to a negative positron work function for the Au surface, that is, the escape of a positron from within the bulk of the Au is an exothermic process.
A positron work function ($\Phi_+$) may be defined, in an analogous way to the electron work function ($\Phi_-$)\textsuperscript{26} as the minimum energy required to move a positron from a point well inside the surface to a point well outside. Tong\textsuperscript{27} defined $\Phi_+$ as

$$\Phi_+ = -\Delta \phi - \mu_+$$

(1.5)

where $\mu_+$ is the potential of a positron relative to the mean electrostatic potential in the metal interior and $\Delta \phi$ is the lowering in the electrostatic potential across the metal surface. Tong\textsuperscript{27} predicted negative values of $\Phi_+$ of a few electron–volts for Al, Mg, Cu and Au. The work function of Au has since been experimentally measured to be positive (Nieminen and Hodges\textsuperscript{28}, Lynn\textsuperscript{29}). The results of Costello \textit{et al.}\textsuperscript{25} may therefore be ascribed to epithermal positron emission or sample impurities causing $\Phi_+$ to become negative.

Considerable effort has been made to improve the understanding of the moderation process in solids\textsuperscript{30} and consequently increase the efficiency of positron moderators. Positrons with energies in the MeV range have implantation depths of a few microns\textsuperscript{31}. The ‘slowing down’ of positrons in a solid from MeV energies to thermalization occurs via several energy loss processes. Radiative slowing as a result of $\beta^+$–nucleus interaction is the dominant process at energies of a few MeV. At energies of several hundred keV energy loss by electron scattering starts to be important while bremsstrahlung becomes inefficient. Below 100 keV down to around 100 eV core and valence electron excitation are the major energy loss processes for implanted positrons and they take roughly $10^{-13}$ seconds to traverse this energy range (Nieminen and Olivia\textsuperscript{32}). Finally, thermalization is achieved via phonon excitation in the band gap. In the time the positron takes to thermalize it diffuses several hundred angstroms\textsuperscript{30} through the solid. Therefore, positrons impacting the surface with energies in the MeV range, will thermalize before reaching the surface. At the surface, slow positrons may either form Ps, become trapped in a surface state, be reflected into the interior of the solid or, if $\Phi_+$ is negative, be ejected into the vacuum. Improvements in moderator efficiencies were made by Murray and Mills\textsuperscript{33} using materials with larger negative $\Phi_+$ and by Dale \textit{et al.}\textsuperscript{34} who heat treated their samples first.
Another important consideration in enhancing the overall moderator efficiency is the geometry of the source/moderator arrangement. Several arrangements exist, and depending on the requirements of the experiment, some are better than others. For example, vane geometries can be carefully constructed to intercept most of the $\beta^+$ particles emitted in its direction. The flux of slow positrons is therefore maximized and the number of fast $\beta^+$ present in the beam reduced. The main disadvantage with this geometry is the difficulty of its manufacture. Grid moderators, on the other hand, are relatively easy to make but transmit more fast $\beta^+$ particles which either have to be filtered out or otherwise accounted for.

Moderator efficiency has recently been improved using materials with positive values of $\Phi_+$. Mills and Gullikson\textsuperscript{35} condensed Ne, Ar, Kr and Xe onto a cup type moderator and measured efficiencies as high as $7 \times 10^{-3}$. The high efficiency of Rare Gas Solid (RGS) moderators is attributed to their having a large band gap. Within the band gap the only means available to a positron to lose energy is via phonon excitation. Since the maximum energy for phonon excitation is small (83 meV for Ar\textsuperscript{36}) the diffusion length before thermalization is increased. Hence, a significant number may reach the surface with energies in excess of $\Phi_+$ and be re-emitted into the vacuum. Further improvements in the efficiencies of RGS moderators have been made by Merrison et al\textsuperscript{37}.

1.4 Positron-Atom (Molecule) Cross Sections

1.4.1 Total

The total cross-section, $\sigma_{\text{tot}}$, is the sum of all the partial cross-sections, $\sigma_i$, that is

$$\sigma_{\text{tot}} = \sum_i \sigma_i \quad (1.6)$$

where $i$ is an elastic (§1.4.2) or inelastic process (e.g. annihilation, $\sigma_{\text{ann}}$ (§1.2), excitation, $\sigma_{\text{exc}}$ (§1.4.3), positronium formation, $\sigma_{\text{Ps}}$ (§1.4.4.1) or direct ionization, $\sigma_{\text{i+}}$ (§1.4.4.2)).

The Beer–Lambert law expresses $\sigma_{\text{tot}}$ as
\[ \sigma_{\text{tot}} = \frac{1}{nl} \ln \frac{I_0}{I} \]  

(1.7)

where \( I \) and \( I_0 \) are the transmitted (unscattered) and incident beam fluxes respectively and \( n \) is the number density of the gas along an interaction region of length \( l \).

The first targets to be studied were the rare gases because they are gaseous and inert at room temperature. Figure 1.2 shows the results of several measurements (Stein et al. 38, Mizogawa et al. 39, Coleman et al. 40, Canter et al. 41 and Sinapius et al. 42) of \( \sigma_{\text{tot}} \) for He for incident energies up to about 30eV, along with a selection of theoretical data. The shape of \( \sigma_{\text{tot}} \) shows a minimum and sharp rise at impact energies 2 and 17.8eV, respectively. The minimum is due to the Ramsauer-Townsend effect, first observed for positron scattering by Stein et al. 38, and is caused by the near cancellation of the opposing static and polarization interactions. The sharp rise is due to the opening of the Ps formation channel and highlights the importance of this process in positron scattering at low energies. It should be noted that in the experiments discussed above positrons elastically scattered at small angles were indistinguishable from unscattered positrons. Thus, all the \( \sigma_{\text{tot}} \) measurements in the low energy elastic scattering region are artificially low. The shape of \( \sigma_{\text{tot}} \) for He is representative of that for all the inert gases.

The Ramsauer-Townsend minimum is also evident in all of the theoretical results shown in figure 1.2, although there are small discrepancies as to its magnitude and position. In particular, much consideration has been given to the low energy elastic region in determining the experimental underestimation of \( \sigma_{\text{tot}} \) due to small angle elastic scattering. Wadehra et al. 43 using the phase shifts of Humberston 44 (s wave), Humberston and Campeau 45 (p wave) and Drachman 46 (d wave) calculated that this underestimation to be about 7% at forward angles of <10°. Their calculations take account of this and are subsequently higher at the low energy elastic region than all of the experimental measurements. Also shown are the results of the polarized-orbital calculation by McEachran et al. 47 and the random-phase approximation calculation of Amusia et al. 48. The results of McEachran et al. 47 are significantly in excess of the experimental values at low energies, but fall below the measured values at higher energies, by around 11% at \( E_{\text{Ps}} \). The results of Amusia et al. 47 agree well with the experimental values at all energies studied.
including the low energy elastic region where the measurements are known to be inaccurate.

![Graph](image-url)

Figure 1.2: Measurements and calculations of the total positron scattering cross-section ($\sigma_{\text{tot}}$) for He.

At low energies the values of $\sigma_{\text{tot}}$ for electron scattering from the inert gases, except in the range of an electron Ramsauer-Townsend minimum, greatly exceed those for positron scattering. In the case of He, for which there is no electron Ramsauer-Townsend minimum, $\sigma_{\text{tot}}$ for electron scattering are higher than $\sigma_{\text{tot}}$ for positron scattering by up to two orders of magnitude at the positron Ramsauer-Townsend minimum. The positron and electron cross-sections are however found to merge at around 200 eV, an energy considerably lower than expected from theory. This is illustrated in figure 1.3, which shows the average values of $\sigma_{\text{tot}}$ for positron scattering (Stein et al 38, Kauppila et al 50) and electron scattering (Kauppila et al 50). The differences in the cross-sections at low energies are believed to be due to the static interaction being attractive for electrons but repulsive for positrons. The polarization interaction is, on the other hand, attractive for both projectiles. Thus, at low energies, there is an addition of the two interactions in the case of electron scattering, and a cancellation for positron scattering, resulting in larger values of $\sigma_{\text{tot}}$ for electron scattering. In addition, the electron scattering total cross-section is further augmented by the exchange interaction. As the energy of the projectile is increased, the target polarization interaction reduces, and eventually becomes negligible in comparison
with the static interaction, which has the same magnitude for both projectiles. This causes the two cross-sections to merge at high energies.

Figure 1.3: $\sigma_{\text{tot}}$ in He for positrons (Stein et al. 38, Kauppila et al. 50) and electrons.

Unlike the room temperature gases, a different behaviour for $\sigma_{\text{tot}}$ is observed using alkali atoms and atomic H. Stein et al. 51 measured the first total scattering cross-sections for electron and positron impact on K in the energy range 5-49eV and found them to be the same to within about 25%. Subsequent studies have extended this energy range to 1-102eV for K, Na and Rb targets and found $\sigma_{\text{tot}}$ to merge with the corresponding electron cross-section for energies greater than only 40eV. It was suggested that the similarity of the electron and positron cross-sections is a result of the high polarizability of the alkali atoms and the consequent dominance of the polarization interaction over the static interaction.

In addition, the $\sigma_{\text{tot}}$ measurements for positron scattering from K and Rb by Parikh et al. 53 showed a broad maxima at around 6eV. Parikh et al. 53 pointed out that this structure might be artificial in origin, perhaps a result of incomplete discrimination against small angle elastic scattering. However, the 5-state close-coupling calculations by Ward et al. 55 and McEachran et al. 56, which take these considerations into account, predict that instead of
peaking at 6eV, \( \sigma_{\text{tot}} \) continues to rise as the positron energy decreases. Parikh et al.\(^{53} \) therefore conclude that the observed structure is not wholly attributable to systematic effects and suggest that it might be evidence of coupling effects between the Ps formation channel, which is open for all positron incident energies, and the elastic and excitation channels below 10eV. The results exhibit good agreement with the close coupling approximation (CCA) calculations of Hewitt et al.\(^{57} \) which take such channel coupling into account and with the coupled state approximation calculations of Kernoghan et al.\(^{58} \).

### 1.4.2 Elastic Scattering

In most positron–atom collisions, the total (angle-integrated) elastic cross-section (\( \sigma_{\text{el}} \)) is, neglecting annihilation, equal to \( \sigma_{\text{tot}} \) below the Ps formation threshold (\( E_{\text{Ps}} \)). Recently, the behaviour of \( \sigma_{\text{el}} \) at energies around \( E_{\text{Ps}} \) has been of interest after Brown and Humberston\(^{59} \) predicted a sudden change of slope in \( \sigma_{\text{el}} \), resulting in a threshold anomaly (cusp or rounded step), in this region. Threshold anomalies, first described by Wigner\(^{60} \) in 1948, are accounted for by flux conservation considerations since the introduction of a new channel which competes strongly with the existing one may influence the energy dependence of the latter. The positronium formation channel is one such process which is expected to cause \( \sigma_{\text{el}} \) to decrease at \( E_{\text{Ps}} \). Since \( \sigma_{\text{el}} \) increases at energies up to \( E_{\text{Ps}} \) a cusp structure centred at this energy is predicted.

Evidence of a threshold anomaly in \( \sigma_{\text{el}} \) at \( E_{\text{Ps}} \) was obtained by Campeanu et al.\(^{61} \) and Kauppila and Stein\(^{62} \) who deduced \( \sigma_{\text{el}} \) by subtracting \( \sigma_{\text{Ps}} \) from \( \sigma_{\text{tot}} \). Discontinuities in the slope of \( \sigma_{\text{el}} \) for the noble gases and \( \text{H}_2 \) were observed, for example the results for He are shown in figure 1.4. Charlton\(^{63} \) rightly cast doubts about the existence of a cusp structure in \( \sigma_{\text{el}} \) of the size shown in figure 1.4 and Campeanu et al.\(^{61} \) themselves regarded the evidence as preliminary since the cross-sections used in the analysis were obtained by different groups under different experimental conditions and the inferred threshold effects could have been exaggerated by differences in the beam energy determination and the absolute values of the cross-sections.

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These problems were circumvented by Coleman et al.\textsuperscript{64} who measured \(\sigma_{\text{tot}}\) and \(\sigma_{\text{Ps}}\) for He by using the same apparatus. At energies below the first excitation threshold (\(E_{\text{exc}}\)) the difference \((\sigma_{\text{tot}}-\sigma_{\text{Ps}})\) was equal to \(\sigma_{\text{el}}\). The results, which were normalized to \(\sigma_{\text{tot}}\) (Stein et al.\textsuperscript{38}) below \(E_{\text{Ps}}\), are displayed in figure 1.5. Within the statistical errors, \(\sigma_{\text{el}}\) is flat across the Ps formation threshold suggesting that if a cusp is present, it is not as pronounced as that deduced by Campeanu et al.\textsuperscript{61}.

Figure 1.5: circles, \((\sigma_{\text{el}}+\sigma_{\text{exc}}+\sigma_{i}^{-})\) from Coleman et al.\textsuperscript{64}; solid line, \(\sigma_{\text{tot}}\) from Stein et al.\textsuperscript{38}; dashed line, \(\sigma_{\text{el}}+\sigma_{\text{exc}}\) from Campeanu et al.\textsuperscript{61}. 

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Moxom et al. recently reported new values of $\sigma_{el}$ for He, H$_2$ and Ar. Measuring the yield of ions created in a combined scattering cell/ion extractor by impact of a gated positron beam of 0.8eV energy resolution, Moxom et al. were able to make detailed measurements of the total ionization cross-section ($\sigma_{i}^{+}+\sigma_{Ps}$) in the vicinity of the Ps formation threshold. Subtracting the ($\sigma_{i}^{+}+\sigma_{Ps}$) results from existing $\sigma_{tot}$ data (Kauppila et al., Stein et al., Hoffman et al., Charlton et al. and Mizogawa et al.), Moxom et al. deduced ($\sigma_{el}+\sigma_{exc}$). In accord with the findings of Coleman et al., cusps of the size predicted by Campeanu et al. were not present in the deduced values of $\sigma_{el}$ for He, H$_2$ and Ar. However, careful analysis of the results did reveal significant drops in $\sigma_{el}$ between $E_{Ps}$ and $E_{exc}$. Moxom et al. have extended this investigation to the remaining inert gases and their results combined with the earlier studies suggest that there is a small threshold effect caused by coupling between the Ps formation and elastic scattering channels but not of the magnitude expected by Campeanu et al. Clear evidence of channel coupling was observed in the O$_2$ study of Laricchia et al. between the cross-sections for total ionization and excitation to the Schumann–Runge continuum.

Recently, there have been several attempts, using various methods, to measure the differential elastic scattering cross-section, $d\sigma_{el}/d\Omega$. The Detroit and Bielefeld groups, who employed a crossed positron-beam gas-beam geometry, have made extensive measurements of $d\sigma_{el}/d\Omega$ for the noble gases. This and other similar work is discussed fully in Chapter 3.

### 1.4.3 Excitation

The first inelastic positron scattering cross-section to be studied experimentally was that of excitation ($\sigma_{exc}$). Using a TOF technique Coleman and Hutton and Coleman et al. measured $\sigma_{exc}$ for He for energies up to 10eV above $E_{exc}$ (at 20.6eV). The TOF spectra contained a peak corresponding to positron scattering at small angles with an energy loss of 20.6eV, attributed to the $1^{1}S-2^{1}S$ transition. From this, the values for $\sigma_{exc}$ for the $1^{1}S-2^{1}S$ transition were obtained. In a later refinement of this method, in which an additional retarding element was used to separate excitation and ionization events, Sueoka and
Mori and Sueoka\textsuperscript{77} were able to extend the range of impact energies up to 120eV. These new measurements were thought to comprise the 1\textsuperscript{1}S–2\textsuperscript{1}S and 1\textsuperscript{1}S–2\textsuperscript{1}P transitions at least, and are shown along with those of Coleman \textit{et al.} \textsuperscript{74} and several theoretical calculations\textsuperscript{78,79,80} in figure 1.6.

![Cross-section (\(\sigma_{exc}\)) for positron impact excitation of He.](image)

**Figure 1.6**: Cross-section (\(\sigma_{exc}\)) for positron impact excitation of He.

### 1.4.4 Ionization

In the case of positron scattering, two ionization processes are possible. One is impact ionization (cross-section \(\sigma_{i^+}\), threshold energy, \(E_{i}\)),

\[
e^+ + X \rightarrow X^+ + e^+ + e^- \tag{1.7}
\]

which is analogous to electron impact ionization (\(\sigma_{i^-}\)). The other one is Ps formation (\(\sigma_{Ps}\), \(E_{Ps} = E_i - 6.8\text{eV}\)),

\[
e^+ + X \rightarrow X^+ + Ps \tag{1.8}
\]

which is followed by Ps decay by 2 or 3\(\gamma\) emission.
1.4.4.1 Positronium formation

The first direct measurements of the absolute, angle-integrated ($\sigma_{\text{Ps}}$) cross-section for Ps formation were obtained by Charlton et al. Measurements of $\sigma_{\text{Ps}}$ were made by counting $3\gamma$ coincidences of the annihilation of $\sigma$-Ps. However, the results were subsequently shown to have serious systematic errors (e.g., the loss of $\sigma$-Ps to the walls of the scattering cell) and were up to a factor of five smaller than values of $\sigma_{\text{Ps}}$ obtained in other experiments. For example, Fornari et al. and Diana et al. derived $\sigma_{\text{Ps}}$ for the inert gases by measuring the fraction of incident positrons that were lost from a beam during its transmission through a scattering cell and attributing this to Ps formation. Another technique, developed by Fromme et al., involved the simultaneous measurements of the total ion yield and of positron–ion coincidences. The data of Fromme et al. for He is shown in figure 1.7. The results from this experiment find good agreement with those of Fornari et al. and Diana et al. below about 80eV. At higher energies the structure observed by Diana et al. has not been reproduced by Fromme et al., but otherwise agreement between these experiments is good.

![Figure 1.7: Cross-section for Ps formation from He.](image-url)
The results of several $\sigma_{ps}$ calculations\textsuperscript{80,89,90} are also plotted in figure 1.7. Both theory and experiment exhibit a broadly similar energy dependence, that is, $\sigma_{ps}$ increases rapidly from $E_{ps}$ before peaking and falling as a function of $E^{-\alpha}$. However, whereas the measurements discussed above are consistent with $1<\alpha<1.5$, theory predicts $3<\alpha<5$. Schultz et al\textsuperscript{91} have suggested that the discrepancy, common to both experimental techniques, is due to the inefficient collection of positrons scattered to large angles following ionization. Recently Overton et al\textsuperscript{92} made measurements of $\sigma_{ps}$ for He using a cell transmission method. The guiding magnetic field was set to ensure radial confinement of all scattered positrons and this field was retuned at each energy studied to eliminate the effects of energy dependent beam deflections. The results, which are shown in figure 1.7, were found to be in much better agreement with the predicted energy dependencies at higher energies.

The only measurements of $\sigma_{ps}$ for atomic hydrogen (H) are those by Sperber et al\textsuperscript{93} and Weber et al\textsuperscript{94}. A positron beam was crossed with a target beam consisting of H and H\textsubscript{2} emerging from a Slevin–type rf discharge tube\textsuperscript{95}. Scattered positrons were transported electrostatically to the positron detector and a DC electric field deflected ions into a quadrupole mass analyzer (QMA), which distinguished between H\textsuperscript{+} and H\textsubscript{2}\textsuperscript{+}. As in the experiments of Fromme et al\textsuperscript{88}, the total ion (H\textsuperscript{+}) yield and positron–ion coincidences were monitored, thus providing relative measurements of $(\sigma_{i^+}+\sigma_{ps})$ and $\sigma_{i^+}$ respectively. Relative values of $\sigma_{ps}$ were obtained by subtraction and absolute cross–sections were attained by normalization to earlier measurements of electron and positron impact ionization cross–sections\textsuperscript{96,97}. Finally, corrections were applied to the data to account for large–angle positron scattering following ionization. Shown in figure 1.8 are the results of Weber et al\textsuperscript{94} where they are compared with theory. The first Born approximation calculations of Massey and Mohr\textsuperscript{98} and the Fock–Tani calculations of Straton\textsuperscript{99} predict cross–sections which peak at an energy 5eV lower than the measurements and with magnitudes greater by about 35% and 50% respectively. The close–coupling method of Hewitt et al\textsuperscript{100} reproduces the observed cross–sections well at most energies studied. The polarized orbital approach of Khan and Ghosh\textsuperscript{101} underestimates the cross–section for incident energies in the range 20–60eV. The accurate Kohn variational calculations of Brown and Humberston\textsuperscript{102} are restricted to incident energies lower than those studied experimentally, but Weber et al\textsuperscript{94} note that the extrapolation of these predictions to higher energies does not.
appear inconsistent with the size and energy location of the observed maximum in $\sigma_{Ps}$.

![Figure 1.8: Positronium formation cross-sections for atomic hydrogen.](image)

1.4.4.2 Direct Ionization

The retarding potential TOF technique employed by Sueoka\textsuperscript{75} to measure $\alpha_{exc}$ has also yielded measurements of the direct single ionization cross-section, $\sigma_{i^+}$, for He, Ne and Ar targets up to about 120eV incident energy. They obtained values of $\sigma_{i^+}$ that were lower than the corresponding electron results, a finding that has not been corroborated by subsequent measurements, discussed below, including those of Sueoka\textsuperscript{76} and Mori and Sueoka\textsuperscript{77}.

As mentioned in §1.4.4.1, Fromme \textit{et al}.\textsuperscript{88} made relative measurements of $\sigma_{i^+}$ as well as $\sigma_{Ps}$ for He and H\textsubscript{2}. More recently, Knudsen \textit{et al}.\textsuperscript{103} measured $\sigma_{i^+}$ for He, Ne, Ar and H\textsubscript{2} targets. In this experiment, a positron beam was magnetically guided through a target chamber from which ions could be extracted and detected. The ion extractor was pulsed for short periods, by signals from the positron detector, thus preventing deflection of the positrons by the electric field. The measured positron-ion coincidences contained a background contribution due to random coincidences. This random coincidence
background was estimated by comparing the measured coincidence rate in the energy range $E_{p}\leq E<E_1$ to available $\sigma_p$ data and was subsequently subtracted from the signal. Jacobsen et al.\textsuperscript{104,105} later improved this technique by measuring the positron–ion coincidences as a function of the ion-extractor pulsing frequency. The random coincidence background discussed above is proportional to this frequency and so by extrapolating the observed ion yield back to zero pulse frequency, Jacobsen et al.\textsuperscript{104,105} were able to account for this background. The results of Jacobsen et al.\textsuperscript{104,105} were found to be smaller than those of Knudsen et al.\textsuperscript{103} below 60eV incident energy for He and approximately 100–200eV for H$_2$, Ne and Ar. These discrepancies have been attributed to inaccurate background corrections in the latter work. Recently, Ashley et al.\textsuperscript{106} modified the technique of Knudsen et al.\textsuperscript{103} to allow more accurate measurement at lower beam energies. The accurate measurement of the beam energy is crucial in the measurement of $\sigma_i^+$ near $E_1^+$. Ashley et al.\textsuperscript{106} measured $\sigma_i^+$ from near $E_1^+$ up to 1keV incident positron energy for He and H$_2$ and are the best available measurement of $\sigma_i^+$ near $E_1^+$.

The various measurements of $\sigma_i^+$ for He are shown in figure 1.9. All experiments are in good accord for most of the impact energies studied. The largest discrepancies are around the maximum in $\sigma_i^+$, with the cross-sections measured by Jacobsen et al.\textsuperscript{105} and Ashley et al.\textsuperscript{106} greater than that observed by Fromme et al.\textsuperscript{88} by about 10%.

![Figure 1.9: Single direct ionization cross-section for He by positron and electron impact.](image)

Figure 1.9: Single direct ionization cross-section for He by positron and electron impact.
The results of several calculations of \( \sigma_i^+ \) are also plotted in figure 1.9. The classical trajectory Monte Carlo calculations of Schultz and Olson\(^{107} \) are in reasonable agreement with the data of Ashley \( et \) \( al \)\(^{106} \) below about 100eV impact energy, but fall more rapidly than the observed cross-section at higher energies. For energies in the range 40–700eV, good agreement is found between the present results and the cross-sections calculated by Ratnavelu\(^{108} \) according to a continuum optical potential model. The coupled-state calculations of Chen and Msezane\(^{109} \) are approximately 10% higher than the calculations of Campeanu \( et \) \( al \)\(^{110,111} \), which agrees well with the experimental data. The latter accounts for the distortion and screening effects in the initial and final channels. The He data was normalized by fitting it, over 600–1000eV, to the electron impact ionization cross-sections measured by Shah \( et \) \( al \)\(^{112} \). At intermediate energies, the electron cross-section are 30–40% lower than those for positrons. This difference might be due to electron exchange occurring between the impacting and ejected electron. Alternatively, it could be due to kinematic differences. At low velocities, positron impact ionization occurs predominantly via Ps formation (§1.4.4.1); as the positron velocity is increased, capture becomes more unfavourable since the positron and electron speeds are very different. In this case the positron charge may serve to enhance the probability of ionization over that for electron impact since the escaping positron effectively drags the ionized electron away from the remnant positive ion. The effect of this type of interaction has been described by Olson and Gay\(^{113} \) and Gay and Olson\(^{114} \).

Measurements of \( \sigma_i^+ \) were first extended to atomic hydrogen by Spicher \( et \) \( al \)\(^{96} \) using the apparatus later employed by Sperber \( et \) \( al \)\(^{93} \) to measure \( \sigma_{Ps} \). As discussed above, relative values of \( (\sigma_i^+ + \sigma_{Ps}) \) and \( \sigma_i^+ \) were deduced from measurements of the total ion yield and positron–ion coincidences and normalized to the electron impact data of Shah \( et \) \( al \)\(^{115} \). Weber \( et \) \( al \)\(^{94} \) later re-examined the data of Spicher \( et \) \( al \)\(^{96} \) using a more elaborate analysis and found the cross section to be smaller than originally published. Jones \( et \) \( al \)\(^{116} \) have also measured \( \sigma_i^+ \) for H. In contrast to Spicher \( et \) \( al \)\(^{96} \), however, a magnetic field was used to confine the scattered positrons, ensuring that the majority were detected. The results of Weber \( et \) \( al \)\(^{95} \), Jones \( et \) \( al \)\(^{116} \) and a selection of the available theoretical results are shown in figure 1.10. The cross sections measured by Jones \( et \) \( al \)\(^{116} \) are, on average, about 30% smaller than those determined by Weber \( et \) \( al \)\(^{95} \); the cause of this discrepancy is not yet known. However, the majority of theoretical predictions support the results of Jones \( et \) \( al \)\(^{116} \), these include the classical trajectory Monte Carlo calculations of Ohsaki \( et \) \( al \)\(^{117} \), the
Optical Method of Ratnavelu\textsuperscript{108}, the distorted-wave Polarized Orbital approximation calculations of Ghosh \textit{et al.}\textsuperscript{118} and Mukherjee \textit{et al.}\textsuperscript{119} and the Close-Coupling approach of Mitroy\textsuperscript{120}.

![Graphical representation](image)

Figure 1.10: Experimental and theoretical predictions for $\sigma_1^+$ of atomic hydrogen.

1.4.5 Differential Cross-Sections

Differential cross-section measurements\textsuperscript{121} provide a more stringent test of theory than their counterpart integral cross-section measurements. The more differential in angle and energy the measurement is, the more detailed information can be obtained about the nature of the process and the fewer uncertainties arise in the description of the collision. The most complete account of an ionizing collision is given by the triple differential cross section (TDCS). The TDCS is a function of the impact energy, $E_0$, the energy of the scattered particle, $E_a$, and the scattering angles ($\theta_a$, $\theta_b$, $\phi_a$ and $\phi_b$) of the two emerging particles denoted by subscripts $a$ and $b$. Consequently, the TDCS, $d^3\sigma/dE_a d\Omega_a d\Omega_b$, contains the most information about the collision process. Simpler but less informative are double differential cross-sections (DDCS) which involve measuring the entire kinematics of just one of the out-going particles. For example, $d^2\sigma/dE_a d\Omega_a$ would involve the measurement of: $E_0$, $E_a$, $\theta_a$ and $\phi_a$. Simpler still are single differential cross-sections (SDCS) because they only require measuring either the energy or solid angle of just one of the out-going particles.
particles. For example, \( \frac{d\sigma}{dE_a} \) and \( \frac{d\sigma}{d\Omega_a} \) are the SDCS with respect to the energy and solid angle of the out-going particle \( a \), respectively. The double and single differential cross-section examples used above can also be written in terms of the out-going particle \( b \).

For decades triple and double differential measurements have been commonplace in electron collision experiments. TDCS measurements using heavy incident particles such as protons are more difficult due to the fact that the scattering angle is small, usually a few mrad, at typical collision speeds. There are, however, many DDCS results for ion-atom collisions. Unfortunately, only a small number of differential measurements using positrons have been performed due to the serious intensity limitation of positron beams. Because of the low intensity, target atoms with large cross-sections, such as argon, tend to be used.

The few DDCS studies of positron-argon collisions which exist have been searching for evidence of Electron Capture to the Continuum (ECC). ECC is a special case of impact ionization where the ejected electron and scattered projectile emerge with closely matched velocities, such that the electron may be considered to have been transferred to a continuum state of the scattered projectile. The DDCS is expected to show an enhancement in the energy spectrum where ECC occurs. ECC is due to the post-collision interaction between the charged fragments and has been observed in heavy-ion impact studies\(^{122,123,124}\). So far ECC has not been observed in the equivalent positron impact studies\(^{66,125}\), despite the many theoretical calculations predicting the contrary\(^{126,127,128}\). ECC is discussed in further detail in chapter 4.

1.5 The aims and motivation of the present work

The main motivation of the present work was to add to the small total of positron differential cross-sections measurements that presently exist.

In chapter 3 the energy dependencies of the differential cross sections for elastic scattering, positronium formation and direct single ionization in positron-argon collisions at 60° and 30° (not elastic scattering) have been measured in the energy range 40–150eV. Of particular interest was the energy range 55–60eV where some studies have reported a drop in the elastic scattering cross section by a factor of two\(^{129}\). This was tentatively attributed to a cross-channel coupling effect with an open inelastic scattering channel. The motivation for the experimental study was to attempt to elucidate the origins of this and other reported structures\(^{130,131}\) by making corresponding measurements of the direct single ionization
SDCS and the positronium formation DCS.

In chapter 4 DDCS measurements have been performed at 30° for 100 and 60eV impact energies to investigate the ECC process. Our measurements showed no evidence of ECC. In addition, the energy spectrum of the scattered positron agrees well with the Classical Trajectory Monte-Carlo calculations of Sparrow and Olson\textsuperscript{132} at low energies. At high energies, however, these calculations exceed the present experimental results. A similar discrepancy was observed in the equivalent measurements of Kővér \textit{et al} \textsuperscript{133}. A possible explanation is offered as to the origin of this discrepancy.
2. Oppenheimer J R Phys. Rev. 35 (1930) 939
3. Anderson C D Science 76 (1932) 238
5. Anderson C D Phys. Rev. 43 (1933) 491
7. Mohorovicic S Astron Nachr 235 (1934) 94
8. Ruark A E Phys. Rev. 68 (1945) 278
9. Deutsch M Phys. Rev. 82 (1951) 455


29. Lynn K G unpublished, from Schultz and Lynn 1988


44. Humberston J W 1979 in "Advances in Atomic and Molecular Physics" eds D R Bates and B Bederson (New York: Academic) 101


Rev. Lett. 55 (1985) 488


60. Wigner E P Phys. Rev. 73 (1948) 1002


63. Charlton M Physica Scripta 42 (1990) 164


38


90. McAlinden M T and Walters H R J Hyp. Int. 73 (1992) 65


131. Dou L, Kauppila W E, Kwan C K and Stein T S 1993 Abstracts of the 18th International Conference on the Physics of Electronic and Atomic Collisions vol 2 (Aarhus, Denmark) 413


Chapter 2

The Experimental Apparatus

2.1 The General Layout of the Apparatus

The general layout of the apparatus which will be described in this chapter was developed by Kövér et al. 1, at University College London. The positron beam used throughout this work was obtained by the moderation of $\beta^+$ particles emitted from commercially obtained radioisotopes. These fast positrons were moderated in energy using annealed W meshes and then formed into a beam using electrostatic optics. The positron beam was guided along an evacuated beamline to the interaction region using a series of electrostatic lenses. At the interaction region the positron beam was perpendicularly intersected by an atomic beam. The beamline was terminated by a charged particle detector.

For the measurement of SDCS a Retarding Field Analyzer (RFA) was used. The energy dependencies of the SDCS for elastic scattering, positronium formation and direct single ionization in positron–argon collisions at 30° and 60° were measured in the energy range 40–150eV and will be discussed in chapter 3. For the measurement of DDCS a Parallel-Plate-Analyzer (PPA) was used instead of the RFA. This modification helped lower the background count measurement and improved the angular resolution of the system. DDCS measurements were performed at 30° for 100 and 60eV impact energies on an argon gas target to investigate the phenomena known as ECC. These DDCS measurements and other associated modifications to the RFA system, are discussed in chapter 4.

The parts of the apparatus that were common to both types of experiment are discussed in this chapter and include the vacuum system (§2.2), the source and moderator assembly (§2.3), the beam transport (§2.4), the gas inlet geometry (§2.5), ion extractor (§2.6) and primary beam detector (§2.7).
2.2 The Vacuum System

The vacuum system is shown schematically in figure 2.1. The cylindrical interaction chamber was approximately 365mm in diameter and 450mm high, constructed from type EN58J stainless steel and access to the chamber was achieved by the removal of a single top flange. Spaced equally around the side wall of the chamber were four ports, as shown in the figure. All electrical feedthroughs, with the exception of the chopper and extraction plates (port 3), were made through port 2. The source and electrostatic lenses, used in transporting the beam (§2.4), were housed in port 1 and port 4 was surplus to requirements. An Edwards water cooled 250/2000C diffstak, backed by an Edwards ED250 rotary pump, was used to evacuate the chamber through an 160mm diameter port on the bottom flange.

The experiment was protected by a series of electrical trips. If the mains power supply or the flow of cooling water was interrupted then the experiment was shut down and required a manual restart when the supplies were resumed. If the backing line pressure, measured by a Pirani gauge P1 (figure 2.1), exceeded 0.1Torr, the power supply to the diffusion pump was cut and the magnetic valve was shut. This protected the diffusion pump from contamination by rotary pump oil which might be sucked into the high vacuum region.

All components were made from non–magnetic materials and attenuation of the contribution from the Earth’s magnetic field and other strong fields was achieved by lining the inside of the vacuum system with 1.6mm thick mu-metal. The residual field when measured with a Bell 120 gaussmeter was found to be less than 3mG throughout the system except at two connecting sections of mu–metal shielding where it was measured to be 0.1G. These two connecting sections were between the Soa gun and transport lens and the exit lens and the interaction chamber.

In order to provide a smooth level surface on which the components of the experiment could stand, a stainless steel baseplate was fixed to the bottom of the vacuum chamber.
Side Port 1
Source and Electrostatic Lenses

Side Port 2
Interaction Chamber

Side Port 3
Extractor and chopper feedthroughs

Diffusion Pump

Valve

Foreline Trap

Magnets Valve

Rotary Pump

Side Port 4

Side Port 1

Side Port 3

Figure 2.1 A schematic diagram of the vacuum system
a) Side View and b) Plan.
2.3 The $\beta^+$ Source and Moderator

The radioisotope used as the positron source in this work was $^{58}\text{Co}$. The decay scheme and branching ratio for $\beta^+$ and electron capture for this isotope is shown in figure 2.2.

Two $^{58}\text{Co}$ sources of initial activities 5.2GBq and 4.2GBq were used during the course of the experiments described below. The $^{58}\text{Co}$ source was electroplated onto a small area in the centre of a rhodium foil and was supplied in this form by Dupont Ltd. The $^{58}\text{Co}$ source was retained underneath a 0.5mm thick brass cap with a 8mm hole in its centre. This cap, shown in figure 2.3, was then placed onto the moderator but separated by a PTFE washer with an internal diameter of 6mm. The moderator consisted of four superimposed 15mm square annealed pieces of 90% transmission W mesh which were held in place by two brass washers, also with internal diameter 6mm; again see figure 2.3. The brass washers holding the moderator were isolated by a PTFE washer from a second pair of brass washers which held another 90% transmission W mesh, labelled E1 in figure 2.3, which was used for focusing.

Figure 2.2: The decay scheme and branching ratio of $^{58}\text{Co}$.
The annealing process, described in detail by Zafar et al., was carried out in a W oven formed by two strips of W foil, between which the moderator meshes were placed. The oven was heated by passing a current through the foils. The annealing cycle consisted of repeatedly raising the moderator temperature to around 2000°C for a few seconds, in a pressure of less than 0.1 Torr. The heating process was initially accompanied by an increase in the pressure in the vacuum chamber, caused by emission of surface contaminants from the moderator and oven. The annealing cycle was repeated for up to several hours, and was continued until the oven could be raised to this temperature without causing the pressure in the vacuum to rise appreciably.

The moderator was set at a positive potential $V_{\text{mod}}$ relative to ground so that positrons which were re-emitted from its surface were accelerated in the forward direction. These slow positrons had kinetic energies $E_0$ given by

$$E_0 = eV_{\text{mod}} + \Delta E_{\text{mod}}$$  \hspace{1cm} (2.1)

where $\Delta E_{\text{mod}}$ is the kinetic energy with which a positron leaves the moderator. As
mentioned in chapter 1, most of these positrons thermalize before being re-emitted, and since a positron may scatter from contaminants on the moderator surface, $\Delta E_{\text{mod}}$ can have any value between zero and $|\Phi_+|$, where $\Phi_+$ is the negative positron work function of the moderator surface. To maximize the yield of slow positrons the source and brass plug were biased to a slightly higher positive potential than the moderator, causing some of the backward emitted positrons to return through the moderator.

2.4 The Beam Transport

There are several electrode arrangements which can provide the electrostatic fields necessary to focus a beam of positrons and the most widely used have been described by Harting and Read\textsuperscript{4}. The two types of lenses employed in this work are shown in figure 2.4. Figure 2.4a shows a double element cylindrical lens. The two lenses are separated by a gap, $G$, and share a common diameter, $D$. The focusing properties of a double element cylindrical lens is dependent on the voltage ratio, $V_2/V_1$. Figure 2.4b shows a triple element cylindrical lens which is defined by the ratios $G/D$ and $A/D$, where $A$ is the distance separating the mid-points of the spaces between the two outer and inner elements ($G$ and $D$ are as above). The focusing properties of a triple element cylindrical lens depend on the two voltage ratios $V_2/V_1$ and $V_3/V_1$.

Figure 2.4: Two (a) and three (b) element cylindrical lenses. The reference planes of each are shown as a dashed vertical line.
Shown schematically in figure 2.5 is the three electrostatic lens and deflector arrangement which was used in this work. In the following sections the design and operational characteristics of this lens systems will be described in detail.

Figure 2.5: Schematic representation of the electrostatic lens arrangement used for focusing and transporting the beam (scale only applies to the length of the lens elements).

2.4.1 The Modified Soa Gun

The purpose of the modified Soa gun was to focus the quasi-monoenergetic positrons, emitted from the moderator and accelerated by the grid, into a narrow beam. The lens system adopted is shown in figure 2.6 and consists of three cylindrical elements. The internal diameters of electrodes E1, E2 and E3 were 10, 19 and 35mm, respectively. Elements E1 and E2 were held at the same potential, whereas E3 was held at an independent potential. Electrodes E1 and E2 and E2 and E3 were separated by a distance of 2.5mm and 0.5mm, respectively. PTFE spacers were used to provide the necessary gaps and the elements were held in place using two M3 screws.
2.4.2 The Transport lens

The transport lens, shown in figure 2.7, consisted of three cylindrical elements (A/D=1.0, G/D=0.1, D=30mm). Electrodes E4 and E6 were held at ground potential. Two apertures, with internal diameter 6mm, were placed at either end of the transport lens to reduce the angular spread of the beam. The potential applied to electrode E5 varied according to the transport energy of the beam. Electrical contact between the electrodes was avoided using PTFE spacers and the elements were held in place using three M3 screws.
2.4.3 The Deflector

A deflector (double-cylindrical condenser), shown in figure 2.8, was used to separate the high energy \( \beta^+ \) particles and \( \gamma \)-radiation from the monoenergetic positron beam and prevent them from entering the interaction chamber. The deflector works, in the case of positrons, by applying the same negative potential to electrodes E7 and E8 sufficient to deflect the beam upwards by 20mm and then parallel to its original trajectory into the interaction region. The construction of the deflector was so designed that it only required eight M3 screws and the same number of PTFE washers to hold it together.

![Figure 2.8: Schematic of the deflector (dimensions are in mm).](image)

2.4.4 The Exit Lens

The exit lens, shown in figure 2.9, consisted of five elements and was held in place using three perspex rods and six M3 screws. Electrical contact between the electrodes was avoided using PTFE spacers. Electrodes E9, E11 and E13 were permanently grounded. The beam entered the exit lens through an aperture of internal diameter 6mm. The voltage applied to electrode E10 was +300V, which was pulsed on everytime a scattered positron was detected. The purpose of E10 was to prevent the positron beam from entering the interaction region whilst the ion extraction field was on. The beam would be stopped provided the potential of E10 exceeded the energy of the positron beam. This was always the case since the highest positron beam energy used throughout this work was 150eV. This process was known as ‘chopping’ the beam. With the beam chopped the ion extraction voltages were applied across the interaction region. The +300V was pulsed on
for 11μs, or less if an ion was detected. When E10 was not being used to chop the beam it was grounded.

The configuration of electrodes E11, E12 and E13 was used as a three element lens system (A/D=1.0, G/D=0.1, D=20mm) for final focusing of the beam before it entered the interaction region. To this end, the potential applied to E12 was varied depending on the energy of the beam.

2.4.5 The Performance of the Beam Transport System

The commercially available software package SIMION 4.0 was used to check the performance of the beam transport system. This software simulates the trajectories of charged particles in an electric field. Using SIMION 4.0 our system was modelled for various different potential settings. Shown in figure 2.10 is a typical computer simulation.

Figure 2.9: Schematic of the exit lens (dimensions are in mm).

Figure 2.10: Simulation of the positron trajectories through the electrostatic lens arrangement at a beam energy of 100eV.
The angular emission range with which positrons leave the surface of a moderator is wide. The desire is to focus as many of these emitted positrons into the interaction chamber as possible in order to preserve the beam intensity. Therefore, for a particular beam energy, the potentials to the electrodes were adjusted until the beam intensity was maximized, $I_{\text{max}}$. The potentials corresponding to $I_{\text{max}}$ were known as the optimum potential settings. In addition to finding the optimum potential settings the individual effect each electrode had upon the beam intensity was investigated. From the optimum settings, the potential to one of the electrodes was adjusted whilst keeping the others fixed and the corresponding reduced intensity recorded. This procedure was repeated for each of the electrodes, each time returning to the optimum settings before beginning the adjustment. Thus a series of potential settings and respective count rates were obtained. Using SIMION 4.0 the maximum emission angle, $\theta_{\text{max}}$, which could be focused by the transport system was determined for each set of potential settings.

<table>
<thead>
<tr>
<th>E1</th>
<th>E3</th>
<th>E5</th>
<th>E12</th>
<th>Rate</th>
<th>$\theta_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-44.1</td>
<td>-54.3</td>
<td>-199.6</td>
<td>-105.6</td>
<td>1596</td>
<td>17</td>
</tr>
<tr>
<td>-25.1</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>1364</td>
<td>16</td>
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<tr>
<td>-10.1</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>1134</td>
<td>16</td>
</tr>
<tr>
<td>-44.1</td>
<td>-48.3</td>
<td>&quot;</td>
<td>&quot;</td>
<td>1291</td>
<td>16</td>
</tr>
<tr>
<td>&quot;</td>
<td>-40.3</td>
<td>&quot;</td>
<td>&quot;</td>
<td>924</td>
<td>16</td>
</tr>
<tr>
<td>&quot;</td>
<td>-54.3</td>
<td>-179.6</td>
<td>&quot;</td>
<td>1461</td>
<td>19</td>
</tr>
<tr>
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<td>&quot;</td>
<td>-169.6</td>
<td>&quot;</td>
<td>1398</td>
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</tr>
<tr>
<td>&quot;</td>
<td>&quot;</td>
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<tr>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>-140.6</td>
<td>1068</td>
<td>13</td>
</tr>
</tbody>
</table>

Table 2.1: Shows how the count rate and largest emission angle to be focused, $\theta_{\text{max}}$, depend on the potential settings for a positron beam of 60eV.

This technique was applied to an arbitrarily chosen beam energy of 60eV and the results of the investigation are shown in Table 2.1. The results showed $\theta_{\text{max}}$ ranged between 13°-19°, but failed to show $I_{\text{max}}$ corresponding to the largest value of $\theta_{\text{max}}$. Instead $I_{\text{max}}$ corresponded to the second largest $\theta_{\text{max}}$ of 17°. Therefore the simulation was found to be in reasonable agreement to the empirical settings of the system. The technique was repeated using a beam energy of 100eV and again reasonable agreement was found between
simulation and experiment.

Note, the simulations described in Table 2.1 assumed that the positrons (each with an initial kinetic energy of 2.5eV) were emitted from the centre of the moderator between the angular range 0° to 90° in increments of 1°, where 0° is defined as the normal to the moderator surface.

<table>
<thead>
<tr>
<th>Start</th>
<th>Initial Energy (eV)</th>
<th>$\theta_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,0</td>
<td>0.5</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>21</td>
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<tr>
<td></td>
<td>2.0</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>16</td>
</tr>
<tr>
<td>0,±1</td>
<td>0.5</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>9</td>
</tr>
<tr>
<td>0,±2</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2.2: Shows how the starting position and energy of the positron affects the largest emission angle to be focused, $\theta_{\text{max}}$, for a positron beam of 60eV.

Shown in Table 2.2 are the results of an investigation using positrons of different starting positions and initial energies (0.5–3.0eV) and their effects on the value of $\theta_{\text{max}}$. Only one parameter was adjusted at a time whilst the other remained fixed and throughout this investigation the potential settings of the system used were the same for each simulation.
Using a coordinate system (0, y), where (0,0) and (0,±2) are the centre and edge of the moderator respectively, different starting positions of the positron were simulated. The results showed that less positrons emitted from the outer edges of the moderator were focused than from its centre. Furthermore, positrons of low initial energies were easier to focus than positrons with higher starting energies. From the data in Table 2.2 the emission cone of the moderator, for starting positions (0,0), (0,±1) and (0,±2) was estimated to be 0.53, 0.51 and 0 sr, respectively.

It should be mentioned, however, that the simulation excluded the deflector component because it could not be modelled with the other electrostatic optics due to limitations of the SIMION 4.0 software. Instead the deflector had to be simulated separately, but here again inadequacies of the software prevented an exact modelling of the curvature of the plates. Presented in figure 2.11 are the trajectories for twenty positrons, all starting from the centre of the entrance of the deflector plates, but emitted with an angular range of ±10°. All twenty positrons were successfully transported. In addition, simulations have been performed from different starting positions along the entrance. Those positrons which had starting positions near the outer edges of the plates failed to be successfully deflected. These unsuccessful positrons accounted for a 40% reduction in beam intensity. However, because the majority of positrons were focused to the centre of the entrance of the deflector plates by the transport lens, see figure 2.10, a 40% loss in flux was thought to be an overestimate.

Figure 2.11: Simulation of the positron trajectories through the deflection system at a beam energy of 100eV (E7=E8=-450V).
2.5 The Gas Inlet Geometry

The gas beam diffused from a multi-capillary array. Each capillary was 4mm in length with a pore diameter of 4µm. The array was inserted into the end of a 4mm wide gas nozzle. This nozzle was mounted at the centre of the interaction region, 5mm above the centre of the positron beam, and is shown schematically in figure 2.12. The gas arrived along 1/4" external diameter copper piping, interconnected with appropriate Swagelok fittings, and entered the interaction chamber through one of the mini-flanges on side port 2 (figure 2.1). A needle valve in the gas line allowed regulation of the target gas flow. The drive pressure was directly monitored using a Type 127 MKS Baratron heated capacitance manometer factory-calibrated to measure absolute pressures in the range 0–10Torr. Beyond the interaction region the gas beam was dumped into the diffusion pump. The pressure in the vacuum chamber measured at a point distant from the nozzle was found to be less than 10⁻⁵Torr during gas runs.

Figure 2.12: Schematic of the Gas Inlet Geometry (dimensions are in mm).

A crossed beam geometry was used, instead of a scattering cell, because it allowed access to the scattered particles. As in many positron crossed beam experiments, a multi-capillary array was used to provide a gas beam of sufficient width to overlap with the positron beam. In order to get adequate signal it was necessary to operate the multi-capillary array at high drive pressures, typically 10Torr. Under 'molecular' flow conditions, calculations have shown that a multi-capillary array produces a well defined gas beam⁶,⁷. Unfortunately, at the high pressures used in our work the flow is 'viscous' and very little is known theoretically about the shape of the beam. Despite this there is, however, experimental
evidence which suggests that the positron beam–gas beam overlap does not adversely affect the angular behaviour of the measured relative DCS.

Firstly, DDCS measurements made on this apparatus by Kövér et al\textsuperscript{1} using electrons agree well with the established electron data of Dubois and Rudd\textsuperscript{8}. A well defined electron beam was obtained using the secondary electron emission from the moderator. The polarities on all the electrodes in the system were reversed and the source and grid shorted to the moderator potential. Due to the same source/moderator geometry and beam defining apertures the electron beam was expected to have a similar profile to positrons.

Secondly, in this work (chapter 4), two sets of measurements of the same process were found to agree using two very different detection instruments, with different acceptance geometries, suggesting that the positron beam–gas beam overlap was sufficiently well localized.

Thirdly, except for elastic scattering, our data was measured using an ion coincidence technique. Here, only ions created within the boundaries of the ion extractor aperture were detected (next section) and this effectively fixed the gas beam geometry for this class of collisions.

2.6 The Extraction and Detection of Ions

The system used to extract and detect ions is depicted in figure 2.13. On receipt of a trigger signal from the positron detector a pulser circuit applies voltages of ±150V to two 30×50mm plates. The plates were placed 20mm apart and positioned either side of the interaction region. Cut into the negative extraction plate was a 10mm circular aperture. Similarly, cut into the positive extraction plate was a rectangular aperture (dimensions 10×20mm) to allow the scattered positrons (or positronium atoms) to be detected. Both apertures were covered with 95% transmission Cu mesh to help maintain the uniform electric field between the plates. The electric field deflected positive ions towards the negative electrode. Only ions created within the boundaries of the aperture were extracted. These ions were focused by a 20mm cylindrical lens, with internal diameter of 10mm, and then accelerated by a grid held at -3kV before striking a type Philips Photonics X919BL channel electron multiplier (CEM). The ion lens, accelerator and CEM were housed in a copper box mainly to shield the positron beam from the high voltages. The ion yield was measured as a function of drive pressure and was found to be linear across the range.
investigated (0–10 Torr).

Figure 2.13: Schematic of the extraction and ion detection system.

Shown in Figure 2.14 is the result of a computer simulation of the ion trajectories through the ion extraction and detection system. The figure shows the trajectories for singly ionized Ar atoms (Ar⁺). The ions started their trajectories with zero kinetic energy and from points spaced 1 mm apart along the central positron beamline. The simulation showed that ions created within the aperture of the negative extraction plate were successfully extracted from the interaction region and transported to the ion detector. Ion trajectories originating along other positron beamlines were also simulated. Again, those ions created within the line of sight of the ion extraction aperture were successfully extracted and detected. Ion flight times for Ar⁺ and Ar²⁺ were around 3.45 and 2.5 µsec, respectively and were sufficiently well time focused to distinguish between different ion states.

Figure 2.14: Simulation of the ion trajectories through the extraction and ion detection system.
2.7 The Primary Beam Detector

Detection of the positrons at the end of the beamline was achieved using a type X919BL CEM. Placed before the CEM was a 4-grid retarder arrangement. The first and third grids were set to ground potential with the retarding potential applied to the second. The fourth grid was connected to the cone of the CEM. The CEM and RFA holder is illustrated in figure 2.15. Approximately +200V and +3.5kV were applied to the cone and end of the CEM, respectively. The RFA signal was amplified and fed through a constant fraction discriminator whereby the beam intensity could be counted using a ratemeter. The ratemeter reading was monitored and used to find the maximum beam intensity as the electrostatic lens voltages were varied. The stability of the beam was checked by periodically measuring its intensity. Any sudden loss in flux was investigated. The detector was switched off during measurements to prevent the chance of electrical interference occurring between it and other electrostatic components in the system. The primary analyzer was also used to measure the energy width of the beam by ramping the potential applied to the RFA across the energy setting of the beam. The count rate was observed to drop rapidly to background levels a few eV beyond the energy setting. The energy width of our beam was measured to be ≈3eV. The primary beam detector was screwed onto the primary detector base depicted in figure 2.12.

![Figure 2.15: Schematic of the primary beam detector holder containing the RFA and CEM.](image)


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Chapter 3

Single Differential Cross-Sections

3.1 Introduction

The single differential cross-section, $\frac{d\sigma}{dE}$, for an ionization collision is a measure of the probability that, at a given impact energy, $E_0$, and ionization threshold energy, $E_{\text{ion}}$, a particle will be detected with energy, $E$, (between 0 and $E_0-E_{\text{ion}}$) irrespective of the angle at which it was scattered or emitted. Measuring this cross-section is equivalent to performing two integrations over the angles of the two emerging particles. Therefore the SDCS is

$$\frac{d\sigma}{dE} = f_1(E_0, E)$$

(3.1)

were $f_1$ is a function of $E_0$ and $E$. The form of the SDCS is shown in figure 3.1.

![Figure 3.1: Schematic representation of the energy-loss spectrum ($d\sigma/dE$) for electron impact integrated over all directions of motion of the postcollision electron (from McDaniel).](image)

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The energy distribution for ionization is symmetrical about the value \((E_0 - E_{\text{ion}})/2\), because the energy is shared between the scattered and ejected electron, that is

\[ E_{\text{proj}} + E_{\text{elec}} = E_0 - E_{\text{th}} \]  

(3.2)

were \(E_{\text{proj}}\) and \(E_{\text{elec}}\) are the energies of the scattered and ejected electron, respectively. In electron impact studies the faster of the two outgoing particles is generally acknowledged as the scattered projectile. This is because direct single ionization is characterized by large impact parameters and small momentum transfers with most of the projectiles scattered inelastically into a narrow cone around the beam direction (zero degrees). Of course, the scattered and ejected electrons in a given event are indistinguishable, but if \(E_0\) is large, the two groups of electrons are widely enough apart to lend validity to the description of them as being separable. The direct determination of \(d\sigma/dE\) is difficult, and this quantity is frequently obtained by integration of \(d^2\sigma/dE.d\Omega^3\). In positron impact studies the positive projectile and ejected electron are distinguishable, allowing the energies and scattering angles to be assigned to the correct outgoing particles. Hence, in positron impact studies there is no need for the high energy assumption as used in the corresponding electron impact ionization experiments. However, even SDCS measurements are difficult due to the serious intensity limitation of positron beams.

The first angular-resolved studies of positron scattering were concerned with the differential elastic scattering cross-section, \(d\sigma_{\text{el}}/d\Omega\), which extracted phase shift information from a transmission-type experiment. In the last two decades progress in positron beam technology, such as the development of positron sources with high intensities and well defined beam energies, and in associated experimental techniques, in particular the development of the crossed atom beam-positron beam technique by Hyder et al., has enabled improved investigations. There has recently been great interest in the energy-resolved elastic DCS for positron scattering from argon gas after Dou et al. found marked structure in the energy range 55-60eV. The reported structure is most pronounced at a scattering angle of 60°, where the DCS was observed to drop abruptly by a factor of two, but is also visible at 90° and 120° in the same energy region. Structures have also been reported by Dou et al. in corresponding elastic scattering studies for K and Ne at positron energies of 25 and 200eV and 100-200eV, respectively. All of these features were unexpected and rather puzzling as to their origin since they did not occur at impact energies close to any known inelastic threshold where resonances and channel-coupling effects are
often observed. Nevertheless, Dou et al. 8,9,10 tentatively suggested that they may have somehow arisen due to coupling between either the ionization or positronium formation and the elastic scattering channels.

The motivation for the present experimental study was to attempt to elucidate the origins of these reported structures by performing corresponding energy–resolved measurements of the direct single ionization \( \text{d} \sigma_{\text{ion}} / \text{d} \Omega \), the first of their kind, and positronium \( \text{d} \sigma_{\text{p}} / \text{d} \Omega \) DCS. Thus, argon gas at 60° was chosen as the starting point. In addition it was found that elastic scattering could be observed, and hence \( \text{d} \sigma_{\text{el}} / \text{d} \Omega \) deduced, and results are presented here for all three DCS in the energy range 40–150eV. Further SDCS measurements for these processes (excluding elastic scattering) were performed at 30°.

3.1.1 Elastic Scattering

There have been several attempts, using various methods, to measure \( \text{d} \sigma_{\text{el}} / \text{d} \Omega \) for \( e^- \)-atom scattering. In a pioneering experiment, differential elastic \( e^- \)-He (Jaduszliwer and Paul4) and \( e^- \)-Ne and \( e^- \)-Ar (Jaduszliwer and Paul5) cross sections were derived from a transmission-type experiment. In this study the number of detected positrons was investigated as the strength of an axial magnetic field was varied. It was thus possible to extract angular information since, as the magnetic field was increased more scattered positrons were counted, the size of this effect depending upon the angle of scatter, \( \theta \). However, poor agreement between the angle–integrated elastic cross–sections deduced from these measurements and the He data of Canter et al. 11 and Campeanu and Humblerton12 has cast doubt on the reliability of these results.

Coleman and McNutt13 and Coleman et al. 14 measured the \( e^- \)-Ar elastic scattering cross–section also as a function of scattering angle, between 20° and 60°, for fixed energies up to 8.7eV. In these experiments, however, flight–times of positrons transmitted through a gas cell and transported to a detector by a 140G magnetic field were measured. The scattered particles were distinguished from those which had suffered no deflection due to their delayed time of arrival at the detector. Time–of–flight (TOF) spectra were obtained with and without gas present, the difference between the two spectra representing the TOF spectra for scattered positrons. These difference spectra were employed to derive \( \sigma_{\text{el}} \) as a function of \( \theta \) (\( \text{d} \sigma_{\text{el}} / \text{d} \theta \)). The results at four incident energies are shown in figure 3.2.
results of the polarization potential model of Schrader\textsuperscript{15} and of the polarized orbital calculations of McEachran \textit{et al} \textsuperscript{16} are shown for comparison. The total cross sections of Schrader\textsuperscript{15} are in good agreement with those measured by Coleman \textit{et al}\textsuperscript{14}, whereas those of McEachran \textit{et al}\textsuperscript{16} are higher. The $d\sigma_{\text{el}}/d\Omega$ values of McEachran \textit{et al}\textsuperscript{16} shown in figure 3.2 have been scaled down by the factor $\sigma_{\text{el}}$ (ref. 13) / $\sigma_{\text{el}}$ (ref. 16). The shapes of the two calculated $d\sigma_{\text{el}}/d\Omega$ curves are seen to be very similar.

![Figure 3.2](image)

Figure 3.2: $e^-\text{Ar}$ elastic scattering cross-sections as a function of $e^-$ scattering angle ($\theta$) at four different incident energies. Experiment: hollow and filled circles, Coleman \textit{et al}\textsuperscript{14}. Theory: full curve, Schrader\textsuperscript{15}; dashed curve, McEachran \textit{et al}\textsuperscript{16}.

More versatile, but also more difficult, are positron-atom crossed-beam experiments on differential scattering which have been pursued for several years by the experimental groups at Detroit and Bielefeld. The basic features of their equipment are similar and the layout of the Bielefeld group (Schwab \textit{et al}\textsuperscript{17}, Floeder \textit{et al}\textsuperscript{18}) is shown in figure 3.3. Various electrostatic lens elements produce a well defined beam of slow positrons which, in this case, is collimated by a 4mm aperture. The gas target is produced by a multichannel capillary array positioned perpendicular to the beam axis. The atomic density of their gas beam was monitored by measuring the attenuation to the primary beam. This technique would require the array to be driven at a pressure of several Torr, as were the measurements by the Detroit group. The primary positron beam was monitored by the offset channeltron, CEM1, whilst the elastically scattered positrons could be detected using a rotatable channeltron, CEM2, with an angular acceptance of $\pm 6^\circ$ ($\pm 8^\circ$ for the Detroit experiment (Hyder \textit{et al}\textsuperscript{7}, Smith \textit{et al}\textsuperscript{19})).
Some of the data of Hyder et al. for e± impact on Ar gas at 100eV and 200eV are shown in figure 3.4. The results were independently normalized at 90° for both projectiles: in the electron case to existing experimental data, whilst for positrons to the theoretical results of McEachran and Stauffer and Nahar and Wadehra. As described by Hyder et al., their electron measurements, in figure 3.4 (a and c), compare favourably with existing experimental results of Srivastava et al. and Dubois and Rudd at angles greater than 60°. Similarly, agreement between the positron results of Hyder et al., in figures 3.4 (b and d), and the theoretical data of McEachran and Stauffer and Nahar and Wadehra is good for θ>60°, but below 60° the measurements exceed the theoretical lines. The discrepancy between the experiments at smaller scattering angles has been attributed to a divergent gas beam in the experiment. Also shown in figure 3.4 are the results of Joachain and Potvliege which are somewhat lower than the other theoretical results and exhibit markedly different structure at small angles. It should be noted that if the data of Hyder et al. are normalized to this theory at 90° for both 100 and 200eV experiment still exceeds the calculated values at small angles in a similar way to that shown in figure 3.4 (b and d). Joachain and Potvliege, in extending the work of Joachain et al. to lower energies, have discussed the differing trends of the theories at small angles (≤30° at 100eV). They have shown that similar behaviour to that found by McEachran and Stauffer and Nahar and Wadehra can be obtained from their calculation if the absorption potential is neglected. Joachain and Potvliege have argued that a full optical model calculation would be the most reliable since, as required by unitarity, proper account is taken (via the
absorption potential) of the inelastic channels.

![Diagram of scattering angles](image)

**Figure 3.4:** $e^{-}$-$Ar$ elastic differential scattering cross-sections at 100 and 200eV.

Experimental tests of these theories are more feasible at lower impact energies, where the structure is seen to move to larger angles. Floeder et al.\(^\text{18}\) and Smith et al.\(^\text{19}\) have measured $d\sigma_{el}/d\Omega$ for Ar at low impact energies. Floeder et al.\(^\text{18}\) extended the earlier work of Schwab et al.\(^\text{17}\) by making relative measurements of $d\sigma_{el}/d\Omega$ at 8.5 and 30eV. Smith et al.\(^\text{19}\) made similar measurements at 8.7 and 30eV using the same apparatus as Hyder et al.\(^\text{7}\). In figure 3.5 the experimental results are compared to the theory of Bartschat et al.\(^\text{26}\) and McEachran et al.\(^\text{16}\). At 30eV, the measurements agree better with the optical model of Bartschat et al.\(^\text{26}\) and not the polarized orbital calculations of McEachran et al.\(^\text{16}\), which ignores scattering from inelastic channels. For scattering angles greater than 60° the data of Smith et al.\(^\text{19}\) are...
in disagreement with both theories.

Figure 3.5: $e^+-$Ar elastic differential scattering cross-sections at 8.7 and 30eV (NB. the 30eV DCS values have been multiplied by ten).

The measurements of $d\sigma/d\Omega$ taken at 8.7eV (Smith et al. 19) and 8.5eV (Roeder et al. 18) are normalized to the 8.7eV data of Coleman and McNutt for comparison. At energies below the positronium formation threshold ($E_{Ps}=8.9eV$) annihilation is the only inelastic channel which remains open. However, as discussed in section 1.2, at these impact velocities the annihilation cross section is negligible and the experimental data are in good agreement with the theory of McEachran et al. 16.

A further comparison between the relative measurements of Smith et al. 19 (normalized at each energy to theory 16 at 120°) and the calculations of McEachran et al. 16 and Bartschat et al. 26 is shown in figure 3.6, where it is seen that at 5eV good shape agreement also exists with the polarized orbital calculations16. However, as the projectile energy is increased
through the Ps formation threshold, the observed minimum in the DCS measurements rapidly diminishes and is also energy shifted away from the theory\(^{16}\). At 20\,\text{eV} the minimum is no longer observed but is still predicted to occur in the polarized orbital calculations\(^{16}\). The calculations of Bartschat \textit{et al.}\(^{26}\) do not exhibit a minimum at 20\,\text{eV} and in that respect are similar to the measurements, but there remains a noticeable difference in their shapes. Similar behaviour in the positron elastic DCS has been observed\(^{27}\) for Kr and Xe for energies above and below the respective Ps formation thresholds when compared with corresponding polarized orbital calculations\(^{28}\).

![Figure 3.6: \(e^+\)-Ar elastic differential scattering cross-sections at 5, 8.7, 15, 20, 30 and 50\,\text{eV}. The numbers in parentheses following the energy values indicate the power of ten by which the corresponding DCS values have been multiplied.](image)

Figure 3.6: \(e^+\)-Ar elastic differential scattering cross-sections at 5, 8.7, 15, 20, 30 and 50\,\text{eV}. The numbers in parentheses following the energy values indicate the power of ten by which the corresponding DCS values have been multiplied.

The apparatus of Hyder \textit{et al.}\(^{7}\) has recently been employed to measure \(d\sigma_{el}/d\Omega\) for Ar\(^8\), Kr\(^9\) and Ne\(^{10}\) as a function of impact energy at fixed scattering angles. Resonance-like structure in the form of sharp drops in the differential cross-sections were reported at 55-60\,\text{eV} for Ar, 25 and 200\,\text{eV} for Kr and 100-200\,\text{eV} for Ne. The results for Ar at 60\degree, 90\degree and 120\degree scattering angles are shown in figure 3.7. The reported structure is visible at all
three angles but is most pronounced at 60°, where the DCS was observed to drop abruptly by a factor of two. It was tentatively suggested\textsuperscript{8,9,10} that these structures were examples of coupled–channel shape resonances between the channels for ionization or positronium formation and elastic scattering. Coupled–channel shape resonances were first predicted by Higgins and Burke\textsuperscript{29} for positron–H scattering using a 6–state approximation $\text{Ps}(1s, 2s, 2p)$ and $\text{H}(1s, 2s, 2p)$. Similar resonances have been found in the calculations of, for example, Hewitt \textit{et al} \textsuperscript{30}, Sarkar \textit{et al} \textsuperscript{31}, Mitroy\textsuperscript{32}, McAlinden \textit{et al} \textsuperscript{33} and Mitroy and Stelbovics\textsuperscript{34}.

Figure 3.7: Differential cross–sections for $e^+–\text{Ar}$ elastic scattering at 60°, 90° and 120°.

The 6–state approximation $\text{Ps}(1s, 2s, 2p)$ and $\text{H}(1s, 2s, 2p)$ of Higgins and Burke\textsuperscript{29} fails to include ionization. Because of this omission the resonances they observed were an area of contention. Later, the coupled–state method was extended by Kernoghan \textit{et al} \textsuperscript{35,36} to the inclusion of 18 final states. The addition of 12 pseudostates of positronium (Fon \textit{et al} \textsuperscript{37}) to the calculations of Higgins and Burke\textsuperscript{29} to represent the ionization channels resulted in the resonances disappearing, or probably more correctly, being minimized. Therefore, Kernoghan \textit{et al} \textsuperscript{35,36} concluded that the resonance structure predicted by
Higgins and Burke\textsuperscript{29} did not exist in reality but were probably a consequence of neglecting, or inadequate representation in other approximations, the ionization channels.

McAlinden and Walters\textsuperscript{38}, using a Truncated Coupled Static (TCS) approximation, calculated the absorption effect of the positronium formation channel upon $\frac{d\sigma_{e\gamma}}{d\Omega}$ for positrons scattering from Ar, Kr and Xe atoms. No structures were observed which could be correlated with the experimental data of Dou \textit{et al} \textsuperscript{8,9,10}. However, because the TCS approximation did not account for the absorption effect of the ionization channel upon $\frac{d\sigma_{e\gamma}}{d\Omega}$ this process could not be ruled out as being the cause of such structures.

3.1.2 Positronium Formation

The successful development of tunable Ps beams\textsuperscript{39} is largely due to exploiting the natural beam collimation of Ps formed by the reaction,

$$e^+ + X \rightarrow X^+ + Ps$$

(3.3)

where $X$ is a gaseous target intercepted by a variable–energy positron beam. The degree of collimation is determined by the behaviour of the differential cross–section, $d\sigma_{e\gamma}/d\Omega$, with respect to the positron incident energy. Theoretical computations of $d\sigma_{e\gamma}/d\Omega$ are, in the main, limited to atomic hydrogen and helium targets using the first Born approximation\textsuperscript{40,41,42} and distorted wave models\textsuperscript{43,44}. These theories predicted $d\sigma_{e\gamma}/d\Omega$ to be strongly peaked in the forward direction.

Brown\textsuperscript{45,46} was the first to obtain direct experimental evidence in support of the energy tunable Ps beam production. A slow positron beam was passed through, and reflected at the end of, a 1m long cell filled with He and the energy distribution of the resulting annihilation quanta monitored using a Ge(Li) detector positioned on axis. In this manner 'wings' were observed on either side of the 511keV peak which were interpreted as red and blue Doppler–shift $\gamma$–rays from annihilation of 'monoenergetic' para–positronium (p–Ps).

Contemporaneously, Laricchia \textit{et al} \textsuperscript{47} began studies into the production of a Ps beam suitable for investigating Ps–gas interactions. The first of these studies was a preliminary investigation of the angular distribution of ortho–positronium (o–Ps) formed in a low density Ar target by a slow positron beam. A very simple set–up was employed consisting
of a short (20mm) gas cell for the Ps production and a CEM for detecting Ps. A set of suitably biased grids preceded the CEM so as to prevent charged particles from reaching the detector which was mounted on a linear manipulator normally to the beam axis. The gas cell incorporated a U-shaped exit aperture such that the CEM would remain in full view from the centre of the cell when off axis. Laricchia et al.\(^47\) found that, if the unknown CEM detection efficiency was neglected, up to 26% of all Ps was emitted in a 7° cone about the beam axis.

More extensive and precise measurements of the Ps ejection angles were later performed by Laricchia et al.\(^48\). The major modifications to the apparatus in comparison to the previous set-up was the substitution of the CEM with a Channel Electron Multiplier Array (CEMA) arrangement and the addition of two NaI counters placed in close proximity to the CEMA. The former modification resulted in a six-fold increase in the detecting surface and ensured that the same detector area was subtended at different acceptance angles to the centre of the scattering cell. A coincidence circuit between the CEMA and either of the NaI counters improved the signal-to-background ratio and resulted in greater stability of the system enabling measurements of higher accuracy. Recently, Tang and Surko\(^49\) have made angular distribution measurements of positronium using H\(_2\). Their experimental arrangement was similar to Laricchia et al.\(^47,48\) except for the detector assembly, where they used a microchannel plate and CsI/photodiode for their coincidence measurements.

McAlinden and Walters\(^38\), prompted by experimentalists, applied their TCS approximation method to calculate d\(\sigma_{Ps}/d\Omega\) for positron scattering from Ne, Ar, Kr and Xe atoms in the energy range up to 75eV. All Ps formation was assumed to come from capture of an electron from the outermost p-shell of the atom, however, McAlinden and Walters\(^38\) emphasized the importance of also considering capture from inner shells. A noticeable feature of these cross-sections, shown in figure 3.8, is that they generally do not peak at 0°. This contrasts with the distorted-wave results\(^43,44\) for H and He which indicate that the Ps(1s) formation cross section is forward peaked at energies comparable to those shown in figure 3.8. This difference is consistent with an experimental observation by Laricchia et al.\(^50\) in the energy range up to 55eV, that d\(\sigma_{Ps}/d\Omega\) in He seemed to be more forward peaked than for Ar.
Figure 3.8: TCS cross-sections for Ps (1s) formation by capture from the outermost p-shell of the atom for (a) Ne, (b) Ar, (c) Kr, (d) Xe. The curves correspond to different impact energies: solid curve, 18eV for Ne, 12eV for Ar and Kr, 9eV for Xe; short-dash curve, 24eV for Ne, 15eV for Ar, Kr and Xe; long-dash curve, 30eV for all atoms; dash-dot curve, 45eV for Ne only; dotted curve, 75eV for all atoms.
In order to measure angular differential Ps formation with higher angular resolution and up to larger angles, crossed-beam experiments are necessary. Falke et al. 51,52 have measured $d\sigma_{P_s}/d\Omega$ on such experiments with an angular resolution of ±4°. Presented in figure 3.9 are their angle-resolved measurements for Ar at a positron incident energy of 75eV together with the theory of McAlinden and Walters 38 convoluted by the angular resolution function of the experiment. Good agreement is observed.

Figure 3.9: Relative differential cross-section measurements for Ar from an incident positron energy of 75eV: (O), secondary electrons; (▲), positronium. The full curve represents the theoretical Ps-formation cross-section of McAlinden and Walters 38, normalized to Ps formation at 0°. The broken curve represents the theory folded with the angular-resolution function of the experiment, also normalized to the value for $\theta=0°$.

Although encouraging, more measurements, on a variety of targets, are required to test theories over a wider energy and angular range.
3.1.3 Ionization

Knowledge of the SDCS for direct (as opposed to electron capture) single ionization provide a deeper insight into ionization dynamics than do comparable total cross-section measurements. For example, an electron removed in proton impact experiences the combination of two attractive potentials during the collision, one due to the proton and the other due to the partially screened target core. In contrast, the electron is subject to the effects of one repulsive and one attractive potential in antiproton impact. The effects of such differences on the SDCS as a function of ejection energy and angle have been calculated by a number of authors\textsuperscript{53, 54, 55, 56} for the collisions,

\[ n + X \rightarrow X^+ + n + e^- \]  

(3.4)

where X is the target gas and n=\( p^+, p^-, e^+ \) and \( e^- \). Shown in figure (3.10) and (3.11) are the results of the calculation of Fainstein \textit{et al} \textsuperscript{54} for He using the continuum distorted wave–eikonal initial state (CDW–EIS) model for protons and antiprotons and the calculations of Olson and Gay\textsuperscript{55} using the Classical Trajectory Monte Carlo (CTMC) method for electrons, positrons, protons and antiprotons. In the distorted–wave model, the initial bound state of the He atom was distorted by an eikonal phase to account for the potential of the incoming projectile. The post collision interaction of the two–centre continuum states of the electron is approximated by a product of two continuum factors (associated with the projectile and residual target) times a plane wave. The CTMC provided a complete description of the scattering process based on the numerical solution of Hamiltonian’s equations of motion for a three–dimensional, three–body system. Also included in the figures are the experimental data of Rudd and DuBois\textsuperscript{57} for protons and Rudd \textit{et al} \textsuperscript{58} for electrons on He.
Figure 3.10: $d\sigma_{\text{ion}}/d\Omega$ as a function of ejection angle for $e^-$, $e^+$, $p$, $p^-$ impact of He at a velocity of 2.83au. Expt. data for $p$: Rudd and DuBois\textsuperscript{57} ($\Delta$) and $e^-$: Rudd \textit{et al}.\textsuperscript{58} ($\Delta$). Theoretical results: for $p$, Olson and Gay\textsuperscript{55} (full curve) and $p^-$, Fainstein \textit{et al}.\textsuperscript{54} (dotted curve). For $e^-$, the theoretical cross-section for the sum of the indistinguishable target and projectile $e^-$ is shown (broken curve).

Figure 3.11: $d\sigma_{\text{ion}}/d\Omega$ as a function of ejection energy for $e^-$, $e^+$, $p$, $p^-$ impact of He at a velocity of 2.83au. Symbols the same as in figure 3.10.
As figure 3.10 illustrates, the positively charged projectiles produce ejection primarily to the forward direction whereas the negatively charged projectiles produce much less forward emission. This behaviour arises because protons and positrons, due to their charge, pull the ejected electrons in the direction of their velocity while antiprotons and electrons repel them. The ejected electron energy distribution, displayed in figure 3.11, shows that, owing to their greater kinetic energy when compared with electrons and positrons of equal velocity, the heavy particles have a much larger cross section at high ejection energies. This figure also indicates that for relatively low ejection energies, the positively charged particles have a larger cross section than their negatively charged antiparticles. This difference has been explained as being due to the sign of the charge-dependent difference in ionization known as the ‘saddle point’ mechanism\textsuperscript{59,60}. That is, at relatively low collision velocities a significant number of ejected electrons, with velocities of about $v_p/2$, where $v_p$ is the velocity of the projectile, are stranded in the saddle, or equiforce, region between the projectile and the target core. With regard to the positive/negative particle difference in the production of low energy electrons, the saddle-point picture provides a simple explanation. Ejected electrons of low energy originate primarily in relatively weak, distant collisions of the projectile with the target electron. In this case, since the positively charged projectile produces a region of reduced binding centred about the equiforce point, the probability of the escape of the electron is enhanced. For the negatively charged particle the midpoint region is one where the electron experiences a repulsion and no net decrease of binding. Thus, positively charged projectiles are more efficient in producing slow ejected electrons due to the effect of force cancellation of the target nucleus and projectile fields. On these bases, the angle or energy distributions of the ejected electrons are seen to be strongly dependent on the sign of the projectile charge.

Analogous differential scattering experiments using positrons are difficult and time consuming due to the low signal rate and have so far, with the exception of Chaplin \textit{et al} \textsuperscript{61}, not been measured. Chaplin \textit{et al} \textsuperscript{61} obtained absolute differential cross-sections for the impact ionization of He by 55eV positrons using a 3m, high resolution, time of flight spectrometer. The angular distribution of the scattered positrons was derived from their TOF distribution, which was extracted from a pair of time spectra accumulated with and without gas in the cell. The results of Chaplin \textit{et al} \textsuperscript{61} are shown in figure 3.12. At 10.8°, their value for $d\sigma^{+}_{\text{ion}}/d\Omega$ of 0.77 $a_0^2$/str agrees well with a calculation of Schultz \textit{et al} \textsuperscript{62} of 0.86 $a_0^2$/str. However, the measurements of Chaplin \textit{et al} \textsuperscript{61} exceed theoretical values at larger angles and exhibit structure not obtained theoretically. Because of the large error bars associated with the measurements the existence of this structure is uncertain. This sort of
experiment is completely inadequate for the derivations of angular information because a TOF technique cannot be used to distinguish between a positron which has lost most of its energy in a collision, from one that has undergone large angle scattering.

Figure 3.12: Differential cross-sections for impact ionization of He. (O) Chaplin et al. (A) Schultz et al. Solid and dashed lines are polynomial fits.

3.2 Experimental Details

The RFA apparatus used to measure our energy resolved SDCS is shown schematically in figure 3.13. Its main features were described in detail in Chapter 2.

Positrons emerged from a \(^{58}\)Co radioactive source, with an initial activity of 5.2 GBq, and were moderated by four annealed tungsten meshes. A modified Soa gun (§2.4.1) was used to focus the monoenergetic positrons. After separating the beam from the high energy positrons and γ-ray flux with a double cylindrical condenser (§2.4.3), a five element lens (§2.4.5) was employed for final focusing. The target gas, in our case argon, emerged from a multi-capillary array (§2.5) situated 5mm above the centre of the beam. The pressure in the buffer behind the array was measured by a MKS capacitance manometer and was set around 10Torr (13.30mbar), whilst the maximum pressures in the vacuum chamber were 10\(^{-5}\) and 10\(^{-7}\)Torr with and without gas present, respectively.

The scattered particle detector CEM1, together with the 4-grid retarder arrangement which
formed the RFA, were placed at an angle $\theta$ to the incident beam. The first (closest to the scattering region) and third grids were set to ground with the retarding potential applied to the second, whilst the fourth was connected to the cone of the CEM1. The energy width of our positron beam was measured to be 3eV using the RFA of the primary detector CEM2. A third channeltron, CEM3, was positioned at the end of the ion extractor and used to detect the ionized argon atoms. Placed in front of the retarding grids of channeltrons 1 and 2 was a 20mm long tube, of internal diameter 10mm, which was used to reduce the detection of particles originating from regions other than the main scattering volume. The diameter of the scattered CEM1 cone was 10mm. The distance from the cone to the centre of the interaction region was 60mm resulting in an angular acceptance of approximately $\pm9.5^\circ$. The energy resolution of the RFA was not known, but measurements using electrons suggest it was probably between 1 and 2eV and had no systematic dependence on energy. The RFA was used to prevent particles with energies below a certain level from reaching the detector and so the fact that the resolution was not known was unimportant. The experimental set-up was encased in mu-metal such that the remnant magnetic field was less than 3mG.
Figure 3.13: Schematic of the RFA experimental arrangement.
3.3 Electronics

The electronics required to provide correlated ion and positron (or positronium atom) signals is shown in figure 3.14. The measuring process was initiated when a positron (or positronium atom) was detected by the scattered CEM1.

![Schematic of the RFA electronics.](image)

Figure 3.14: Schematic of the RFA electronics.

The CEM1 pulse was fed to a voltage–sensitive Pre–Amplifier, PA1. Noise present on the output from this pre–amp was rejected using an Ortec 584 Constant–Fraction Discriminator, CFD1. The CFD1 timing output was fed into an Ortec 567 Time–to–Amplitude Converter (TAC). The ‘valid start’ signal of the TAC initiated a +300V, 50ns rise–time pulse which was applied on the second electrode of the five element exit lens for the time of the measuring sequence (≈1μs) in order to stop the projectile beam whilst the extraction field was on (§2.4.4). After a further 50ns delay, to enable all of the projectiles to leave the scattering region, ±150V pulses were applied to the plates on either side of the scattering region to extract any ions present. If an ion was detected by CEM3 the TAC was stopped. Thus the ionized target atoms were extracted and their charge–to–mass ratio analyzed by measuring their flight times. These coincidences were recorded by a DEC 222 personal computer equipped with an Ortec Maestro Multi–Channel–Analyzer (MCA) Card. The potential difference, V, applied to the second grid of the scattered RFA was controlled by the Ortec Multi–Channel–Scaler (MCS) Plus card and a Digital–to–Analogue Converter (DAC). The incident positron beam intensity was measured using CEM2, shown in figure 3.13, but was switched off during measurements to prevent possible electrical interference occurring between it and other electrostatic components in the system.
3.4 Data Collection

Relative values for the DCS were obtained by varying the voltage, $V$, applied to the RFA of the scattered CEM1 and measuring the corresponding signal. Total ionization measurements were obtained by setting the RFA to ground ($V=0$). That is, all scattered positrons were detected and ionization was selected by imposing the coincidence with the ion. This signal also included that from positronium formation and random extraction (background). The effects of both of these were found by repeating the measuring process, but with $E/e > V > (E-E_{exc})/e$, where $E$ is the positron beam energy, $E_{exc}$ is the excitation threshold and $e$ is the elementary charge, thus eliminating all positrons which had undergone an ionizing collision. Positronium formation, again using the ion coincidence, and elastic scattering signals were obtained simultaneously by alternately ramping the RFA between two values of $V$, namely when $V > E/e$ and, as above $E/e > V > (E-E_{exc})/e$. With $V > E/e$, the counts were attributed to positronium atoms and detector background. When $E/e > V > (E-E_{exc})/e$, the counts were due to positronium atoms, detector background and elastically scattered positrons. The difference in the CEM counts at these two retarding voltages, which were recorded on a MCS, yielded the elastically scattered positron signal, $N_{el}$. Dividing $N_{el}$ by the run-time of the measurement yielded the elastically scattered positron intensity, $I_{el}$. Using this value and equation (3.5) the relative elastic scattering DCS, $d\sigma_{el}/d\Omega$, were determined for fixed scattering angles,

$$
\frac{d\sigma_{el}}{d\Omega} = \text{const} \left( \frac{I_{el}}{I_0} \right)
$$

(3.5)

where $I_0$ was the incident beam intensity. Each measurement was normalized for pressure variations. The temperature was assumed to be constant. Because of the relatively high background on the scattered positron detector ($\approx 0.5\text{s}^{-1}$, compared to a typical elastic scattering signal of $(0.014\text{s}^{-1}$)) elastic scattering DCS measurements were time-consuming. For example, with the scattered CEM1 positioned at 60°, a 65 hour run-time was required to measure $d\sigma_{el}/d\Omega$, with a 15% statistical accuracy, at a beam energy of 40eV with a primary beam intensity of 1800 $\text{e}^{+}\text{s}^{-1}$.

The difference in the scattered $e^+$--ion coincidence signals when $V=0$ and $E/e > V > (E-E_{exc})/e$ yielded the number of scattered positrons causing direct single ionization of the target,
Thus, the direct single ionization intensity, $I_{\text{ion}+}$, was simply $N_{\text{ion}+}$ divided by the run-time of the measurement. Substituting $I_{\text{ion}+}$ for $I_e$ into equation (3.5) allowed the relative SDCS for direct single ionization, $d\sigma_{\text{ion}}^+/d\Omega$, to be determined (and where the constant of proportionality was different for each process). The background contribution to the $V>E/e$ signal was measured by replacing the scattered CEM1 signal by a pulse generator and repeating this measurement at this RFA setting. The system could be gated randomly whilst timing the ions in the usual way. The signal from the pulse generator was similar in size and shape to that of the scattered CEM1 signal. A spectrum taken in this way revealed the background to be flat across the energy range studied, that is, contributing approximately 3% and 15% to the signal at 40 and 150eV, respectively. This contribution was subtracted from the $V>E/e$ spectra measured with the scattered CEM1 signal. The difference, $N_{\text{Ps}}$, was due to liberated positronium atoms only. Dividing $N_{\text{Ps}}$ by the run-time of the measurement yielded the scattered positronium intensity, $I_{\text{Ps}}$. Using this value and equation (3.5) the relative positronium formation differential cross-sections, $d\sigma_{\text{Ps}}/d\Omega$, were determined for fixed scattering angles. Note that the detection efficiency of Ps by a CEM was not known. A table of the RFA settings and corresponding processes detected are shown for both the scattered CEM counts and the coincidence with the ion detector.

<table>
<thead>
<tr>
<th>RFA Settings</th>
<th>Single CEM Counts</th>
<th>CEM Ion coincidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V=0$</td>
<td>Background, Elastic, Ps-formation, Ionization</td>
<td>Background, Ps-formation, Ionization</td>
</tr>
<tr>
<td>$E/e&gt;V&gt;(E-E_{\text{exc}})/e$</td>
<td>Background, Elastic, Ps-formation</td>
<td>Background, Ps-formation</td>
</tr>
<tr>
<td>$V&gt;E$</td>
<td>Background, Ps-formation</td>
<td>Background, Ps-formation</td>
</tr>
</tbody>
</table>

Table 3.1: RFA settings and corresponding processes detected for the single CEM counts and the imposed coincidence with the ion.
3.5 Results and Discussion

Presented in figure 3.15 are the positronium differential cross sections for Ar measured at 30° and 60° scattering angles (with background subtracted). Included in the spectra are the TCS calculations of McAlinden and Walters\textsuperscript{38} for differential scattering from Ps in the 3s (dashed), 3p (dotted) and 3s+3p (solid) states. The data and theory were normalized at 150eV to each other, allowing the shapes to be compared. Both sets of $d\sigma_{\text{ps}}/d\Omega$ measurements exhibit an approximately exponential decay with increasing incident positron energy. The intensity at the more forward angle of 30° was, as might be expected, higher than that at 60°. The difference was approximately a factor of six at 40eV. Agreement with our measurements and the calculations of McAlinden and Walters\textsuperscript{38} is good at 30°, but poor at 60°. Scattering to larger angles is harder to model because of the greater energy and momentum exchanges involved. The disagreement at the larger angle might thus be expected to be due to inadequacies in the theoretical calculation. Hence a more advanced TCS calculation might be needed at the larger angles.

Figure 3.15: Positronium differential cross sections, $d\sigma_{\text{ps}}/d\Omega$, for Ar measured at 30° and 60° scattering angles (with background subtracted): (•) this work; TCS calculations of McAlinden and Walters\textsuperscript{38} (the solid line is the sum of the 3s (dashed) and 3p (dotted) contribution).
Presented in figure 3.16 are our direct single ionization differential cross sections for Ar measured at 30° and 60° scattering angles. Again the data was normalized at 150eV to each other. In the energy range (40–60eV) $d\sigma^\text{ion}/d\Omega$ at 60° is found to remain approximately constant; above 60eV ionization falls off noticeably. The energy dependence of $d\sigma^\text{ion}/d\Omega$ at 30° falls away across the full energy range 40–150eV. Therefore no structures of the kind found by Dou et al.\textsuperscript{8,9,10} were observed. The intensity of the scattered signal at 30° was approximately twice the magnitude of the 60° measurements at 40eV. So far no theoretical calculations exist.

Figure 3.16: Direct single ionization differential cross sections, $d\sigma^\text{ion}/d\Omega$, for Ar measured at 30° and 60° scattering angles: (●) this work; angle integrated single ionization cross section, $\sigma^\text{ion}$; (dotted line) Knudsen et al.\textsuperscript{65} and (solid line) Moxom et al.\textsuperscript{66}. (Both measurements of $\sigma^\text{ion}$ were normalized to our data at 40eV).
Presented in figure 3.17 are our elastic scattering differential cross section measurements for 60° plotted along with the equivalent measurements of Dou et al.\textsuperscript{8} and the corresponding TCS calculations of McAlinden and Walters\textsuperscript{38}. Though the measurements of Dou et al.\textsuperscript{8,9,10} where taken with a better energy resolution (2eV) and better angular resolution (±8°) compared with the present work, it should not affect our ability to distinguish a structure of the size or form of that reported by them. Our data and those of Dou et al.\textsuperscript{8} were normalized at 45eV to the TCS calculations. Unlike the Detroit measurements\textsuperscript{8,9,10} our data does not exhibit an abrupt drop in the magnitude of the $d\sigma_{el}/d\Omega$ between 55 and 60eV, but instead, a gradual fall with increasing beam energy is observed. This is similar to the situation for electron scattering where, prompted by the findings of Dou et al.\textsuperscript{8}, $d\sigma_{el}/d\Omega$ has been measured by Cvejanovic and Crowe\textsuperscript{63} for argon, as a function of electron energy from 20-110eV, at angles of 60°, 90° and 120°, and found to vary smoothly. Their 60° data are also shown in figure 3.17.

Figure 3.17: Comparison of the energy dependence of the elastic differential cross-sections as a function of energy, at a fixed scattering angle of 60° for Ar. Experimental data for e$^+$ impact of Dou et al.\textsuperscript{8} (♦) and this work (□) compared (and normalized at 45eV) to the calculations of McAlinden and Walters\textsuperscript{38} (—). The electron–argon data are those of Cvejanovic and Crowe\textsuperscript{63}. 
It had been suggested (Dou et al, McAlinden and Walters, Kauppila et al) that the ‘knee’ shaped structure observed by Dou et al in the elastic scattering DCS was due to a cross channel coupling effect with the ionization channel since earlier measurements by Knudsen et al found that the direct single ionization cross section, $\sigma_{ion}^+$, for $e^+–Ar$ scattering peaked at 60eV impact energy (see figure 3.16). However, more recent work by Moxom et al (also shown in figure 3.16) and Jacobsen et al have found that the peak in $\sigma_{ion}^+$ lies at around 100–120eV. Smooth lines were drawn through the data of Moxom et al (solid) and Knudsen et al (dotted) and they were both normalized to our differential data at 40eV which, as mentioned earlier, showed no sign of structure. The measurements of Moxom et al are considered to be the most accurate that exist in this energy region and therefore weakens the argument for channel coupling as being the cause of the resonance structures observed by Dou et al.

3.6 Summary

The energy dependencies of the differential cross sections for elastic scattering, positronium formation and direct single ionization in positron–argon collisions at 60° and 30° (not elastic scattering) have been performed in the energy range 40–150eV. Our measurements show no evidence of structure and therefore disagree with the findings of Dou et al. Nor have new experiments by the Detroit group, presented at a recent meeting (Kauppila et al), been able to reproduce the previously reported structures. Our study was undertaken contemporaneously with the most recent one of the Detroit group, and a preliminary account of the data was given at the same meeting. Presented in figure 3.18 are the measurements of Kauppila et al plotted with the data of Dou et al and the corresponding TCS calculations of McAlinden and Walters. Taken together these results now seem to rule out the occurrence of the resonance–like structure at intermediate energies in the elastic scattering DCS for positron–rare gas collisions as reported by Dou et al.

The dearth of theoretical calculations to compare with our measurements highlights the need for more and better calculations. Similarly, more differential measurements are required, ideally from the same targets as used in the theoretical models, so that physicists can compare like with like. However, before such measurements can be made methods of increasing beam intensities must be developed.
Figure 3.18: Comparison of the energy dependence of the positron elastic differential cross-sections as a function of energy, at a fixed scattering angle of 60° for Ar. Experimental data of Dou et al. (∗) and Kauppila et al. (□) compared (and normalized at 45eV) to the calculations of McAlinden and Walters (—).


42. Sural D P and Mukherjee S C Physica 49 (1970) 249

91


58. Rudd M E, Toburen L H and Stolterfoht N At. Data Nucl. Data Tables 18 (1976) 413


92
64. Kauppila W E, Dou L, Kwan C K and Stein T S 1991 Abstracts of the 17th International Conference on the Physics of Electronic and Atomic Collisions (Brisbane, Australia) 331


Chapter 4

Double Differential Cross-Sections

4.1 Introduction

Ionization can occur when a positron (impact energy, $E_0$, and vector, $k$) collides with an atom (ground state ionization energy, $E_i$, and of initial excited energy state, $E_{exc,i}$) where $E_0 > E_i$. Figure 4.1 shows the scattered projectile and ejected electron leaving the collision region with energies $E_{proj}$ and $E_{elec}$, respectively. The solid angle of the projectile $d\Omega_{proj}$ ($\theta_{proj}, \phi_{proj}$) and of the ejected electron $d\Omega_{elec}$ ($\theta_{elec}, \phi_{elec}$) are defined with respect to $k$. The ion is left behind in the excited energy state, $E_{exc,f}$, with respect to its ground state. Energy conservation requires:

$$E_0 = E_{proj} + E_{elec} + E_{elec} - E_{exc,i} + E_{exc,f} \quad (4.1)$$

If the atom before the collision and the ion after the collision are in their ground states, the excitation energies $E_{exc,i}$ (atom) and $E_{exc,f}$ (ion) are zero and therefore

$$E_0 = E_{proj} + E_{elec} + E_i \quad (4.2)$$

A TDCS experiment would involve measuring the energies and angles of both out-going particles in coincidence with the ion for each ionization collision. TDCS have so far not been measured for positron impact studies because of a lack of sufficient beam intensity. The low positron flux also makes DDCS difficult to measure but not impossible. A DDCS experiment would involve measuring the energy and angle of just one of the out-going particles. This is equivalent to the integration of the TDCS over all angles of the disregarded scattered particle. Consequently angular distributions\(^1\) ($E_0$ and $E_{proj}$ fixed) or energy loss spectra\(^2,3,4\) of the first kind ($E_0$ and $\theta_{proj}$ are constant) and of the second kind ($E_{proj}$ and $\theta_{proj}$ are constant) have been obtained. Despite this integration DDCS provide detailed information about the collision dynamics and post-collision interactions. In particular, the Coulomb interaction between a scattered projectile and an ejected electron may cause the two particles to emerge from a collision with velocities closely matched,
Figure 4.1: Schematic diagram of the kinematics of an ionizing positron collision with an atom
such that the ejected electron may be considered to have been transferred to a continuum state of the scattered projectile; this process has been called ECC. When positively charged projectiles are used, capture of the ionized electron into a bound state becomes possible.

Indeed, ECC is considered as the extrapolation of the capture process from the bound to the continuum state of the projectile and electron. ECC is predicted to give rise to a cusp-like peak in the ejected electron energy spectrum, particularly for heavy positive particle impact. The electron energy at which the peak occurs, $E_{\text{ECC}}$, may easily be found using equation 4.2. At the ECC peak, the projectile and electron velocities are equal, written $v$, such that

$$E_0 = \frac{1}{2} M v^2 + \frac{1}{2} m v^2 + E_i$$

where $M$ and $m$ are the projectile and electron mass, respectively. Rearranging gives

$$E_{\text{ECC}} = \frac{1}{2} m v^2 = \frac{m}{M + m} (E_0 - E_i)$$

The ECC peak is a well known feature of the electronic energy spectra arising from the ionization by the impact of protons and positive ions of gaseous targets$^5,6,7$ and from thin foils$^8$. For heavy–particle impact, the massive projectile is essentially undeflected by the collision, hence the ECC peak is located at very small electron angles.

Recently it has been proposed that ECC may also result in structures in the ejected electron energy spectra arising from positron impact ionization$^9,10,11$. Since a positron has the same mass as an electron, ECC would result in the excess kinetic energy being shared approximately equally, resulting in electrons ejected with a distribution of kinetic energies peaked, from equation (4.4), at $(E_0 - E_i)/2$. Additionally the collision may deflect the positron through much larger angles$^{12}$ than is the case for heavy ions, and consequently, there is some doubt as to whether or not an ECC structure would be visible in the DDCS.

4.1.1 ECC in Ionization by Protons and Positive Ions

The first experimental evidence of ECC was obtained by Rudd and Jorgensen$^{13}$ and Rudd et al$^{14}$ while studying proton impact ionization of He and H$_2$. They measured the doubly differential ionization cross-section $(\frac{d^2\alpha}{dE_{\text{elec}} \cdot d\Omega_{\text{elec}}})$ over a range of impact energies from 100 to 300keV and a range of angles from 10° to 160°. For both targets their results
did not agree with the first order Born approximation calculation of Oldham\textsuperscript{15} which predicted that the electron energy distribution would fall almost monotonically with energy, $E_{\text{elec}}$. The discrepancy manifested itself as humps when plotted against $E_{\text{elec}}$ and was most pronounced at 10$^\circ$. The humps occurred around energies for which $v_{\text{elec}}=v_{\text{proj}}$. The discrepancy between experiment and the calculations of Oldham\textsuperscript{15} was because a first order Born approximation does not account for correlation in the final state between the ion and the two out-going particles.

Salin\textsuperscript{16} used the more elaborate distorted-wave Born-approximation to calculate $\frac{d^2\sigma}{dE_{\text{elec}} d\Omega_{\text{elec}}}$ for 300keV proton impact on H. Here correlation was accounted for by a Coulomb distortion of the final state wave function. The forward enhancement in $\frac{d^2\sigma}{dE_{\text{elec}} d\Omega_{\text{elec}}}$ observed by Rudd and Jorgensen\textsuperscript{13} and Rudd \textit{et al} \textsuperscript{14} for $v_{\text{elec}}=v_{\text{proj}}$ was successfully reproduced, however a quantitative comparison with the experimental results was not possible due to the different targets employed by the two groups.

Macek\textsuperscript{17} calculated $\frac{d^2\sigma}{dE_{\text{elec}} d\Omega_{\text{elec}}}$ for He and H$_2$ bombarded by 300keV protons, using Fadeev's three-body formalism\textsuperscript{18}. The structures in $\frac{d^2\sigma}{dE_{\text{elec}} d\Omega_{\text{elec}}}$, noted by Rudd and Jorgensen\textsuperscript{13} and Rudd \textit{et al} \textsuperscript{14} for emission at 10$^\circ$ were accurately reproduced and the results for both targets were found to be in reasonable agreement in the experimental values. In addition, a pronounced cusp in the ejected electron energy distribution was predicted for electrons emitted at 0$^\circ$, when $v_{\text{elec}}=v_{\text{proj}}$.

This was experimentally verified by Crooks and Rudd\textsuperscript{5}, who measured $\frac{d^2\sigma}{dE_{\text{elec}} d\Omega_{\text{elec}}}$ for electron emission around 0$^\circ$ for He bombarded by 100-300keV protons. The results for 300keV are presented in figure 4.2 along with the Born approximation predictions of Oldham for 0$^\circ$ and the Macek theory for 0$^\circ$ and 1.4$^\circ$. The latter angle was chosen because the angular resolution of the apparatus was ±1.4$^\circ$. Both the experimental and theoretical results contain a similar cusp-like peak at around 163eV, the ejection energy corresponding to $v_{\text{elec}}=v_{\text{proj}}$. The magnitude of the experimental peak lies somewhere between the theoretical curves 0$^\circ$ and 1.4$^\circ$. Harrison and Lucas\textsuperscript{8} observed similar structures in the energy spectra of secondary electrons ejected in the forward direction, by proton and H$_2$ ions transmitted through thin C and Au foils. The ejected electron energy spectra were taken at five impact energies between 110 and 320keV and all were found to contain ECC peaks. Further experimental studies of this process have now been performed with
different targets\(^6\) (eg. Ne and Ar) and projectiles\(^7\) (eg. C\(^{6+}\), O\(^{8+}\), Cl\(^{11+}\), etc). Rodbro and Anderson\(^6\) measured \(d^2\sigma/dE_{\text{elec}}d\Omega_{\text{elec}}\) for proton impact at energies in the range \((15-1500)\text{keV}\) and found the yield of ECC electrons to reach a maximum when \(v_{\text{proj}}=1.4v_i\), where \(v_i\) is the velocity of the target electron to be captured. For increasing impact energies the ECC yield was found to fall off in a similar way to that for capture to bound states.

\[
\begin{align*}
\text{Figure 4.2: Cross-sections for electrons ejected from He at 0° by 300keV H}^+.
\end{align*}
\]

\subsection*{4.1.2 ECC in Ionization by Positrons}

Calculations by Brauner and Briggs\(^9,19,20\) predict that an ECC cusp should be present in the TDCS for ionization of H by positron impact, whilst in the case of electron projectiles an anti-cusp should occur. DDCS calculations on the same system by Mandal \textit{et al} \(^21\), Bandyopadhyay \textit{et al} \(^22\) and Sil \textit{et al} \(^10\) predict the existence of the cusp over a range of forward emission angles. In contradistinction, Schultz and Reinhold\(^11\) predict a ridge in the DDCS, rather than a cusp, which persists over a wide range of ejection energies and angles. The results of Schultz and Reinhold\(^11\), Mandal \textit{et al} \(^21\) and Bandyopadhyay \textit{et al} \(^22\) are shown in figure 4.3.
Figure 4.3: The double differential ionization cross-section for the impact of 100eV positron on atomic hydrogen as a function of electron ejection energy for several ejection angles. Bandyopadhyay et al.\(^{22}\) (solid lines, where I to XII represent the curves corresponding to 0°, 5°, 10°, 20°, 30°, 40°, 50°, 60°, 80°, 90°, 120° and 180° ejection angles); Schultz and Reinhold\(^{11}\) (broken lines); Mandal et al.\(^{21}\) (dashed–dot line) for 0° ejection angle.

Brauner and Briggs\(^9\) calculated the triple differential cross-section at 0°, as a function of the electron emission energy. They used a first order Born approximation with only an electron–positron Coulomb wave to represent the final state, thus neglecting the positron–ion potential. For collisions of 1keV positrons with H a cusp was predicted around \(E_{\text{ECC}}\). A later paper\(^{19}\) by these same authors investigated the energy dependence of the ECC peak with impact energy. At 250eV impact energy, no dramatic changes in the shape of the ECC cross-section were observed, however, as the impact energy was
increased, a new structure, in the form of a sharp minimum on the low-energy side of the 
ECC cusp, was seen at 45°. This structure was attributed to Ps formation by a double, or 
Thomas, scattering process\textsuperscript{23}. This process is well documented in proton scattering\textsuperscript{24} and 
from simple kinematics the Thomas angle at which the double scattering process occurs for 
positron impact can be shown to be 45° (compared to 0.03° for protons). Brauner and 
Briggs\textsuperscript{20} modified their earlier work\textsuperscript{9} by multiplying the first order Born approximation by 
two Coulomb distortion factors to represent the separate two-body interactions between the 
electron and positron and between the positron and ion and found the ECC cusp still to be 
present in the TDCS.

Conversely, Brauner and Briggs\textsuperscript{9} predicted the existence of a dip or anti-cusp in the TDCS 
when the projectile was an electron. This anti-cusp has now been observed (Guang-yan \textit{et al} \textsuperscript{25}) for He and Ar targets over a variety of impact energies from 600eV to 1keV. As yet 
no anti-cusp has been observed in the equivalent antiproton measurements. Yamazaki \textit{et al} \textsuperscript{26} measured the electron energy spectra, in the forward direction, for electrons emitted 
from carbon foils bombarded by antiprotons of energies from 500 to 750keV. Their results 
did not show evidence of an anti-cusp. However, if any cusp existed it would be hidden 
by a high background of energetic electrons and be small in magnitude because of multiple 
collisions within the thick carbon foils.

Mandal \textit{et al} \textsuperscript{21} calculated $\frac{d^2\sigma}{dE_{\text{elec}} \, d\Omega_{\text{elec}}}$ for 100eV positron impact ionization of H at 0° 
electron emission angle. They used the three-body scattering formalism of Fadeev\textsuperscript{18}, to 
construct the Coulomb wave, used to represent the final state of the collision. This 
formalism treated the Coulomb interaction between the three pairs of post collision particles 
equally, that is, without preference to any one particular pair. Their calculation, shown in 
figure 4.3, predicted a pronounced cusp in the electron energy distribution peaked at $E_{\text{ECC}}$ 
as given by equation 4.4, despite originally overestimating its magnitude\textsuperscript{27}.

By employing the same final state wave function as Brauner \textit{et al} \textsuperscript{28}, Bandyopadhyay \textit{et al} \textsuperscript{22} and Sil \textit{et al} \textsuperscript{10} calculated $\frac{d^2\sigma}{dE_{\text{elec}} \, d\Omega_{\text{elec}}}$ for positron impact on H. At impact 
energies 100 and 250eV, Bandyopadhyay \textit{et al} \textsuperscript{22} predicted the existence of ECC cusps in 
$\frac{d^2\sigma}{dE_{\text{elec}} \, d\Omega_{\text{elec}}}$ for all twelve angles investigated ranging from 0° to 180°. These results 
are also shown in figure 4.3. At an impact energy of 100eV, Sil \textit{et al} \textsuperscript{10} also predicted ECC 
cusps in $\frac{d^2\sigma}{dE_{\text{elec}} \, d\Omega_{\text{elec}}}$ for a range of emission angles from 0° to 60°.
In a Classical Trajectory Monte-Carlo (CTMC) calculation, Schultz and Reinhold obtained a different result for the same system. The resulting variation of $d^2\sigma/dE_{\text{elec}}\,d\Omega_{\text{elec}}$ with electron energy is shown in figure 4.3, for a range of emission angles from 2° to 120°. In contrast to the findings of Mandia et al., Bandyopadhyay et al. and Sil et al., the results of Schultz and Reinhold do not contain the pronounced cusps due to ECC. Instead, small ridges are present around $E_{\text{ECC}}$, for ejection angles up to 30°. Schultz and Reinhold attribute the near absence of a cusp in their results to the scattering of positrons to wide angles, as with all positron processes. Therefore, although ECC may occur, such electrons were thought to be distributed over a wide range of angles causing the magnitude of the peak in $d^2\sigma/dE_{\text{elec}}\,d\Omega_{\text{elec}}$ to be significantly reduced.

4.1.3 Experimental Studies of ECC in Positron-Atom Collisions and the Present Work

The first evidence that electrons may be emitted with energies close to $E_{\text{ECC}}$ was obtained by Charlton et al. using an axial magnetic field system. Retarding field spectra of the ejected electrons were measured by applying a variable potential to a grid in front of the electron detector, causing only those electrons with kinetic energies greater than a certain value to be detected. However, a consequence of using a magnetic beamline was that in reality only axial energy loss, rather than the total energy loss of kinetic energy, could be assigned. Their results for 200eV positron impact on Ne is shown in figure 4.4, plotted as a function of a reduced retarding voltage, with the theoretical results of Brauner and Briggs which are shown integrated and normalized for comparison. When plotted in this way, $E_{\text{ECC}}$ corresponds to around 0.5V. The electron count rate appears to fall to a plateau, with values just above zero, before falling to around zero by 0.5V, indicating that there is some electron emission around $E_{\text{ECC}}$. However, the large statistical uncertainty of the measurements restricts any quantitative assessment from being made.
More recently Moxom et al. 4, also using a magnetic field (25G) to guide their positron beam through a scattering cell, studied the energy distribution of electrons ejected from Ar at angles around 0°. Using impact energies of 50, 100 and 150eV ECC was expected to occur around 17, 42 and 67eV, respectively. Their method involved measuring the kinetic energies of the ejected electrons by analyzing the electron flight times in coincidence with the remnant ion. In order to reduce the angular acceptance of their system, the magnetic field strength at the scattering cell was reduced to 10G. To estimate the angular acceptance of the detection system, the transmission probability function, T(E,θ), of the apparatus was evaluated. T(E,θ) was defined as the probability of an ejected electron passing through the exit aperture of the scattering cell and reaching the detector, as a function of emission energy (E) and angle (θ), relative to the incident beam. T(E,θ) was estimated by solving the equations of motion for electrons with a given E and θ but with a large number of different starting coordinates, equally spaced over the entire range of possible starting points within the interaction region. The angular acceptance of the system was thus estimated to extend, at most energies, to angles <±10°. The results of Moxom et al. 4, shown in figure 4.5, exhibit, bar 50eV, a small ridge which could be compatible with the predicted ECC peak. The shape and position of these ridges resemble those predicted by Schultz and Reinhold11.
The first ECC measurement via the energy loss technique was performed by Kőver et al.\(^1\) using an electrostatic system in conjunction with a double-pass 30° PPA. The positrons and electrons inelastically scattered from Ar at angles around 0° were measured in coincidence with the remnant ion. Their energy distributions were measured by ramping the potential difference between the plates of the PPA. Their results at the three impact energies (100, 150 and 250eV) investigated are shown in figure 4.6. At these energies, the ECC loss peak would be expected to occur at energies 58, 67 and 117eV respectively. The distributions were found to be very similar for both projectiles. No structure was observed in the scattered positron spectrum at any incident energy which could be attributed to the predicted ECC process. By employing an electrostatic system in conjunction with a double-pass 30° PPA the angular acceptance of the system was <±6°.
Figure 4.6: Kövér et al.\textsuperscript{2} scattered $e^+$ (●) and $e^-$ (○) results around 0° at impact energies 100eV (a), 150eV (b) and 250eV (c) compared to the CTMC calculations of Sparrow and Olson\textsuperscript{20}.

Kövér et al.\textsuperscript{3} extended this work to the DDCS for 100eV incident electrons and positrons scattered from Ar at 30° and 45°. The experimental set-up and method was similar to that used in Kövér et al\textsuperscript{2}, the main difference being the use of a RFA, of angular acceptance ±9.5°, instead of the PPA. Again the scattered or ejected particle was measured in coincidence with the remnant ion. The performance of the PPA, in terms of energy resolution and ensuring a low annihilation $\gamma$-ray background of the particle detector, was superior to that of the RFA but the latter had the advantage of being able to measure a wider energy range over a reasonable period of time to achieve adequate statistical accuracy. The 30° results for positron impact are shown in figure 4.7 where they are compared with results of a CTMC calculation on the same target\textsuperscript{30}. According to equation (4.4) ECC was
expected to occur at around 42eV in the energy spectra. No ECC cusp was observed at either of the angles investigated. Good agreement was observed between the CTMC calculations\(^{30}\) and the measured ejected electron spectra of Kõvér et al \(^{3}\), but less so with the scattered positron spectra. At the higher scattered positron energies theory exceeds the measurements of Kõvér et al \(^{3}\); being higher by a factor of about 3–4 at the ionization limit. The cause of this discrepancy was not understood but is later discussed in section 4.3.2.

![Figure 4.7: Kõvér et al \(^{3}\) double differential cross-section of ejected e\(^{-}\) (triangles) and scattered e\(^{+}\) (diamonds) as a function of energy at 30° for 100eV e\(^{+}\) impact on Ar. The solid line is the CTMC calculations of Sparrow and Olson\(^{30}\).](image)

The motivation for our work was to repeat the 30° study of Kõvér et al \(^{3}\) using a different detection system, namely the PPA, to see whether the disagreement persists, that is, whether it had physical meaning or was simply caused by some systematic effect in the measurement.

### 4.2 Experimental Details

The apparatus is shown schematically in figure 4.8. Its main features were described in detail in Chapter 2. DDCS measurements using a tandem 30° PPA were performed at a scattering angle of 30° to the incident beam; the only angle studied.
Figure 4.8: Schematic of the PPA experimental arrangement
Positrons emerged from a 4.2GBq $^{58}$Co source and were moderated by four annealed tungsten meshes. A modified Soa gun (§2.4.1) was used to focus the monoenergetic positrons. After separating the beam from the high energy positron and γ-ray flux with a double cylindrical condenser (§2.4.3), a five element lens (§2.4.5) was employed for final focusing. The energy distributions of the positrons or electrons, scattered off the target gas, in our case argon, were measured by ramping the potential difference between the plates of the double-pass PPA using a controlled power supply. The angular acceptance of the PPA was approximately ±8° (§4.2.1.1) and its energy resolution was 5.8% determined by measuring the width of the peak of the electrons scattered from argon at different impact energies (§4.2.1.1). The argon gas emerged from a multi-capillary array (§2.5) situated 5mm above the centre of the beam. The maximum base pressure in the vacuum chamber during the measurement taking was approximately $10^{-5}$Torr. The experimental set-up was enclosed by mu-metal to reduce the remnant magnetic field to less than 3mG. At impact energies 100 and 60eV the intensity of our beam was ≈4750 and 1600e+s⁻¹, respectively.

The electronics of the system were the same as used for obtaining our SDCS measurements (§3.3). The potential difference, $V$, applied to the plates of the double-pass 30° PPA was controlled by the MCS card and DAC. The voltage was ramped between a minimum voltage, $V_{\text{min}}$, and a maximum voltage, $V_{\text{max}}$ by the MCS channel advance pulse and reset at the end of each pass by the MCS reset pulse. The MCS card stored the output from the TAC in the channel corresponding to the pass-energy of the PPA. The dwell time was the same for each channel. The voltage range was selected according to the impact energy of the collision. A range of pass lengths (2, 4, 8, 16 and 128 channels) were available, that is, the number of stepped increases in voltage required to get from $V_{\text{min}}$ to $V_{\text{max}}$. The greater the number of voltage steps the more detailed the spectrum. However, the more channels chosen the longer the data acquisition time needed to attain a measurement with reasonable statistical value. For our investigation we chose a pass length of 16 channels as a compromise between avoiding lengthy acquisition times and of minimizing loss of definition. For example, a 7 day run-time was required to produce the scattered positron spectrum, shown in figure 4.14b, at the impact energy of 100eV. The statistical accuracy of the data was ≈15% at the high energy range.

Included in the measurements was a background contribution which arose from uncorrelated timing signals from CEM1 arriving in coincidence with a signal from CEM3. Since the signals from CEM1 and CEM3 were mainly randomly correlated in time the background contribution was expected, and found, to be flat across the energy range.
scanned by the PPA. However, because the resolution of the PPA was proportional to its pass-energy (§4.2.1) this background contribution, along with our measurements, were normalized to account for this energy dependence. The correction factor applied to each channel was the reciprocal of the PPA pass-energy associated with that channel. Hence, in section 4.3, the background contribution appears instead to fall off in magnitude with increasing energy. In order to determine the magnitude of this background, the CEM1 signal was replaced by a pulse train from a signal generator, thus gating the system randomly, whilst timing the ions in the usual way.

4.2.1 The Parallel Plate Analyzer (PPA)

For many years electrostatic deflection analyzers have been employed in ion (electron, photon)–atom collision research\(^3\). However, they have not been used for studying positron–atom collisions until very recently because they require a field-free scattering region which can only be easily done using an electrostatic lens systems. In an electrostatic lens system all electric fields used for focusing and transporting the positron beam are applied prior to entering the interaction chamber. Thus, a scattered positron will continue along the trajectory with which it left the interaction centre and using an electrostatic analyzer its energy and angle can be measured. The excellent resolving power of electrostatic analyzers make them a very good detection system. However, high resolution can only be obtained at the expense of intensity.

Improving the signal for a given resolution can be achieved by focusing the beam in two planes, although most electrostatic analyzers focus in one. In addition, the higher the order of focusing the greater the detector current will be for a given resolution.

Shown in figure 4.9 is a schematic of the double–pass 30° PPA used to measure our DDCS. In a double–pass PPA a scattered positron undergoes two opposite parabolic trajectories, that is, the path of the scattered positron describes a sine wave type deflection. A 30° PPA was chosen because of its unique second order focusing\(^3\) at this angle. This excellent focusing property meant that the resolution of the analyzer was good even at relatively large acceptance angles. This feature is important in positron collision investigations because of the low intensities of laboratory based beams compared to equivalent ion (electron) currents. Furthermore, a double–pass PPA, as used in the 0° work of Kövér et al\(^2\), had the advantage over a single–pass PPA in that it reduced the detection of high energy secondary electrons. These high energy secondary electrons are generated
by positrons of incorrect energy colliding and annihilating with electrons from the inner parts of the analyzer. These secondary electrons cause a high background count in the energy distribution of a single-pass PPA. The additional parabolic deflection of a double-pass PPA, however, filters out most of these unwanted secondary electrons, reducing the background.

Figure 4.9: Schematic representation of the double-pass 30° Parallel Plate Analyzer.

The double-pass PPA consists of three parallel plates each separated by a distance, \( h (=14\text{mm}) \). A uniform electric field was created by applying a potential difference between these plates. In our set-up, the middle plate was earthed and a voltage, \( V \), applied to the upper and lower plates. Three slits of width 12, 15 and 8mm were cut into the middle plate. These slits were covered with 95% transmission Cu mesh to maintain a uniform electric field within the PPA. Furthermore, five guard electrodes were also used to help keep a uniform electric field; their potentials being subdivisions of the total via a resistor chain. All metal surfaces were coated with colloidal graphite to reduce the secondary electron emission.

The positron travels in a straight line from the interaction volume to the entrance slit of the analyzer. Entering the analyzer the electric field deflects the positron along a parabolic path. For the positron to pass through all three slits depends on its initial kinetic energy and the strength of the field. The total displacement of the positron, \( x_o \), along the x-axis in a constant electric field is given by

\[
x_o = (d_s + d_i)\cot\theta + 4h(E/V)\sin2\theta \tag{4.7}
\]
The resolution of an analyzer is described analytically by the base resolution $R_B$. The base resolution is defined as the width of a spectral line measured at its base divided by the mean energy of the peak. In order to predict how far positrons with incorrect energy or entrance angle will either overshoot or undershoot the distance $x_0$ from the 'point' source to image, one expands the distance in a Taylor's series about both a variation in base energy, $\Delta E_B$, and in angle, $\Delta \theta$,

$$
\begin{align*}
x &= x_0 + \sum_{i=1}^{\infty} \frac{1}{i!} \frac{\partial^i x}{\partial \theta^i} (\Delta \theta)^i + \sum_{i,j=1}^{\infty} \frac{1}{j!} \frac{\partial^i x}{\partial E^j} (\Delta E_B)^j + \sum_{i,j=1}^{\infty} \frac{c_{ij}}{(i+j)!} \frac{\partial^i x}{\partial \theta^i \partial E^j} (\Delta \theta)^i (\Delta E_B)^j
\end{align*}
$$

where $\Delta \theta = \theta - \theta_0$, $\Delta E_B = E - E_0$ and $c_{ij}$ is the binomial expansion coefficient. The first series defines the linear angular dispersion, $\Delta x(\Delta \theta)$. The individual terms in this series correspond to the degree of focusing associated with an analyzer. The second series defines the linear energy dispersion, $D (=\Delta x(\Delta E))$. To a good approximation $D$ is equal to the first term in this series,

$$
D = E \frac{\partial x}{\partial E}
$$

The cross terms of the third series can be neglected because they are much smaller than the other terms.

The spread as expressed in equation (4.6) requires an additional term to account for the size of the exit slit and the finite source. This additional term is,

$$
R(w_x, w_s) = \frac{(w_x + w_s)}{D}
$$

where $w_x$ and $w_s$ are the widths of the exit slit and source along the x-axis.

Incorporating the above expressions, equation (4.6) can be used approximately for the base resolution,

$$
R_B = \frac{(w_x + w_s)}{D} + \frac{\Delta x(\Delta \theta)}{D}
$$

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For a Parallel Plate Analyzer the partial derivatives are

\[ \frac{\partial x}{\partial \theta} = -d \sin^2 \theta + 8h \frac{E}{V} \cos \theta \]

\[ \frac{\partial^2 x}{\partial \theta^2} = 2d \sin^2 \theta \cos \theta - 16h \frac{E}{V} \sin 2\theta \]

\[ \frac{\partial^3 x}{\partial \theta^3} = -2d(1 + 2\cos^2 \theta) \sin^4 \theta - 32h \frac{E}{V} \cos 2\theta \] (4.10)

and the dispersion is

\[ D = 4h(E/V) \sin \theta \] (4.11)

Second order focusing occurs only at 30°, so that both

\[ \frac{\partial x}{\partial \theta} = 0 \text{ and } \frac{\partial^2 x}{\partial \theta^2} = 0 \] if \( \frac{E}{V} \) is made equal to \( \frac{d}{h} \). (4.12)

The base resolution for a 30° Parallel Plate Analyzer is thus,

\[ R_b = \frac{(w_e + w_s)}{D} + 4.6(\Delta \theta)^3 \] (4.13)

(see Appendix)

In our set-up \( w_e, w_s, \) and \( \Delta \theta \) were measured to be 8mm, 4mm (§2.5) and 0.140rad (§4.2.1.1), respectively.

The dispersion was 97mm (Kövér et al 35). To a first approximation\(^{36}\),

\[ \Delta E_b = 2\Delta E \] (4.14)

where \( \Delta E \) is the Full energy Width at Half Maximum (FWHM) which was easier to
measure than $\Delta E_B$. Hence the resolution, $R (=\Delta E/E)$, of our analyzer was calculated to be 6.1%.

4.2.1.1 Design and Performance

The performance of the PPA was modelled, before manufacture, using SIMION 4.0. Shown in figure 4.10 are the trajectories for positrons of 100eV impact energy and the corresponding potential settings.

![Figure 4.10: Simulation of the positron trajectories through the PPA from 100eV e\textsuperscript+ impact.](image)

The PPA was placed so that the angle between the centre of the entrance slit of the PPA and the direction of the incident beam was 30°, see figure 4.8. The width of the entrance slit was 12mm and the PPA was positioned 40mm away from the interaction region giving an angular acceptance of $<\pm 8^\circ$.

The energy resolution of the analyzer was determined experimentally from electron measurements. Using the secondary electron emission from the moderator to obtain an electron beam (§2.5) the FWHM of the elastic peak was measured from electron–argon scattering at a particular impact energy, $E_0$. A typical elastic spectrum is shown in figure 4.11.
Figure 4.11: Measured beam energy profile for 50eV electrons elastically scattered at 30° from e–Ar collisions.

This procedure was repeated for nine different values of \( E_0 \) ranging from 15 to 100eV. The total energy resolution of the PPA, \( \Delta E_T \), was assumed to be the sum of the resolution of the electron beam, \( \Delta E_{\text{elec}} \), and analyzer, \( \Delta E \), in quadrature, thus,

\[
(\Delta E_T)^2 = (\Delta E)^2 + (\Delta E_{\text{elec}})^2 \quad (4.15)
\]

Since the fractional energy resolution of the PPA is a constant, \( \Delta E/E_0 = C \), equation (4.15) can be rewritten as

\[
(\Delta E_T)^2 = C^2 E_0^2 + (\Delta E_{\text{elec}})^2 \quad (4.16)
\]

A plot of \((\Delta E_T)^2\) against \((E_0)^2\) is shown in figure 4.12 and yields a value for the energy resolution of the PPA of \((5.8\pm0.2)\%\) which was close to the expected performance of
6.1% as derived in section 4.2.1. In addition, the plot yields a value for the electron beam energy width, $\Delta E_{\text{elec}}$, of $(1.4 \pm 0.2)\text{eV}$. The width of the electron beam was large compared with that of a filament source, but consistent for a beam obtained by secondary electron emission from a moderator. Its width was of similar size to our measured positron beam ($\approx 3\text{eV} \pm 2.7$).

Figure 4.12: The total parallel plate analyzer resolution ($\Delta E_T$) measured as a function of the energy of the electron beam, $E_0$.

4.3 Results and Discussion

4.3.1 Ejected Electron Spectra

Displayed in figure 4.13 are the signal, background and background–subtracted spectra for the ejected electron at impact energy $100\text{eV}$. The horizontal error bars represent the energy resolution of the PPA.
Figure 4.13: Measurements of the ejected electron at 100eV impact energy from e⁺–Ar collisions at 30°. (a) ● signal, ○ background and ▲ background-subtracted data.

The signal was unfortunately entirely swamped by background. The high background was due to the low expected signal count rate from the PPA detector thus allowing the chance for an uncorrelated secondary electron to trigger the coincidence. The secondary electrons contribute to the high background in the electron measurement because there is no way of screening them out.

4.3.2 Scattered Positron Spectra

Displayed in figures 4.14 and 4.15 are the scattered positron spectra for impact energies 100 and 60eV, respectively. Presented in figures 4.14a and 4.15a are the spectra for the signal, background and background-subtracted measurements, with the horizontal error bars again representing the energy resolution of the PPA. Fortunately, at the higher scattered positron energies, the background contribution was less than the scattered positron signal allowing measurements into their energy distribution possible. For example, the background contribution at 100eV impact energy was around 82% and 28% of the signal at scattered positron energies of 33 and 84eV, respectively. Presented in figures 4.14b are our normalized DDCS along with the 100eV data of Kővér et al.⁴ and the results of Sparrow and Olson⁵ for their CTMC calculation.
Figure 4.14: Measurements of the scattered positron at 100eV impact energy from $e^+\text{--Ar}$ collisions at 30°. (a) ● signal, ○ background and ▲ background-subtracted data. (b) — Sparrow and Olson\textsuperscript{30}; ◇ Kövér \textit{et al.}\textsuperscript{3}; ▲ background-subtracted data (normalized).
Figure 4.15: Measurements of the scattered positron at 60eV impact energy from $e^+$–Ar collisions at 30°. (a) ● signal, ○ background and ▲ background-subtracted data. (b) ▲ background-subtracted data (normalized).
The absolute scale for the present experimental data was obtained by normalization to the work of Sparrow and Olson\textsuperscript{30}. The normalization constant was determined from the average of the data at the four scattered positron energies 43, 47, 51 and 55eV for 100eV impact energy. The choice of these energies was somewhat arbitrary, although in this range the shape of the earlier work of Kóvér \textit{et al.}\textsuperscript{3}, which was normalized independently, agrees with the calculation. However, whatever the uncertainty on the absolute scale assigned to the experimental data it does not affect the discussion which follows.

The relative shapes of the DDCS between the present work, taken with the PPA, and that of Kóvér \textit{et al.}\textsuperscript{3}, taken with the RFA, were in good agreement at all the scattered positron energies. When these two experiments are compared with theory reasonable agreement was observed at scattered positron energies up to 70eV, however at the higher energies theory exceeded the measurements. In addition, this discrepancy at the higher energies seems to be dependent on angle. For example, in their experiment at zero degrees, Kóvér \textit{et al.}\textsuperscript{2} and Moxom \textit{et al.}\textsuperscript{4} found that their data could be fitted to the calculation of Sparrow and Olson\textsuperscript{30} (communicated privately by R E Olson) for scattering at 3°. The data at 30° are presented in this work, whilst those of Kóvér \textit{et al.}\textsuperscript{3} at 45° display an even larger discrepancy with theory.

The present measurement has established that this discrepancy is not, for instance, an instrumental effect based upon the use of a RFA in the experiment of Kóvér \textit{et al.}\textsuperscript{3} but is a genuine feature of the scattering process (ie. that there are less scattered positrons with higher energies than predicted by theory). It is notable in this respect that the work of Kóvér \textit{et al.}\textsuperscript{2}, which agreed with the calculation of Sparrow and Olson\textsuperscript{30}, was undertaken with the PPA used in the present study.

The fact that there are less scattered positrons with higher energies than expected suggests that there is greater energy sharing between the two outgoing particles. Tentative support for this viewpoint comes from the work of Berakdar and Klar\textsuperscript{37}. This work considered positron and electron impact ionization of atomic hydrogen though detailed positron results were presented only at 500eV impact energy such that only qualitative comparisons are feasible. In figure 4.16 their TDCS for electrons ejected at zero degrees following positron impact contain three features. Most prominent is that they are heavily peaked at low electron energies, with most having energies below 100eV. Secondly, there is only a small peak in the TDCS around the energy expected for ECC. Finally, the cross section has a broad peak at high ejected energies before falling rapidly as the ionization limit is approached. Berakdar

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and Klar\textsuperscript{37} have found that the latter feature is due to close projectile–electron collisions in which most of the projectile energy and momentum is transferred to the bound electron. Examining the TDCS calculated by Berakdar and Klar\textsuperscript{37} it is clear that such events progressively contribute more to the ionization cross-section as the positron scattering angle is increased. Thus, we tentatively link our observation of a diminishing DDCS for positrons scattered with small energy loss at angles other than the forward direction to the same physical phenomenon.

There are currently no theoretical calculations at 60eV impact energy to compare with our results. The average signal of the first four data points in figure 4.15a is zero within statistical uncertainties. Figure 4.15b shows the cross–sections plotted on an absolute scale by applying the normalization constant obtained from the 100eV data. A similar energy dependence to that found at 100eV data is observed for 60eV.

For impact energies 100 and 60eV the ECC cusp is expected, using equation (4.4), to occur at 42 and 22eV, respectively. Neither of the spectra shown in figures 4.14b and 4.15b exhibited such a cusp.

Figure 4.16: Berakdar and Klar\textsuperscript{37} TDCS calculations for positron impact ionization of atomic hydrogen as a function of the positron scattering angle and the electron–ejection energy. The projectile incident energy is 500eV. The secondary electron is detected in the forward direction.
4.4 Summary

In conclusion, positron–argon DDCS have been measured at a scattering angle of 30°, and for 60 and 100eV impact energies, using a double–pass PPA. The 100eV measurements agree with the results of Kövér et al. but are in discord with the CTMC calculations of Sparrow and Olson at higher scattered positron energies. The measurements suggest that, at least for angles away from the incident beam direction, there is much greater energy sharing between the scattered positron and the ejected electron. By analogy with the theoretical work of Berakdar and Klar for atomic hydrogen we tentatively attribute this to the importance of close positron–electron collisions in the ionization process. Similar to previous findings, our work has failed to discern any contribution of ECC to the DDCS, suggesting that this process makes only a minor contribution to the overall positron impact ionization cross–section.


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Chapter 5

Conclusion

The work presented in this thesis concerns experimental studies of differential scattering from positron-argon collisions. Differential cross-section measurements provide a more stringent test of theory than their counterpart integral cross-section measurements. Double and single differential measurements were performed using a tandem 30° PPA and a RFA, respectively.

A low energy positron beam was crossed with a gas jet and the remnant ions detected in coincidence with the scattered particle. This was achieved by pulsing on an ion extraction field across the interaction region when a particle was detected by the scattered channeltron fitted with a RFA (figure 3.13). Depending on the potential applied to the retarding grid of the RFA different collision processes could be investigated. The ions were detected using a time-of-flight technique in order to count only those of the desired charge-to-mass ratio. These coincidences were recorded on a PC installed with a multi-channel-analyzer card.

This set-up was used to measure the energy dependencies of the DCS for elastic scattering, positronium formation and direct single ionization in positron-argon collisions at 30° and 60° in the energy range 40-150eV. Of particular interest was the energy range 55–60eV where the Detroit group (Dou et al.1) reported a drop in the elastic scattering cross section by a factor of two. This was tentatively attributed to a cross-channel coupling effect with an open inelastic scattering channel.

Our $d\sigma_e/d\Omega$ measurements showed no evidence of structure. This agrees with the results of new experiments2 in which the Detroit group have not been able to reproduce the previously reported structure1. These new results2, together with our own, now seem to rule out the occurrence of the resonance-like structures at intermediate energies in the elastic scattering DCS for positron-rare gas collisions as reported by Dou et al.1,3,4.

Similarly, our $d\sigma_p/d\Omega$ measurements showed no evidence of structure, but instead, exhibited an exponential-type decay with increasing incident positron energy. The intensity at the more forward angle of 30° was, as might be expected, higher than that at 60°.
difference was approximately a factor of six at 40eV. Measurements of \( d\sigma_{Ps}/d\Omega \) are highly beneficial in the research of Ps beams. Knowledge of the differential cross-section for Ps production is a measure of a gases efficiency, and hence usefulness, as a neutralizer in \( e^+\)-gas collisions.

Finally, our \( d\sigma^+_{ion}/d\Omega \) measurements at 60° were found to remain approximately constant in the energy range (40–60eV). Above 60eV ionization was observed to fall off appreciably. The energy dependence of \( d\sigma^+_{ion}/d\Omega \) at 30° falls away across the full energy range 40–150eV. The intensity of the scattered signal at 30° was approximately twice the magnitude of the 60° measurements at 40eV. Our \( d\sigma^+_{ion}/d\Omega \) are the first of their kind. In the future it would be desirable to compare the energy dependence with some theoretical calculations or to make absolute measurements of these cross-sections.

Repeatedly stated throughout this thesis is that differential cross-section measurements are time-consuming. Therefore methods of reducing the run-time of these measurements would be desirable. A future improvement to the RFA set-up would be to install two scattered CEM positioned at \( \pm\theta^\circ \) measured with respect to the incident beam. This would double the scattered signal and the frequency at which the ion extraction plates are pulsed on. Hence, the \( e^+\)-ion coincidences would be twice the value as before and a measurement of the same statistical accuracy would only require \( 1/2 \) of the run-time.

The RFA set-up is also suitable for measuring the ratio of double and single ionization cross-sections. In particular, the angular dependency of this ratio is of considerable theoretical interest in that it could be used to provide a better understanding of the mechanism for double ionization.

Double differential ionization cross-sections were measured at 60 and 100eV impact energies to investigate the energy distribution of the scattered or ejected particle in coincidence with the remnant ion. In particular, these measurements provided an opportunity to study the phenomena known as Electron Capture to the Continuum (ECC) for positron impact. ECC is a special case of impact ionization where the ionized electron and scattered positron emerge with closely matched velocities, such that the electron may be considered to have been transferred to a continuum state of the scattered positron. ECC has been observed in heavy-ion impact studies^5,6,7^, manifested by a cusp in the energy
spectrum of the DDCS. Some theoretical calculations predict the existence of the ECC cusp for positron impact\textsuperscript{8,9,10}, while others, most notably the Classical Trajectory Monte-Carlo (CTMC) calculations of Sparrow and Olson\textsuperscript{11}, do not. The experimental investigations of Moxom \textit{et al}\textsuperscript{12} and Kövér \textit{et al}\textsuperscript{13} at 0° qualitatively support the latter. DDCS for 100eV incident positron scattering at 30° and 45° have also been measured by Kövér \textit{et al}\textsuperscript{14} using an RFA set-up. Again no cusp was observed. However, agreement with the CTMC calculations deteriorated at the higher scattered positron energies. The cause of this discrepancy was not known. The motivation for our work was to repeat the 30° study of Kövér \textit{et al}\textsuperscript{14} using a different detection system, namely the PPA, to see whether the disagreement persisted, that is, whether it had physical meaning or was simply caused by some systematic effect in the measurement.

The experimental set-up and method was similar to that used in our earlier study, the main difference being the use of a tandem 30° PPA. The performance of the PPA, in terms of energy resolution and ensuring a low-annihilation $\gamma$-ray background of the particle detector was superior to that of the RFA.

Unfortunately, our ejected electron spectrum was entirely swamped by background caused by stray electrons triggering a coincidence. However, the scattered positron spectra did not suffer from this effect and agreed well with the results of Kövér \textit{et al}\textsuperscript{14} in that, within the statistical accuracy of the measurement, no ECC cusp was observed. The lack of a cusp would imply that ECC is not a major contributor to the integral single ionization cross-section, $\sigma_{\text{ion}}$. Furthermore, the discrepancy with the CTMC calculations of Sparrow and Olson\textsuperscript{15} at the higher scattered positron energies remained, suggesting that it was a real effect and not instrumental in origin. Because there are less positrons of higher energies than predicted by the CTMC calculations suggests that there is a greater degree of energy sharing occurring between the scattered positrons and ejected electrons. The work of Berakdar and Klarić\textsuperscript{16} seem to confirm this viewpoint.

A TDCS has been proposed to investigate the ECC cusp by measuring the energy distribution of the ejected electron and scattered positron in coincidence. This will be achieved by modifying the PPA set-up by cutting a slit into its upper plate and installing a second CEM behind it to measure the ejected electrons (§4.2.1). The signal from this detector is sufficiently delayed to allow a scattered positron time to be detected by the CEM positioned at the end of the PPA. These measurements are currently in progress.
The triple DCS is the most complete description of an ionization event and therefore provides the most stringent test of a theory. With improvements in the intensities and qualities of positron beams it is only a matter of time before measurements of TDCS become widely available.


Appendix

The Base Resolution of a PPA.

Equation (4.9),

\[ R_B = \frac{(w_{x_2} + w_{y_2})}{D} + \frac{\Delta x(\Delta \theta)}{D} \]  

(4.9)

can be simplified by substituting,

\[ \frac{\Delta x(\Delta \theta)}{D} = \frac{1}{3!} \frac{\partial^3 x}{D \partial \theta^3} (\Delta \theta)^3 \]

where

\[ \frac{\partial^3 x}{\partial \theta^3} = -2d(1 + 2\cos^2 \theta)\sin^{-4} \theta - 32h \frac{E}{V} \cos \theta \]  

(4.10)

and

\[ D = 4h(E/V) \sin \theta \]  

(4.11).

For 2nd order focusing,

\[ \theta = 30^\circ, \]

\[ d = d_s + d_i = h(E/V), \]

therefore,

\[ \frac{\partial^3 x}{\partial \theta^3} = -80d - 16d = -96d \]

and \( D = 2d \sqrt{3} \).

Hence,
\[
\frac{\Delta x(\Delta \theta)}{D} = \left[ \frac{1}{3!} - \frac{96d}{2d\sqrt{3}} \right] (\Delta \theta)^3 = \frac{48}{6\sqrt{3}} (\Delta \theta)^3 = 4.6(\Delta \theta)^3
\]

Substituting this expression into equation (4.9) gives,

\[
R_B = \frac{(w^* + w^*)}{D} + 4.6(\Delta \theta)^3
\]  
(4.13).