Low energy positron scattering from helium

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Abstract. Positron scattering from helium has been historically limited to experiments with energy resolution of 0.5 eV or worse. A new apparatus has been developed that allows the investigation of scattering processes with an energy resolution as good as 30 meV, allowing new experimental insight into positron helium interactions. High resolution measurements of low energy scattering from helium will be presented, with a particular emphasis on the development of benchmark cross sections, the investigation of threshold behaviour and the search for positron scattering resonances.

1. Introduction
The advent of buffer gas trapping as a method for creating high resolution positron beams has created the opportunity for the study of positron scattering to be undertaken in unprecedented detail [1, 2]. In particular, there is a need for benchmark cross sections for relatively simple scattering systems, especially above the positronium formation cross section threshold where the theoretical description of scattering becomes significantly more complicated. In addition to this, the investigation of threshold effects with any clarity has been impossible to date, as typical energy resolutions have been 0.5 eV or more. For example, in the case of positron impact ionisation, the extent of the “Wannier region” is not well understood. In this region, the escape of the two charged particle from the residual ion core is described by a simple threshold law. While resonances in positron scattering are far less likely than in the case of electron scattering, any search for resonant features must also rely on a high resolution beam and such searches have been virtually impossible until the development of the Surko trap. The present work describes the first experiments using a new positron trap system based on the San Diego design. Positron scattering from helium has been measured for energies up to 60 eV and the grand total and positronium formation cross sections have been determined. High resolution scans have been undertaken over various regions to both search for resonances and to elucidate threshold behaviour, especially at the positronium threshold where channel coupling effects have previously been reported [3].

2. Experimental apparatus
A detailed explanation of the operation of this apparatus will be provided in the near future [4], so only a brief description is presented here. Positrons are obtained from a 22-Na radioactive source which is located at the end of a two-stage cryogenic cold head, capable of maintaining a temperature of less than 8K. Neon is frozen onto the conical mount containing the 22-Na and...
Figure 1. A cutoff curve measured at 50 eV, showing the energy resolution of the positron beam. The fit (solid line) indicates an energy resolution of 65 meV.

acts as a moderator, re-emitting approximately 1% of the high energy (up to 500 keV) positrons in a low energy beam with an energy width of approximately 1.5 eV. This low energy beam is radially confined using a series of solenoids, which provide a magnetic field of approximately 100 gauss. With a 50 mCi source (current source strength is $\sim 30$ mCi), a beam of up to 10 million positrons/second is obtained. This positron beam is directed into a Surko trap located in a 530 gauss magnetic field. The trap consists of a series of cylindrical electrodes (with their axis parallel to that of the magnetic field) into which nitrogen and $CF_4$ buffer gases are admitted. The electrodes form a potential well structure into which the incoming positrons are trapped, losing energy by exciting an electronic transition in the nitrogen molecules. Positrons trapped in the electrode structure continue to collide with the buffer gas, losing energy by exciting electronic, vibrational and rotational transitions in the gas mixture until they are confined in the final stage of the electrode structure and cooled to the gas temperature (room temperature). This reservoir of cooled positrons is then emptied by carefully raising the confining potential so that the positrons are emitted as a pulsed beam, maintaining the energy spread of the cooled positron cloud.

In a strong magnetic field, the energy of the positrons can be considered as having two components, one parallel and one perpendicular to the field lines, $E_\parallel$ and $E_\perp$ respectively. The $E_\parallel$ component can be measured using a retarding potential analyser (RPA), which can simply be a cylindrical electrode with its axis parallel to the magnetic field (in this case, the defocussing effects that are a problem for RPAs in an electrostatic configuration are eliminated). By varying the potential of the RPA until the positrons are no longer transmitted, a “cutoff curve” can be measured and the energy of the positron beam determined. The width of the cutoff step then gives a measure of the energy resolution of the beam. Such a measurement is shown in figure 1, which demonstrates a resolution of 65 meV, typical of the experiments presented in this paper.

Positrons pulses are detected using a microchannel plate combined with a transimpedance
amplifier. The signal from the amplifier is proportional to the positron current hitting the plate, and is stored on a computer and analysed to determine the signal strength. The pulses contain 100-500 positrons each and the repetition rate of the pulsed beam is typically 200 Hz.

After their release from the Surko trap, the positrons are directed to a gas cell, also located in a 530 gauss magnetic field. The cell contains the target gas, in this case helium, and the potential on the gas cell (relative to the energy of the positrons released from the trap) defines the interaction energy of the positrons with the gas. Positrons that scatter elastically with a gas atom have energy transferred from the parallel to the perpendicular direction according to the scattering angle with $E_{||} = E_T \sin^2(\theta)$, where $E_T$ is the energy of the collision and $\theta$ is the scattering angle. This parallel energy loss can be measured and related to the differential scattering cross section (DCS) [1].

The total cross section can be measured in a similar way, by measuring the proportion of positrons that have lost any parallel energy and then applying Beer’s Law, as for a conventional transmission experiment. Unlike a conventional transmission measurement, in this case the angular resolution is not determined by the geometry of the system, but rather by the energy resolution of the beam which will limit the rejection of forward scattered positrons. This problem becomes worse at low energies, as the energy transferred to the parallel direction in a scattering event becomes smaller. Currently, data for the total cross section has had a correction applied below an energy of 1 eV, to correct for the missing forward angle contribution to the total cross section. This correction has used the shape of the theoretical cross sections provided by Bray [5] to estimate the forward angle contribution. As the energy resolution of the experiment is improved, it is anticipated that the impact of this problem on the very low energy measurements can be reduced.

If an inelastic scattering channel is open, it is no longer possible to relate the parallel energy distribution to the differential scattering cross section [1], but the method for measuring the total cross section remains valid. In addition to this, the process of positronium (Ps) formation appears as a loss of beam intensity, as Ps formed in the gas cell annihilates before reaching the MCP detector. This process allows the positronium formation cross section to be measured, in much the same way as the total cross section.

3. Results
Preliminary measurements of the elastic DCS (below the first excited state threshold) have been made at several energies and an example is shown in figure 2, for an incident energy of 5 eV. Data is shown for angles from 10 to 60 degrees, and the error bars in the figure represent the absolute errors in the measurements. While the angular range of the measurements is currently limited, there appears to be good agreement with the theoretical calculations of both McEachran [6] using the polarised orbital approach and Bray [5] who used the convergent close coupling technique. Although the agreement appears to be better with the calculation of McEachran, it is not possible to distinguish between the two calculations with any confidence as there remains some possible systematic errors in the data as the scattering angle increases. Further measurements are planned to both increase the angular range of the measurements and improve the accuracy of the results, with the goal of establishing a benchmark for low energy positron scattering, such as has been achieved in the case of electron scattering from helium [7, 8].

Low energy total elastic cross sections are presented in figure 3. As expected, the measurements agree well with all the latest theoretical calculations [9, 10, 11] as well as the measurements of Mizogawa [12]. High resolution measurements of this cross section have been made at small energy intervals to investigate the claims of resonant features in the Ramsauer-Townsend minimum made by Karwasz et al. [13]. No evidence of these resonant structures was found [14], suggesting that the previous observation was due to some systematic effect in the measurement, as suggested by Zecca [15].
Figure 2. Differential cross section for positron scattering from helium at an energy of 5 eV. Points are the experimental data with the solid line the theory of McEachran [6] and the dashed line the theory of Bray [5].

Figure 3. Total elastic cross section for positron scattering from helium.
Grand total cross section measurements have been performed up to an energy of 60 eV, with a sharp increase evident in the cross section at the positronium formation threshold, as shown in figure 4, and emphasising the important role that positronium formation plays in the scattering process. The cross section rises smoothly to the maximum energy measured and is in good agreement with previous experimental data [16, 17], although some discrepancies remain with older theoretical calculations [3, 18]. The recent theory of Bray [5] is in good agreement everywhere except in the region between the positronium formation and ionisation thresholds, where difficulties still remain with their theoretical treatment of the positronium formation problem. The challenge of including further open channels in the calculations, especially the Ps formation channel, is one that clearly still needs to be satisfactorily solved.

For energies above the Ps formation cross section, it is also possible to measure the grand total cross section minus the Ps formation cross section. In the Ore gap, where Ps formation is the only inelastic channel available, this amounts to the total elastic cross section. It can be seen from figure 6 that this cross section displays a change in slope or perhaps even a small dip as the energy is increased above the Ps formation threshold, but displays no sign of the sharp cusp predicted by Campeneau [3], in line with the observations of Coleman et al. [19]. This would suggest that there is perhaps some channel coupling effects present, although to nowhere near the extent predicted by Campeneau. In contrast to Coleman, however, we do not see the sharp increase in the cross section as it passes through the first excitation threshold at 20.6 eV (for
the $2^1S$ state of helium). This suggests that the excitation cross section does not turn on as sharply as they suggested, and it is hoped that future measurements may be able to measure this process directly.

4. Conclusion
Results have been presented for positron scattering from helium, giving the grand total, total and differential elastic cross sections over a range of energies. These measurements have been compared to other available data, both experimental and theoretical, with the goal of establishing benchmark values for the processes investigated. Some discrepancies remain, which suggest that further theoretical work is needed to try and resolve the differences. The present data have been taken with the highest resolution available to date for positron scattering from helium, and are able to provide some insight into threshold behaviour. Future measurements will extend the data available for positron scattering from helium, especially with regard to high resolution studies of threshold processes and the measurement of positronium formation, excitation and ionisation cross sections. Once a benchmark experimental data set for positron-helium scattering has been established, it is hoped that this will provide a spur for theoretical calculations to be improved to incorporate the positronium formation process into the theoretical description. In the future, studies of other targets of both fundamental and applied importance will be undertaken using this apparatus.
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