

Excitation of the $n=2$ states of helium by positron impact

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A high-resolution ($\Delta E \sim 55$ meV) trap-based positron beam has been used to measure absolute scattering cross sections for the excitation of the resolved $2^1S, P$ states of helium at energies between threshold and 38 eV. The experimental integral cross sections, which have typical uncertainties of 10% or less, are compared with several theoretical calculations, and the agreement is generally very favorable. In particular, a new convergent close-coupling approach shows excellent agreement with the experimental data.

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Positron collision physics has become increasingly sophisticated in recent years, with new experimental techniques leading to the production of bright high-resolution beams and novel analysis and detection schemes (see, e.g., [1,2]). Measurements of excitation and ionization processes, in particular, are now possible with experimental uncertainties that begin to rival those achievable within the more mature field of electron collision physics. Theoretical approaches have also become considerably more sophisticated but continue to be challenged by the role that positronium (Ps) formation plays in the collision process and how this important reaction channel, which leads to ionization below the “direct” ionization potential, might be described in a rigorous scattering calculation.

The helium atom has been the workhorse for many of the recent advances in low energy electron physics. It is the simplest experimentally tractable atomic target for which state-of-the-art theory can be compared with similar quality experiment. The results of this comparison have been uniformly excellent across a range of energies and scattering processes and have greatly assisted the development of both experimental and theoretical techniques. For positron interactions a similar scenario is emerging, with measurements of total scattering from several laboratories now in excellent agreement ($\pm 5\%$) with theory at energies below the Ps formation threshold, while above this threshold, there remain some outstanding issues [3,4]. A critical challenge for theory is the ability to include Ps formation, which constitutes a multicentered break-up reaction, when calculating cross sections for discrete processes, such as elastic and inelastic (excitation) scatterings, above the Ps formation threshold.

Two experimental groups have previously reported experimental studies of the scattering cross sections for the excitation of the $n=2$ states of helium [5,6]. Both of these ground-breaking approaches employed time-of-flight (TOF) techniques and made some assumptions regarding the partitioning of the features seen in the timing (energy) spectra that were measured. In one case [5], cross sections were measured that were believed to be predominantly due to the

excitation of the 2^1S state by positrons subsequently scattered in the forward direction. In the other case [6], a total excitation cross section was measured, but it was assumed to be dominated by contributions from the $n=2$ excitations. Note that of the four excited states in the $n=2$ manifold, only the 2^1S and 2^1P states are accessible from the ground state of He by positron impact. Excitation of the triplet levels requires a spin-flip mediated either by the exchange interaction, which is absent for positrons, or the spin-orbit interaction, which is negligibly small for the helium atom. Previous measurements of electronic excitation on several atoms and molecules, using a trap-based beam, have also been reported [7].

In this Rapid Communication we present absolute cross sections for the excitation of the resolved $2^1S, P$ states of He at incident positron energies from their thresholds (20.6 and 21.2 eV, respectively) to 38 eV. A theoretical approach using the convergent close-coupling (CCC) theory, with Ps formation explicitly included, has also recently been formulated [8]. These CCC calculations are the first pseudoresonance-free close-coupling calculations for positron scattering that are valid for all transitions and at all energies. We compare our results with this calculation and with other previous experiment [5,6] and theory, including two other close-coupling approaches [9,10].

The apparatus used to acquire these measurements has been described elsewhere [11], so only a brief overview of its operation will be discussed here. In the present approach we have used a cold trap-based positron beam with an energy resolution of 55 meV (full width at half maximum) to conduct measurements of the $n=2$ excitation cross sections. Positrons are obtained from a 23 mCi radioactive ^{22}Na source. A solid neon moderator is used to reduce the energy spread of the positrons emanating from the source by six orders of magnitude. Using electrostatic and solenoidal magnetic fields, these moderated positrons are then guided into a buffer gas trap, which is located in a 530 G uniform magnetic field region. The trap is approximately 30 cm in length and consists of nine cylindrical gold-coated copper electrodes. It operates on a three-stage accumulation, trapping, and cooling cycle. N_2 and CF_4 buffer gases are continuously fed into the system at low pressures and differentially pumped at both ends of the trap. The electrodes form stepped

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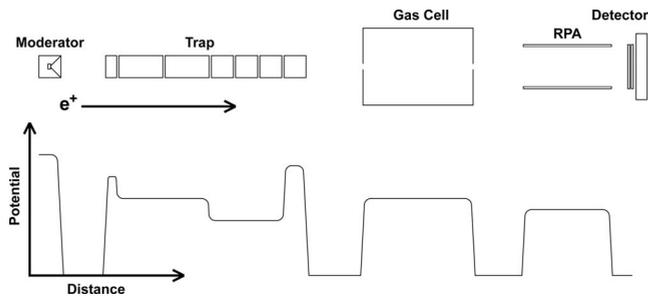


FIG. 1. Schematic representation of the positron beam apparatus.

electrostatic potential wells, and positrons confined in these wells lose energy rapidly through inelastic collisions with the buffer gases. The principal cooling mechanisms are electronic excitation of the N_2 molecules and vibrational excitation of the CF_4 . The positrons are typically trapped for about 20 ms in which time they thermalize to the buffer gas temperature. The measured energy resolution of these cooled positrons is, on average, around 55 meV. The contents of the trap are then “dumped” in a short pulse of a few microsecond duration which contains anywhere between 900 and 1500 positrons. The repetition rate of the trap operation for these measurements is typically 200 Hz.

On exiting the trap, the pulsed positron beam is electrostatically and magnetically guided through a 200-mm-long gas cell that is also located in a 530 G uniform magnetic field. Helium gas is continuously fed into the scattering cell using a manually controlled needle valve, and the pressure is monitored using an MKS Baratron pressure transducer, with a manufacturer’s stated uncertainty of $\pm 0.05\%$. The target gas is differentially pumped at both ends of the cell using two turbomolecular pumps. This establishes a well-defined higher gas pressure through the scattering cell region (typical pressures are 1–3 mTorr) such that the effective scattering length is well approximated by the physical length of the gas cell. To avoid multiple scattering effects the probability of scattering inside the cell is kept to $< 10\%$ [12]. All positrons that exit the gas cell pass through a retarding potential analyzer (RPA) and are detected using a chevron-mounted pair of microchannel plates. A schematic diagram of the apparatus is given in Fig. 1.

The retarding potential analyzer measures that component of the positron energy which is parallel to the \mathbf{B} field (E_{\parallel}), and this information can be interpreted in terms of the positron scattering cross sections. The way that this is done has been discussed in detail previously [12] and only a brief account is given here. For the present measurements, both elastic and inelastic scatterings can occur at a given impact energy. The technique used to distinguish between these different scattering channels is directly connected to the motion of positrons in a magnetic field. The total positron energy can be expressed in terms of the components that are parallel and perpendicular to the field, $E_{\text{tot}} = E_{\parallel} + E_{\perp}$, respectively. For an inelastic collision, the energy of the scattered positron is given by $E_s = E_{\text{tot}} - E_{\text{ex}}$, where E_{ex} is the excitation energy of the state.

The issue then is how to separate measured changes in E_{\parallel}

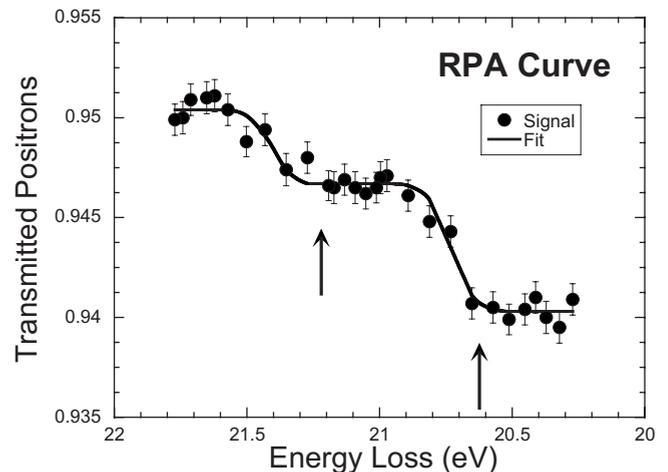


FIG. 2. Spectrum of the transmitted positron flux, normalized to the incident unscattered flux, as a function of the RPA voltage, for an incident energy of 24 eV. The arrows represent the $2^1S, P$ state threshold energies. The solid line is a fit using overlapping error functions.

that resulted from inelastic scattering to those that might be due to angular elastic scattering. For a slowly varying magnetic field, the magnetic moment of a charged particle, E_{\perp}/B , is an adiabatic invariant. As a result, by changing the ratio of the field in the scattering cell to that at the RPA ($M = B_{\text{cell}}/B_{\text{RPA}}$, where B_{cell} and B_{RPA} are the values of the magnetic field at the cell and RPA, respectively) we can use this invariant quantity to our advantage. It enables us to convert almost all of the positron’s perpendicular energy back into the parallel component. In this way we can separate losses of E_{\parallel} that are due to various inelastic events from those losses that are due to transfer of energy from E_{\parallel} to E_{\perp} due to angular scattering. For a given E_{tot} , an M value can be selected which allows for the effective separation of different excitation events. When more than one inelastic channel is open, a series of steps will appear in the RPA spectrum (the transmitted positron signal as a function of voltage) at the energy loss values corresponding to the excitation energies of the excited states. In this way, what effectively amounts to an “integral energy loss spectrum” can be measured for a given incident positron energy, and the height of each step in the spectrum can be directly related to the integral cross section for that state at that incident energy [12].

Examples of such measurements for the present study are shown in Fig. 2. Here the incident positron energy is 24 eV and we have used a value of $M = 20$, which was achieved by lowering B_{RPA} to ~ 27 G. In the present case, the steps that appear in the spectra correspond to the excitation of the 2^1S and 2^1P states of helium. As expected no evidence of the excitation of the $2^3S, P$ states is observed. Note also that the relation between the step position and width, and the threshold energy of the state, can be affected by the nature of the angular differential cross section, as this information is also present in the shape of the step. The cross sections (σ) for the separate processes are determined from the RPA spectrum by fitting two complementary error functions in order to obtain the parameter H , which is the ratio of the scattered

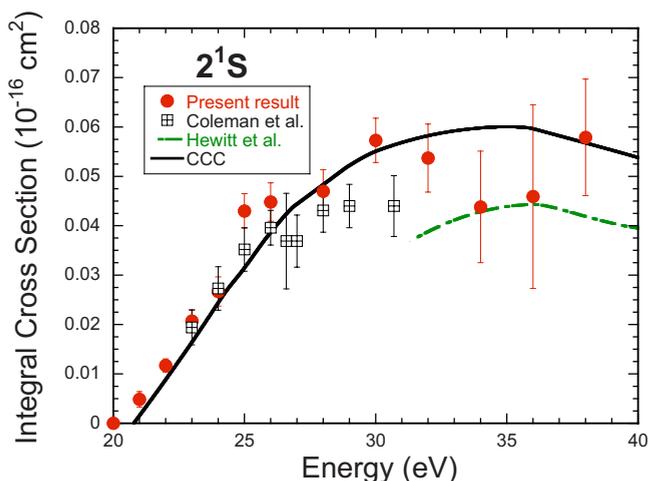


FIG. 3. (Color online) Absolute scattering cross section for the excitation of the 2^1S state of He (units of 10^{-16} cm 2). The present data are the solid circular points, while the previous measurements in [5] are shown as squares. The solid line is the CCC calculation in [8] and the dashed line is the calculation of Hewitt *et al.* [9].

intensities before and after each step, normalized to the incident intensity, and then applying the Beer-Lambert formula

$$\sigma = -(1/nl)\ln(H),$$

where n is the gas number density and l is the length of the scattering cell.

The scattering cross sections, which have been derived from these spectra, are shown in Figs. 3 and 4 for the 2^1S and 2^1P states, respectively, and for incident energies between threshold and 38 eV.

In Fig. 3 we compare the present cross section for the 2^1S state with the TOF results of Coleman *et al.* [5], the close-coupling calculations of Hewitt *et al.* [9], and the recent con-

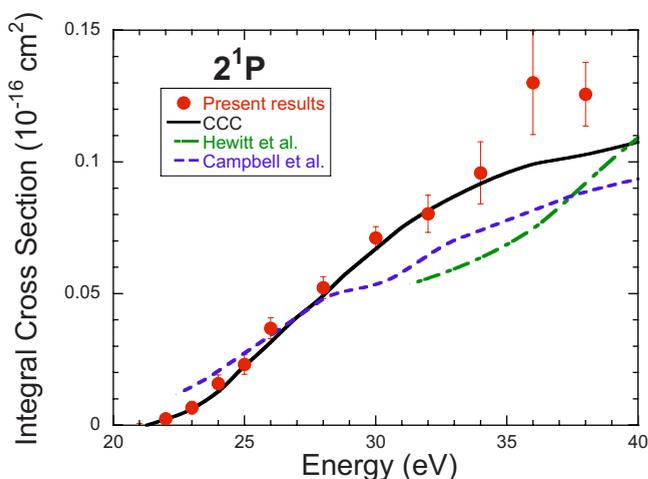


FIG. 4. (Color online) Absolute scattering cross section for the excitation of the 2^1P state of He (units of 10^{-16} cm 2). The present data are the solid points and the solid line is the CCC calculation in [8]. The long dashed line is the close-coupling calculation of Hewitt *et al.* [9] and the short dashed line is the calculation of Campbell *et al.* [10].

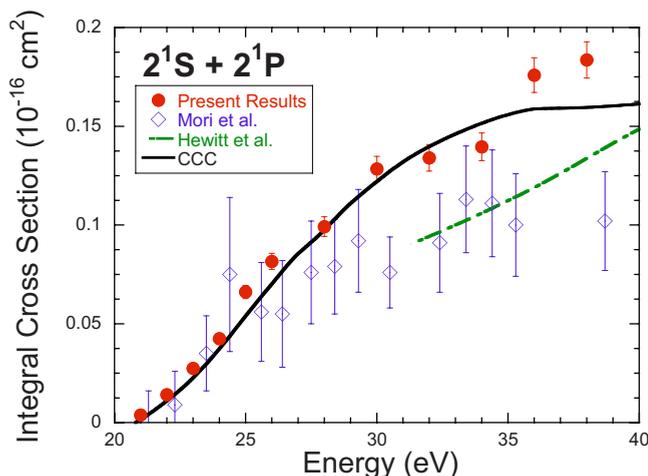


FIG. 5. (Color online) Absolute scattering cross sections for the excitation of the 2^1S+2^1P states of He (units of 10^{-16} cm 2). The present data are the solid points, the data in Ref. [6] are the open diamonds, and the solid line is the CCC calculation in [8]. The close-coupling calculation of Hewitt *et al.* [9] is shown as the dashed line.

vergent close-coupling calculations by Utamuratov *et al.* [8]. The agreement with the previous experiment is good in the overlapping energy range (23–30 eV). The TOF-derived cross section [5] was thought to represent a lower bound on the 2^1S state cross section as it corresponded to a subset of positrons that were scattered within an angular range of 0° – 70° . However it was noted in [5] that the 2^1S differential cross section appeared to be peaked in the forward direction and, that as a result, their measurement was likely a good estimate of the total 2^1S cross section. The good agreement with the present state-resolved measurements appears to confirm this rationale. The agreement with the CCC calculation is excellent at near-threshold energies, while at higher energies the scatter in the data does not allow us to discriminate between the CCC calculation and the close-coupling calculation of Hewitt *et al.* [9].

In Fig. 4 we show the results for the 2^1P cross section measurement and compare them with the close-coupling calculations of Hewitt *et al.* [9] and Campbell *et al.* [10], as well as with the CCC calculation. There are no other experimental results for this excited state. The agreement between experiment and theory is again clearly very good between threshold and 38 eV. This is particularly the case for the CCC calculation. The calculated cross section of Hewitt *et al.* lies some 30–40% below the present experimental result, while that of Campbell *et al.* is in good agreement with the experiment for energies below about 28 eV but lower in magnitude above that.

It can be noted in Figs. 3 and 4 that the uncertainties on the present measured cross sections increase for energies above about 32 eV. This is due to the fact that contributions from the two excited states begin to overlap in the RPA spectrum, as the incident energy is increased, for the value of the field ratio ($M=20$) that was used. This leads to a potential error in the determination of the individual step magnitudes H due to correlation terms in the fitting procedure. As

a result, in the present case it is likely that the magnitude of the 2^1S cross section is underestimated, with a corresponding overestimation in the 2^1P cross section. While this could, in principle, be overcome by using a higher value of M , this has not been explored in the present measurements.

However, one measured quantity which is not affected by this potential overlap is the sum of the two $n=2$ cross sections, and the combined cross section for both $n=2$ states, as a function of incident positron energy, is shown in Fig. 5. This not only enables us to make a rigorous quantitative comparison with the CCC calculation across the whole energy range but it also allows us to compare with other experimental measurement available in the literature. It can be seen in Fig. 5 that the agreement with the CCC calculation for the combined cross section is very good across the entire energy range. The cross section measurement of Mori and Sueoka [6], which has been principally attributed to the combined excitation of the $n=2$ states, is in reasonably good

agreement with the present measurement particularly at lower energies. The close-coupling calculation of Hewitt *et al.* [9] lies below the present experimental cross section.

The present experiments provide energy-resolved excited state cross sections for the two $n=2$ states of He that are accessible by positron impact. We find good agreement with the previous TOF results in [5] for the 2^1S state and reasonable agreement with the TOF measurements in [6] for the sum of the 2^1S+2^1P states. The agreement with a new convergent close-coupling calculation for the individual excited states and their sum is extremely good at most energies. A detailed discussion of the effect of the explicit inclusion of Ps formation in the recent CCC calculations can be found in [8].

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