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(e,2e) collisions at intermediate energies

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ABSTRACT. Recent experimental results will be reviewed for the atomic (e,2e) ionisation process at incident energies in the 'low energy' region, from a few eV to about 100eV above threshold. This region is particularly interesting because it embodies all the possible complexities that can be present in the electron-impact ionisation process, such as distortions, multiple scattering, correlations, post-collisional interactions and exchange effects. The helium (e,2e) experimental results presented recently by the Manchester group have been obtained over an exceptionally wide range of scattering angles, and have provided the first opportunity to derive multipole angular correlation information in a direct way. This type of analysis has been applied to measurements symmetric in both scattering angle and outgoing electron energy obtained at incident energies from 10 to 50eV above threshold. A significant result is that the lower incident energies give rise to the highest multipole components. This is a clear and direct indication that the profound effects known to be produced by electron-electron interaction in the threshold region continue to exist in the low energy region.

1. Introduction.

Atomic (e,2e) experiments in which an incident electron ionises an atomic target and the resulting outgoing electrons are detected in coincidence provide the most detailed tests of current ionisation theories¹. These tests are particularly severe for incident electron energies in the range from a few eV to about 100eV above the ionisation threshold, because this range is too high for the Wannier threshold model to be valid and is too low for the usual versions of the Born approximation to be applied. Ionisation in this energy range involves all the complexities of exchange and capture processes, distortions in the incoming and outgoing channels, and short and long range correlations.

Tests of the various ionisation theories can be further strengthened by including a wide range of directions of the scattered and ejected electrons, rather than restricting the experiments to the usual coplanar geometry or to the recently introduced perpendicular plane geometry. The purpose of the experiments presented here has therefore been to make the first detailed and comprehensive measurements in this energy region over a wide range of scattering directions.

The (e,2e) process may be represented by:

where e_0 indicates an incident electron with energy E_0 and momentum $\mathbf{k}_0$, and (e_1, e_2) indicate the two outgoing electrons with energies (E_1, E_2) and momenta $(\mathbf{k}_1(\theta_1, \phi_1), \mathbf{k}_2(\theta_2, \phi_2))$. The parameters $(E_0, E_1, \theta_1, \phi_1, E_2, \theta_2, \phi_2)$ are experimentally selectable within the constraints that energy and momentum must be conserved. For an unpolarised target and incident electron beam the azimuthal angle of significance is $\phi = \phi_1 - \phi_2$.

Coplanar geometry is defined by ϕ is 0° (or 180°) and the perpendicular plane is defined by $\theta_1 = \theta_2 = 90^\circ$. In the experiments discussed here, the detection plane defined by the momenta of the outgoing electrons at detection angles ξ_1 and ξ_2 is held constant in the laboratory frame and the angle ψ defined as the angle between the direction of the incident beam and the detection plane is varied (see figure 1). The coplanar and perpendicular plane geometries correspond to $\psi = 0^\circ$ and 90° respectively, and it may be shown that the relationship between the scattering angles in the detection plane and those defined in conventional geometries are given by :

$$\tan \phi_i = \cot \xi_i \sin \psi \quad (1)$$

$$\cos \theta_i = \cos \xi_i \cos \psi \quad (2)$$

In the experimental results presented here, the detected electrons are selected to have equal angles ξ with respect to the projection of the incident electron momentum onto the detection plane. All geometries therefore coincide at the angles $\xi_1 = \xi_2 = 90^\circ$, allowing a convenient point of normalisation as the incident electron beam angle ψ is varied. The measured (e,2e) differential cross sections are placed on an absolute scale by normalising against the coplanar symmetric results of Gélébart and Tweed^{2,3}. In most of the experiments described below the detected electrons have the same energy (ie $E_1 = E_2$), while in a few of the experiments this symmetry is relaxed.

Figure 1. The (e,2e) Coincidence Geometry (Coordinates with respect to the Detection Plane)

2. The Electron Coincidence Spectrometer.

Figure 2. The Spectrometer configured in the Perpendicular Plane

The electron coincidence spectrometer was designed to measure angular correlations from electron impact ionisation in the range from 1 to 100eV above ionisation. The spectrometer is capable of accessing all geometries from coplanar to the perpendicular plane geometry. Initial experiments^{2,4} were confined to the perpendicular plane, with the incident energy ranging from near threshold to 80eV above threshold.

Figure 2 shows a schematic of the apparatus configured in the perpendicular plane. The electron gun has an energy resolution of approximately 600 meV, the incident electron beam energy being selectable from 20eV to 300eV. To facilitate focussing of the electron gun onto the interaction region, radiation from this region is accurately focussed onto a photomultiplier tube via a lens, an aperture and an optical filter. The gun, photomultiplier tube, atomic beam source and Faraday cup are mounted so as to allow rotation from coplanar to the perpendicular plane geometry. Two identical hemispherical deflection analysers with acceptance half angles of 3° rotate in the horizontal detection plane.

Unique to this (e,2e) electron spectrometer is the computer interface which controls and optimises all aspects of the spectrometer from the tuning of the electron gun and analysers to the setting of the analyser positions and subsequent data collection. Figure 3 shows the computer software controlling the experiment. Seventeen electrostatic lens and deflector voltages are optimised under computer control at regular intervals using a modified simplex technique based upon the method of Nelder and Mead⁷. The spectrometer runs unattended for continuous periods of typically one week, the results obtained being more reliable and consistent than was previously possible with manual optimisation. Full details of the hardware and software interfacing can be found in reference 6.

Figure 3. The Computer Control Software

3. Symmetric Perpendicular Plane Results.

Figure 4a. The Helium DCS in the Perpendicular Plane (34.6 eV)

Initial experiments² were carried out in the perpendicular plane, where the two outgoing electrons are detected at 90° to the incident electron beam, using helium as a target. Two examples of the results from these experiments for the symmetric case, where the two outgoing electrons following the collision have equal energy, are shown in figures 4a and 4b. In the perpendicular plane, the symmetry about the incident electron beam direction requires that the differential cross-section must be symmetric about $\phi = 180^\circ$ and this is evident in the data. The evolution of the observed angular correlation peaks

as the energy changes is clearly seen. At the lower incident energy there is a single peak at 180° . At higher incident energies peaks appear in the region of $\phi = 180^\circ \pm 90^\circ$. These peaks are thought to be due to an initial elastic scattering of the incident electron by the atomic system through an angle of approximately 90 degrees^{8,9} followed by a quasi-free collision between the elastically scattered electron and a bound electron. The electrons are then able to emerge at approximately 90° with respect to each other in the perpendicular plane, as is observed. This type of double collision process must therefore be modelled using higher order scattering terms, and this is achieved with reasonable success using the DWBA⁸. The peak at 180° can be explained in terms of either single or multiple scattering. In terms of single scattering it is due to the incident electron selecting a bound electron whose momentum is equal in magnitude but opposite in direction to its own momentum. As the most probable momentum distribution of the bound electron is zero, this peak diminishes with increasing incident electron energy since the probability of finding a bound electron with the required momentum decreases. In terms of multiple scattering, particularly at the lower incident energies, the 180° peak has additional contributions that can be described by the Wannier model^{4,5}.

Figure 4b. The Helium DCS in the Perpendicular Plane (64.6 eV)

4. Intermediate Plane Results

4.1 Introduction

Experimental results have been obtained over a range of incident energies from 34.6 eV to 74.6 eV and over the complete range of scattering angles, $\psi = 0$ to 90° , $\xi_1 = \xi_2$, accessible in the experiment. The energies chosen straddle the coplanar results of Rösler *et al* (1991)¹⁰, and during these experiments these coplanar results were reconfirmed. The data was normalised at each energy as described in Murray *et al* (1992)² and

was placed on an absolute scale using the coplanar symmetric results of Gélébart and Tweed (1990)³. The results for incident energies of 34.6eV, 44.6eV and 64.6eV are presented here.

4.2. Experimental Results at 44.6eV Incident Energy.

This incident energy was the first to be used in these studies. Nine gun angles ψ were used. Figure 5 shows the results with numerical fits added to aid in the description (see below). A number of interesting features are apparent. Firstly, it can be noted that the coplanar ($\psi = 0^\circ$) forward scattering peak is smaller than the backward scattering peak, as previously found by Rösel *et al* (1991)¹⁰ at an incident energy of 50eV and below. This indicates that simple "binary" collision processes are not dominant at this energy.

Figure 5. The Helium differential cross-section at an Incident Energy of 44.6eV

As ψ increases from 0° to 90° , the forward scattering peak retains its identity and position, whereas the backward scattering peak evolves into the peak at $\xi = 90^\circ$ in the perpendicular plane. A high angle tail develops in the backscatter peak and evolves into the peak at $\xi \approx 140^\circ$ in the perpendicular plane. The minimum in coplanar geometry located at $\xi \approx 80^\circ$ evolves into a minimum at $\xi \approx 65^\circ$ in the perpendicular plane geometry.

A symmetry relationship that can be used to generate results for $\psi = 90^\circ$ to 180° is

$$\text{DCS}(180^\circ - \xi, 180^\circ - \psi) = \text{DCS}(\xi, \psi) \quad (3)$$

provided that $\xi_1 = \xi_2$ and $E_1 = E_2$, as in the present experiments. Using this we see that as ψ increases from 90° to 180° , the backscatter peak evolves into the forward scatter peak and vice versa.

The range of geometries used in this study allows a 3-dimensional map of the differential cross-section to be produced, since results obtained at a particular value of ψ characterise a 2-dimensional 'slice' of the complete differential cross-section. The 3-D map possesses two planes of reflection symmetry due to the indistinguishability of the detected electrons and the unpolarised nature of the electron beam and atomic source. Figure 6 shows an example of such a map. The differential cross section obtained in each detection plane is only shown above the coplanar (x-z) scattering plane, since the differential cross section possesses reflection symmetry in this plane. The surface is seen to have reflection symmetry in the y-z (gun angle) plane, necessary due to the indistinguishability of the electrons. The evolution of the forward scattering coplanar lobe into the lower perpendicular plane lobe can be seen, since there is a global minimum in this half of the x-z plane corresponding to the minimum between forward and backscatter peaks in figure 5.

Figure 6. The Full helium 3D Differential Cross Section @ 44.6eV Incident Energy

4.3. Experimental Results at 34.6eV and 64.6eV Incident Energy.

Figure 7 present the results at incident electron energies of 34.6eV placed on a linear scale and 64.6eV for $\psi = 0^\circ, 22.5^\circ, 45^\circ$ and 67.5° on a logarithmic scale and $\psi = 80^\circ$ and 90° on a linear scale. A notable feature present in the coplanar 34.6eV result is the continuation of the trend as seen in the 44.6eV data which shows a smaller forward scatter peak compared with the backscatter peak. This contrasts strongly with the higher energy result. At 64.6eV incident energy and $\psi = 67.5^\circ$ a deep minimum is observed at $\xi \approx 70^\circ$. This effect

Fig 7a. The 34.6eV (e,2e) Differential Cross Section

Figure 7b The 64.6eV Helium DCS for $\psi = 0^\circ, 22.5^\circ$ Figure 7d The 64.6eV Helium DCS for $\psi = 80^\circ, 90^\circ$ Figure 7c The Helium 64.6eV DCS for $\psi = 45^\circ, 67.5^\circ$

is not observed at either 34.6eV or 44.6eV incident energies, where the differential cross section is seen to vary smoothly between coplanar and perpendicular geometries, nor at 54.6eV and 74.6eV (not presented here). This deep minimum at 64.6eV incident energy is possibly due to interference between the scattering amplitudes for the forward and backward scattering processes, since the amplitudes of these peaks is approximately equal at this gun angle. In order to elucidate the true depth of this minimum, an estimated experimental response function can be deconvoluted from these results, as described below.

At 64.6eV incident energy the results at $\psi = 80^\circ$ and 90° have been plotted on a linear scale to enhance the observations at these higher angles. At all energies the forward scatter peak evolves into the lower peak in the perpendicular plane, whereas the backscatter peak evolves into the main central peak with the higher angle wing evolving into the third perpendicular plane peak. At 64.6eV it is noted that the minimum at $\psi = 67.5^\circ$ is deeper than the minimum observed at $\psi = 80^\circ$ and 90° . By contrast at 34.6eV incident energy, the minimum is much less pronounced at all gun angles and monotonically decreases to a minimum in the perpendicular plane.

4.3.1 Exploration of the Minimum at $\psi = 67.5^\circ$.

The measured differential cross section is a convolution of the experimental angular response function with the true differential cross section. The experimental response function is in turn a convolution of the angular acceptance of the analysers together with the observed electron beam pencil angle at the interaction region. It is possible to estimate the width and depth of the true minimum at $\psi = 67.5^\circ$ by deconvolving the experimental response function from the measured data. The result of doing this for the data at $\psi = 67.5^\circ$ is presented in figure 8 for various values of the apparatus angular width w , estimated to be approximately 8° . It can be seen that as the width approaches the estimated value, the depth of the minimum rapidly decreases towards zero. This behaviour is consistent with the suggestion given above that the dip is due to interference between the forward and backward scattering amplitudes, since the forward and backward yields are approximately equal. To explore this dip further

Figure 8. Deconvolving the 64.6eV $\psi = 67.5^\circ$ Experimental Response Function

we have carried out experiments in which the symmetry in energy is relaxed. We have used four pairs of outgoing electron energies (E_1, E_2) from (20eV, 20eV) to (5eV, 35eV). Figure 9 shows how the energy sharing affects the shape of the differential cross section at $\psi = 67.5^\circ$ for the four different energy detection pairs. For asymmetric energy sharing the deconvolved cross section at the minimum is insensitive to the width of the estimated experimental angular function, the deconvolved cross section being almost unchanged from the measured cross section. As the degree of asymmetry decreases this sensitivity correspondingly increases, until for symmetric energy sharing the calculated deconvolved differential cross section changes by two orders of magnitude compared to the measured cross section. The sharpness of the dip clearly depends critically on the energy sharing of the detected electrons.

Figure 9. The Differential Cross Section @ $\psi = 67.5^\circ$ showing the evolution of the Dip

5. Tensor Analysis of the Angular Distributions.

The derivation of angular correlation information from measured angular distributions of reaction products has a long history in the general area of nuclear physics¹¹⁻¹⁴, however such a derivation has not been applied previously to the atomic (e,2e) ionisation process. Klar and Fehr¹⁵ have recently suggested this possibility, and the results presented here provide an opportunity for such an analysis to be performed.

We have chosen to analyse the differential cross section in terms of tensorial angular components related to the two outgoing electrons and the ingoing electron respectively. Associated with these tensors are quantum numbers l_a, l_b and l_0 related to the linear momentum vectors $\mathbf{k}_a, \mathbf{k}_b$ and $\mathbf{k}_0$ which define the detected and incident electron trajectories. Other possible choices are given by l_q, l_b and l_0 (see Klar and Fehr¹⁵) together with their corresponding linear momenta $\mathbf{k}_q, \mathbf{k}_b$ and $\mathbf{k}_0$, where $\mathbf{q} = \mathbf{k}_0 + \mathbf{k}_a$.

In the present experiments the incident electrons and target atoms are not polarized, the outgoing electron polarisations are not measured and the target atom and final ion have zero angular momenta. The differential cross-section for particular ingoing and outgoing energies can therefore be decomposed into angular functions that depend only on $l_a, l_b, l_0, \hat{k}_a, \hat{k}_b$ and $\hat{k}_0$. These angular functions are necessarily scalars that do not depend on the choice of co-ordinate system. They are therefore¹¹⁻¹⁵ the scalar invariants

$$I_{l_a l_b l_0}(\hat{k}_a, \hat{k}_b, \hat{k}_0) = \sum_{m_a m_b} \langle l_a m_a l_b m_b | l_0 m_0 \rangle C_{l_a m_a}(\hat{k}_a) C_{l_b m_b}(\hat{k}_b) C_{l_0 m_0}^*(\hat{k}_0)$$

$$\text{where } C_{lm}(\hat{k}) = \left(\frac{4\pi}{2l+1} \right)^{\frac{1}{2}} Y_{lm}(\hat{k}) \quad (3)$$

The decomposition of the (e,2e) differential cross-section $\sigma(\hat{k}_a, \hat{k}_b, \hat{k}_0)$ is then given by

$$\sigma(\hat{k}_a, \hat{k}_b, \hat{k}_0) = \sum_{l_a l_b l_0} B_{l_a l_b l_0} I_{l_a l_b l_0}(\hat{k}_a, \hat{k}_b, \hat{k}_0) \quad (4)$$

The amplitudes $B_{l_a l_b l_0}$ in principle provide a complete parameterisation of the measured cross-section, allowing comparison with calculated differential cross-sections and also allowing comparison between sets of experimental results obtained over different ranges of angles and with different choices of the angles that are varied.

Restrictions on the allowed combinations of l_a , l_b and l_0 arise from inherent symmetries in the (e,2e) process and also on the energy and angular symmetry of the experiments. The first restriction is given by

$$I_{l_a l_b l_0}(-\hat{k}_a, -\hat{k}_b, -\hat{k}_0) = (-1)^{l_a + l_b + l_0} I_{l_a l_b l_0}(\hat{k}_a, \hat{k}_b, \hat{k}_0) \quad (5)$$

Since the differential cross-section is unaffected by an inversion of the co-ordinate system, odd values of $(l_a + l_b + l_0)$ must be excluded from the summation in equation (4). A further restriction arises from the exchange symmetry :

$$I_{l_b l_a l_0}(\hat{k}_b, \hat{k}_a, \hat{k}_0) = (-1)^{l_a + l_b + l_0} I_{l_a l_b l_0}(\hat{k}_a, \hat{k}_b, \hat{k}_0) \quad (6)$$

which therefore implies that

$$B_{l_b l_a l_0} = B_{l_a l_b l_0} \quad (7)$$

when the outgoing electrons are symmetric in the energy and angle of scattering.

Figure 10. Fitting Parameters $B_{l_a l_b l_0}$ for $l_a, l_b = (6,7)$ as a function of the Incident Electron Energy $E_{inc} = 34.6\text{eV}, 44.6\text{eV} \text{ \& } 64.6\text{eV}$

Figure 10 shows the result of fitting equation (4) to the experimental results at incident energies of 34.6eV, 44.6eV and 64.6eV respectively. The amplitudes $B_{l_a l_b l_0}$ have been extracted by a least squares analysis in which subsidiary conditions have been imposed to ensure that the calculation is well behaved in the angular regions inaccessible to the experiment. Several different sets of $\max(l_a, l_b)$ and $\max(l_0)$ have been explored as a function of the goodness of fit, and the figure shows the results for the preferred set ($\max(l_a, l_b) = 7$ and $\max(l_0) = 6$). At all energies the largest amplitude occurs for $l_a = 1$, $l_b = 3$ and $l_0 = 2$.

A point of interest is that higher values of l_a and l_b become significantly more prominent as the incident energy is lowered, which is presumably a consequence of the increasing importance of electron-electron interactions between the outgoing electrons as their respective energies decrease.

6. Conclusion & Summary.

Experimental angular correlation results for the electron impact ionisation of a helium target from the coplanar geometry to the perpendicular plane geometry have been presented. The electrons were detected symmetrically in scattering angle, and usually also symmetrically in energy, the results being collected using a fully computer-controlled and real-time computer-optimised (e,2e) spectrometer. The differential cross-sections were placed on an absolute scale using the absolute coplanar symmetric results of Gélébart and Tweed^{2,3}.

The experimental data at 64.6eV incident energy shows a deep minima at $\psi = 67.5^\circ$, which appears to approach zero when the experimental response function is deconvolved. This is provisionally attributed to interference between the amplitudes of the forward and backward scattering processes since they are observed to be approximately equal at this energy and at this gun angle. The energy symmetry of the experiment is found to contribute significantly to this effect, since experiments where the energy symmetry is removed show a rapid decrease in the depth of the minimum.

These measurements are the first to experimentally couple the differential cross-section obtained in coplanar geometry to the differential cross-section obtained in the perpendicular plane at these energies. The full differential cross-section surface with respect to a chosen scattering plane can therefore be modelled using a technique in which the cross-section is decomposed into irreducible constituent angular functions. At present no theoretical results exist with which to compare these results.

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