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LETTER TO THE EDITOR

Exploring the helium (e, 2e) differential cross section at 64.6 eV with symmetric scattering angles but non-symmetric energies

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Abstract. Helium (e, 2e) measurements are presented for an incident energy of 64.6 eV over a wide range of scattering angles from the coplanar to the perpendicular plane geometry. These measurements were taken for symmetric scattering angles and a range of detection energies from symmetric energy sharing where each electron has an excess energy of 20 eV to asymmetric sharing where the electrons have energies of 5 eV and 35 eV. A deep minimum observed for an electron gun angle of 67.5° was explored as a function of this energy sharing.

Recent low energy and threshold helium (e, 2e) angular correlation experiments in which the scattering process is investigated over a wide range of geometries (Murray and Read 1992, 1993, Rösel *et al* 1992) have provided the most detailed and rigorous tests of current electron impact ionization theories, since an adequate description of the scattering process tolerates few approximations and simplifications. In these energy regions the complexities of short and long range correlations, distortions in the ingoing and outgoing channels, post-collisional interactions and exchange processes are all expected to play important roles.

Previous low energy experiments (Murray and Read 1992, 1993) were conducted from the usual coplanar geometry to the recently investigated perpendicular plane geometry (Murray *et al* 1992b) at incident energies from 20 eV to 50 eV above the helium ionization threshold at 24.6 eV. The outgoing electrons were selected to have the same energy and the same scattering angle ξ with respect to the projection of the incident electron trajectory onto the detection plane spanned by the electron analysers (figure 1). A common point exists at $\xi = 90°$ for all gun angles ψ.

In the experiments described here the gun angle ψ has again been varied from coplanar geometry ($\psi = 0°$) to the perpendicular geometry ($\psi = 90°$) and the scattering angles ξ are again symmetric (as shown in figure 1), but the symmetry of the outgoing electron energies has been relaxed. The incident electron energy has been set to 64.6 eV, and the detected electron energies have been selected to range from the symmetric energy sharing, in which each electron carries 20 eV away from the reaction, to highly

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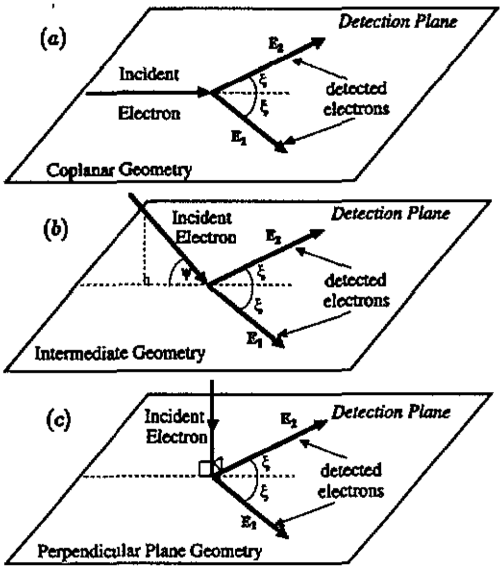


Figure 1. The experimental geometry, showing the evolution from coplanar to perpendicular plane geometry (*a*)–(*c*). The gun angle ψ is defined as the angle between the detection plane and the direction of the incident electron beam. The scattering angle ξ is defined as the symmetric electron scattering angle in the detection plane.

asymmetric sharing in which the electron energies are 5 eV and 35 eV. Two other detection energy pairs that have been included are $(E_1, E_2) = (15\text{ eV}, 25\text{ eV})$ and (10 eV, 30 eV).

The previous fully symmetric experiments showed the existence of a very deep minimum in the (e, 2e) differential cross section at $E_{\text{inc}} = 64.6$ eV, $\psi = 67.5°$ and $\xi = 70°$. Deconvolution of the experimental results using an estimated angular response function indicated that this dip is five or more orders of magnitude smaller than the maximum differential cross section at this energy. The dip is less pronounced at other incident energies. One purpose of the present experiments is to investigate the dependence of the dip on the symmetry of the outgoing electron energies.

The spectrometer is a fully computer controlled and real-time computer optimized (e, 2e) coincidence spectrometer which has been described previously (Murray *et al* 1992a). The optimization software monitors and controls the lens and deflector voltages, electron beam current, high voltage supplies and vacuum pressure. The spectrometer is maintained at its optimum working condition during data accumulation, with automatic adjustment for any long term drifts.

The vacuum pressure during operation is typically 10^{-5} Torr, with a background pressure of 10^{-8} Torr. The incident electron beam has a resolution of approximately 600 meV and is focused at the interaction region to a 1 mm diameter beam with zero beam angle and a pencil angle of approximately 2°, as determined from a SIMION ray tracing program. Two hemispherical deflection analysers with acceptance half angles of 3° rotate in the detection plane (figure 1). Following energy selection the electrons are detected by channel electron multipliers, whose pulses are amplified and noise discriminated. The discriminators feed a time-to-amplitude converter via appropriate delay lines, resulting in an 8 ns FWHM coincidence signal accumulating in a multichannel analyser located on the controlling computer bus. The computer optimizes the spec-

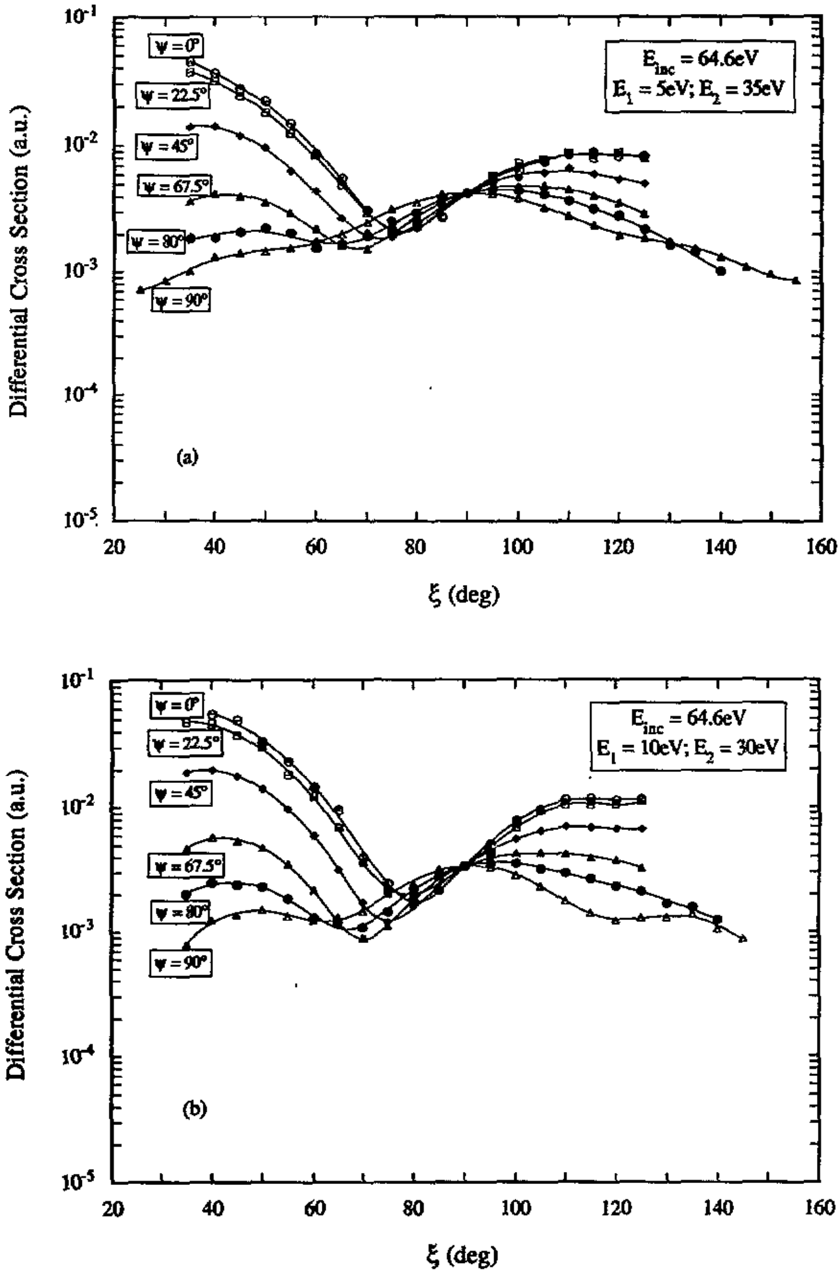
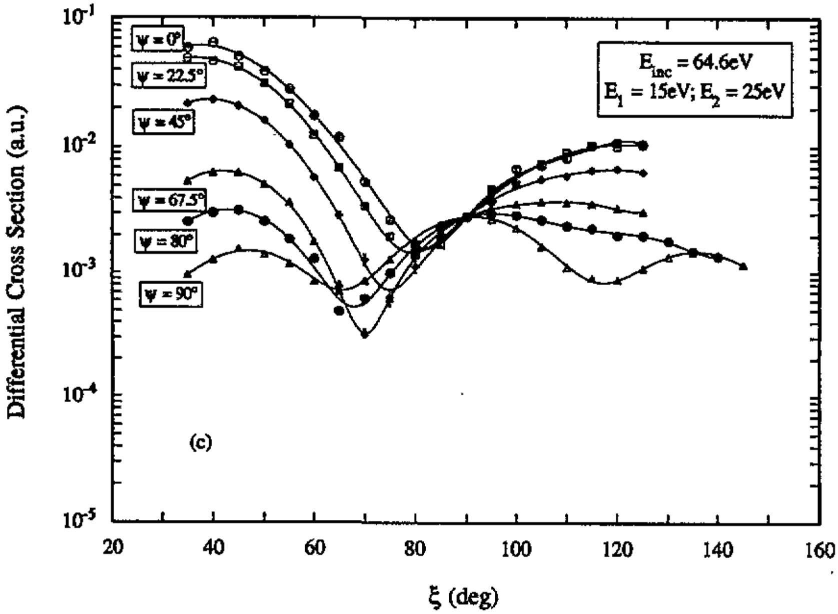


Figure 2. The helium (e, 2e) differential cross section for an incident energy of 64.6 eV for detection energies E_1, $E_2 = 5$ eV, 35 eV (*a*), 10 eV, 30 eV (*b*), 15 eV, 25 eV (*c*) and 20 eV, 20 eV (*d*). There are six gun angles ψ for each set of data. ξ is the symmetric scattering angle in the detection plane. The curves are included as a visual aid. The uncertainty in the absolute scale of the differential cross section is ±44%.

trometer at regular intervals as the analysers sweep around the detection plane, using a modified simplex technique (Nelder and Mead 1965). Full details of the spectrometer may be found in Murray *et al* (1992a). An additional check of the apparatus has been made to verify that the measured differential cross section is unchanged when the detected energies E_1 and E_2 are exchanged.

Figures 2(*a*)–(*d*) show the helium (e, 2e) differential cross sections obtained for the four selected energy pairs. Six gun angles ψ were chosen, $\psi = 0°$ (coplanar), 22.5°,



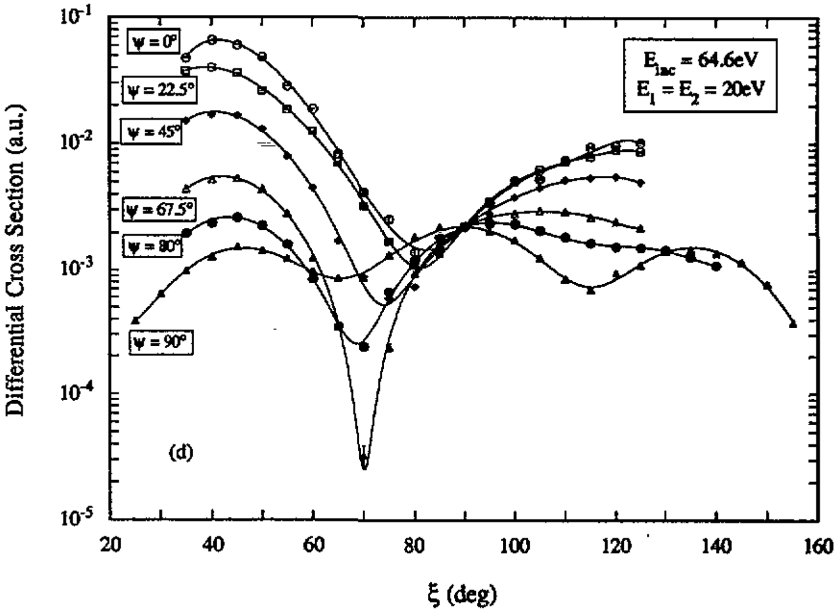


Figure 2. (continued)

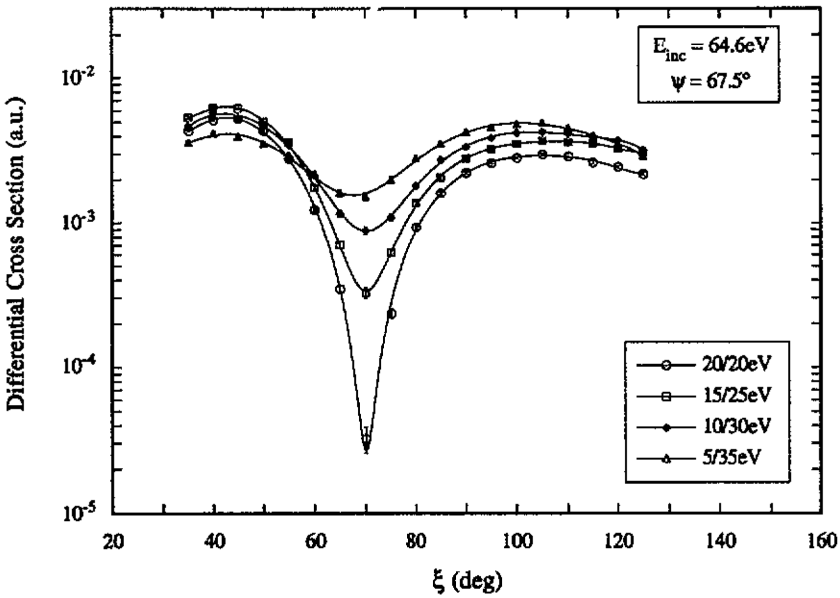


Figure 3. The (e, 2e) differential cross section at a gun angle ψ of 67.5°, showing the evolution of the dip as a function of the energy sharing of the detected electrons.

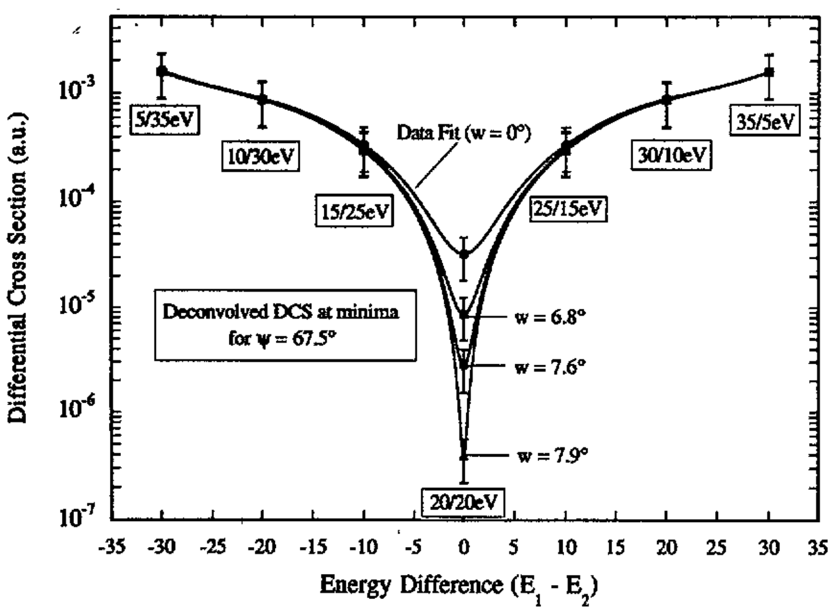


Figure 4. Variation of the minimum of the dip shown in figure 3 as a function of the energy difference $(E_1 - E_2)$ when the experimental angular function is deconvolved from the measured data.

45°, 67.5°, 80° and 90° (perpendicular plane). All the results have been placed on the same absolute logarithmic scale which has been normalized with an uncertainty of ±44% at the common point ($\xi = 90°$) to the results of Gélébart and Tweed (1990), using the technique described previously (Murray *et al* 1992b). At gun angles less than 70° the analyser angular range is constrained to be between $\xi = 35°$ and $\xi = 125°$ by the presence of the electron gun for backward scattering and the Faraday cup for forward scattering. At higher gun angles the angular range is limited only by the physical size of the analysers.

A trend that can be noticed in the data is that the differential cross section becomes more isotropic as the energy asymmetry increases. Another feature is that the differential cross section at the relative normalization point ($\xi = 90°$) does not change markedly with increasing asymmetry, being lowest at 2.2×10^{-3} au for symmetric energy sharing and increasing monotonically to 4.3×10^{-3} au for the most asymmetric sharing.

The forward and backward scatter peaks in the coplanar differential cross section tend to move to lower values of ξ as the energy asymmetry is increased, the forward peak lying outside the range of measured angles for energy sharing of 10/30 eV and 5/35 eV. This tendency does not exist for gun angles of 45° and higher. For all energy sharing the forward scatter peak evolves into the lower angle peak in the perpendicular plane, while the backscatter peak evolves into the central peak.

In the perpendicular plane the central peak becomes broader as the asymmetry increases, and the side peaks become less distinct, almost disappearing at the highest asymmetry. As discussed previously (Murray *et al* 1992b), the side peaks near $\xi = 45°$ and 135° are thought to arise from a double scattering process in which the incident electron scatters elastically from the nucleus and then collides with the valence electron in a quasi-free interaction. If the two electrons emerge from this reaction in the perpendicular plane then they have an angle of approximately 90° to each other, as observed. The peak at $\xi = 90°$ can arise either from collision with a valence electron whose momentum is equal in magnitude but opposite in direction to that of the incident electron, or via multiple collision processes due to long range Coulombic interactions between the outgoing electrons, as in the threshold region (Read 1985).

The existence of the sharp dip at $\psi = 67.5°$, $\xi = 70°$ and $E_1 = E_2$ has been noted previously (Murray and Read 1993). Figure 3 shows how the energy sharing affects the shape of the differential cross section for the four different detection energy pairs, and figure 4 shows the dependence on the energy sharing of the minimum differential cross section at the dip, deconvoluted as described by Murray and Read (1993). The estimated width w of the experimental angular response function is 8°.

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.

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