LETTER TO THE EDITOR

Near-threshold doubly-symmetric (e, 2e) measurements in helium

N J Bowring†, A J Murray‡ and F H Read

Department of Physics and Astronomy, Schuster Laboratory, University of Manchester, Manchester M13 9PL, UK

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Abstract. Electron-impact ionization of helium has been studied in the energy range from 3–10 eV above the ionization threshold by measuring (e, 2e) angular correlations over a wide range of scattering angles from the coplanar to the perpendicular plane geometry. In these measurements the two outgoing electrons are observed at symmetric scattering angles and with equal energies.

Angular correlation experiments in which an incident electron ionizes a helium atom and the resulting electrons are detected in coincidence provide rigorous tests of electron-impact ionization theories, particularly when carried out at excess energies from a few eV to approximately 50 eV above the ionization threshold, sometimes called the intermediate range of energies. In this range the ionization mechanism involves all the complexities of exchange and capture, distortions in the incoming and outgoing channels, and both long- and short-range correlations, but the energy range is too far above threshold to benefit from the simplifications offered by the Wannier model (Wannier 1953, Read 1985, Selles *et al* 1987). The testing and development of current theories (for a recent review see McCarthy and Weigold 1995) can be further challenged by including a wider range of scattering and ejected electron angles in the experiments than is obtained with the usual coplanar geometry. Such an extended range has been employed in the present work.

Previous coincidence measurements in helium have been carried out for various energies in the intermediate energy range and with variously restricted geometries (which are usually the coplanar and perpendicular plane geometries) by Cvejanovic and Read (1974), Hawley-Jones *et al* (1992), Murray *et al* (1992b), Fournier-Lagarde *et al* (1984, 1985), Selles *et al* (1987), Rösel *et al* (1992b, c), Röder *et al* (1996a) and Asmis and Allan (1997). Previous theoretical studies of the intermediate energy region include those of Botero and Macek (1992), Pan and Starace (1993), Jones and Madison (1994), Berakdar and Briggs (1994) and Bray *et al* (1997). Experimental studies with less restricted geometries have been carried out by Rösel *et al* (1992a), Murray and Read (1993), Murray *et al* (1993) and Röder *et al* (1996b), but the energy region from 4–20 eV above the ionization threshold has not yet been covered. The purpose of the present work is to fill this gap, making measurements over a wide range of scattering angles. Preliminary results have been presented previously

† E-mail address: Nick@fs3.ph.man.ac.uk

‡ Present address: Faculty of Science, Griffith University, Nathan QLD 4111, Australia.

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by Murray *et al* (1997), in connection with a detailed parametrization of all the available results for the range from 1–50 eV above threshold, but we now wish to present the final results.

As in the previous experiments of Murray *et al* (1993), the outgoing electrons have been observed at the 'doubly-symmetric' condition for which the scattering angles ξ_1 and ξ_2 (see figure 1) of the two outgoing electrons with respect to the incoming electron beam are the same (but with the electrons on opposite sides of the incoming direction) and the energies E_1 and E_2 of the electrons are also the same. At each incident electron energy the gun angle ψ has been varied from the coplanar geometry ($\psi = 0°$) through to the perpendicular plane ($\psi = 90°$) geometry in three steps. In the perpendicular plane geometry the range of ξ is restricted only by the sizes of the analysers and is 35°–145°, while for the other two gun angles the maximum value of ξ is further restricted to 125° by the presence of the electron gun in the backward scattering direction.

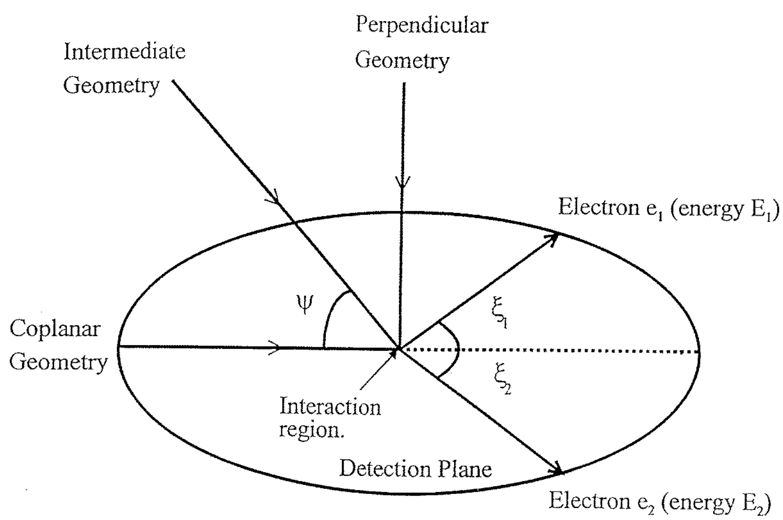

Figure 1. The (e, 2e) coincidence geometry used in the present experiments, showing the coplanar, intermediate and perpendicular plane geometries. The gun angle ψ is the angle between the detection plane and the direction of the incident electron beam. The symmetric scattering angles ξ in the detection plane are also shown. In the present studies $E_1 = E_2, \xi_1 = \xi_2$.

The existence of a common point for all gun angles ψ when $\xi_1 = \xi_2 = 90°$, which we refer to as the 'doubly-perpendicular' point, allows relative normalization (and also absolute normalization, see below) of the results for each incident electron energy.

The spectrometer is fully computer controlled and computer optimized and is essentially that described previously (Murray *et al* 1992a). An unselected electron gun produces a beam of energy width 600 meV, which is focused onto the interaction region with a zero beam angle and a pencil angle of approximately 2°. Scattered and ejected electrons from the ionization process are collected by two hemispherical deflection analysers which have energy resolutions of 500 meV and acceptance half angles of approximately 3°.

Figure 2 shows the measured helium (e, 2e) differential cross sections at the incident energies 27.6, 29.6 and 34.6 eV (corresponding to excess energies E_x of 3, 6 and 10 eV, respectively) and at the three gun angles 0° (coplanar), 45° (intermediate plane) and 90° (perpendicular plane). The data have been put on an absolute scale at each energy by using

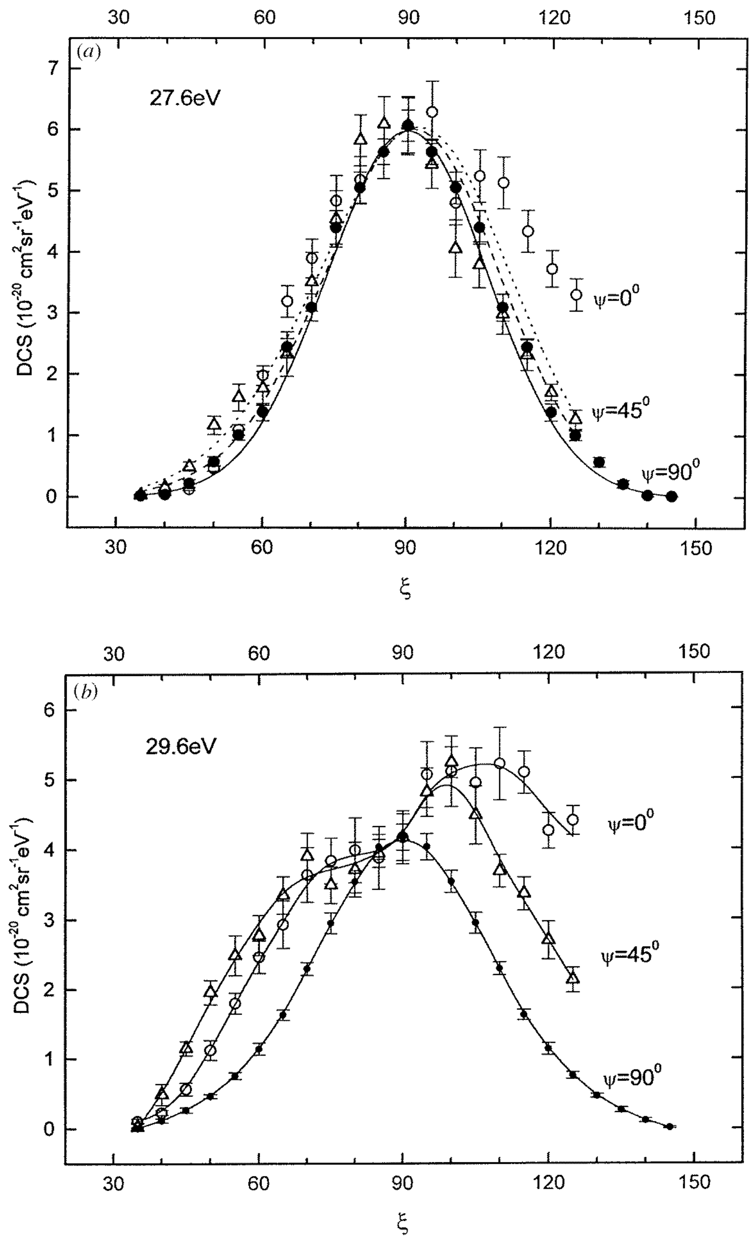

Figure 2. The (e, 2e) differential cross sections for equal detection energies $E_1 = E_2$ and symmetric analyser angles $\xi_1 = \xi_2$ at the incident energies: (*a*) 27.6 eV; (*b*) 29.6 eV and (*c*) 34.6 eV, corresponding to excess energies of 3, 6 and 10 eV, respectively, above the ionization threshold. The gun angles are $\psi = 0^\circ$ (coplanar) 45° and 90° (perpendicular plane). At each incident energy the data are normalized at $\xi = 90^\circ$, which is the common point for all gun angles, using the values given by Pan and Starace (1993). The curves in (*a*) are derived from the Wannier model of Selles *et al* (1987), and are full, broken and dotted for gun angles of $0^\circ, 45^\circ$ and 90°, respectively, while in (*b*) and (*c*) arbitrary fits have been added to aid the eye.

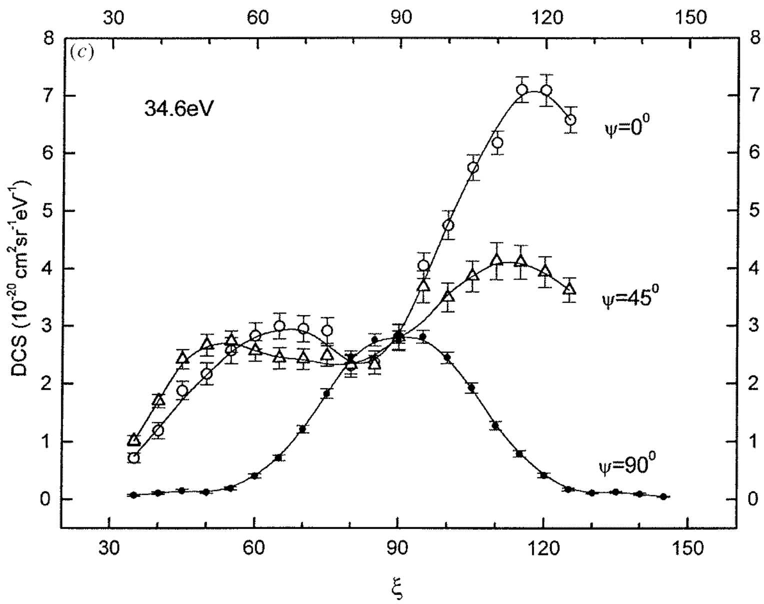

Figure 2. Continued.

the values calculated by Pan and Starace (1993) for the 'doubly-perpendicular' common point at $\xi_1 = \xi_2 = 90^\circ$. Pan and Starace have used a first-order distorted partial wave procedure which seems to be particularly appropriate for final state electrons in the coplanar $\theta_{12} = \pi$ geometry, and which gives results at the doubly-perpendicular point and in the range $E_x = 2$–100 eV that agree to within approximately 20% with the experimental results of Rösel *et al* (1992a, b, c), Murray *et al* (1992b) and Gélébart and Tweed (1990).

The data in figure 2(*a*) correspond to the lowest excess energy of 3 eV. The curves are derived from the Wannier model (Wannier 1953) using the equations given by Selles *et al* (1987). The scattering parameters used are those derived by Hawley-Jones *et al* (1992) from the results obtained at 1 eV above threshold by the Manchester and Paris groups. The energy scaling defined by Selles *et al* is applied to the scattering parameters to make them appropriate for the present excess energy. There is reasonably good agreement between the experimental results for the perpendicular plane and the corresponding predictions of this 'extrapolated' Wannier model. Significant differences are apparent, however, for the coplanar geometry, presumably because the experimental results show the first indications of the backward scattering peak that becomes stronger at higher energies (see below), but which is not reproduced in the Wannier model. The disagreement indicates that the model is not valid this far above threshold, which is in accordance with the tentative conclusion of Hawley-Jones *et al* (1992) that the Wannier model starts to lose its validity at 2 eV above threshold for helium.

It can be seen from the data in figure 2(*b*), obtained at an incident energy of 29.6 eV, that in the perpendicular plane geometry the differential cross section continues to exhibit a single peak, which is of course necessarily symmetric about $\xi = 90^\circ$. As the gun angle decreases towards the coplanar geometry a twin-lobe structure develops. The curves in this figure and in figure 2(*c*) are arbitrary fits that have been added to aid the eye. In each case the data and the fits are normalized to the common 'doubly-perpendicular' point at $\xi = 90^\circ$ (see above).

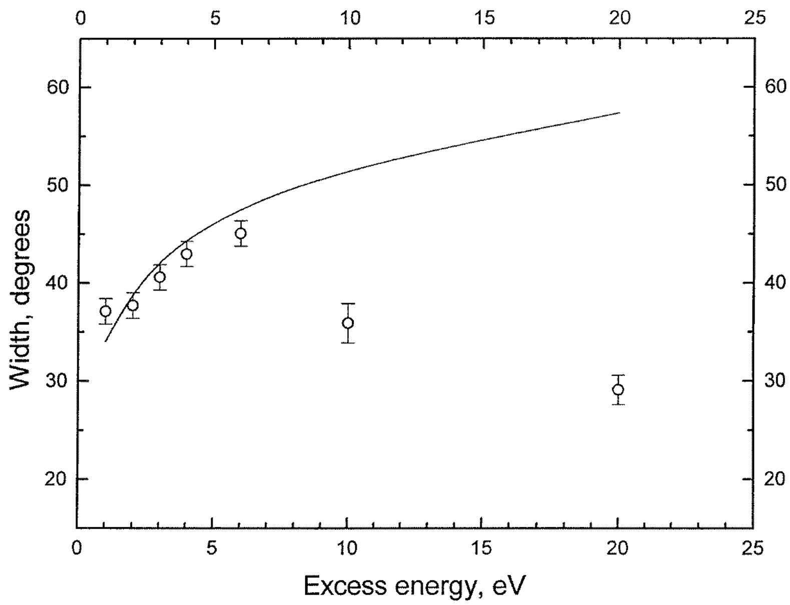

Figure 3. The dependence on excess energy of the width of the central peak in the (e, 2e) differential cross section in the perpendicular plane. The data points are obtained from the present results and those of Hawley-Jones *et al* (1992) and Murray *et al* (1992b), while the curve is derived from the 'extrapolated' Wannier model discussed in the text.

Figure 2(c) shows the results obtained at the highest incident energy of 34.6 eV. In the perpendicular plane geometry the triple-peak structure observed previously at incident energies of 44.6 eV and higher (Murray and Read 1993) starts to appear. The width of the central peak also decreases, which is in accordance with the behaviour found previously at higher incident energies. Figure 3 shows how the width (full width at half height) depends on the excess energy, in the range from threshold to 20 eV above threshold. The curve in the figure is obtained from the 'extrapolated' Wannier model discussed above. This figure shows that the Wannier model is certainly inappropriate above 5 eV. At the two other gun angles the backward scattering peak is more dominant than the forward peak, which also happens at the incident energy of 44.6 eV, but not at higher energies (Murray and Read 1993). Therefore at energies of 44.6 eV or less the simple 'binary' collision process, which gives rise to a peak in the forward direction, is not yet dominant. The mechanism that is responsible for the large and predominantly backward scattering at these low energies is thought (e.g. Murray *et al* 1996) to be mainly due to a double-scattering process in which the incident electron is firstly involved in a binary collision with a target electron, after which one of the resulting slow outgoing electrons is strongly deflected by the interaction with the ion core.

The only previous experimental measurements in the present energy range are those of Rösel *et al* (1992a) at $E_x = 4$ eV, but although these were carried out for the symmetric energy condition $E_1 = E_2 = 2$ eV they were confined to the coplanar $\theta_{12} = \pi$ geometry and so the scattering angles of the two detected electrons were, in general, different.

This energy range presents formidable theoretical difficulties at present, particularly for the doubly-symmetric condition. The authors are not aware of any relevant theoretical studies, and it is hoped that the results presented here will inspire such studies, thus helping to complete the theoretical understanding, at least in outline, of electron impact ionization of atoms over the whole range of incident energies and of outgoing energies and angles.

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