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LETTER TO THE EDITOR

Coplanar doubly-symmetric helium (e, 2e) measurements with excitation of the residual ion

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Abstract. Coplanar helium (e, 2e) measurements are presented for simultaneous ionization and excitation to the He II 2s, 2p manifold at an incident electron energy of 145.3 eV. The electrons resulting from the collision were detected doubly-symmetric in both energy and angle with respect to the direction of the incident electron beam. These results are compared with the analogous measurements in which the ion is left in the ground state.

Angular correlation (e, 2e) experiments provide a rigorous test of theories of electron impact ionization of atoms (Lahmam-Bennani 1991). These experiments have, until recently, usually been concerned with ionization in which the residual ion is left in its ground state, and have principally been carried out in either coplanar geometry or the recently introduced perpendicular plane geometry. The incident electron energy ranges widely from near threshold to many keV above threshold, allowing different theoretical approximations to be investigated.

In contrast to these direct ionization experiments, only a few coincidence studies have been concerned with processes in which the ion (invariably He^+) is left in an excited valence state:

$$e + He \Rightarrow He^{+*} + e + e. \tag{1}$$

These studies have all been carried out at incident electron energies greater than 650 eV. The earliest experiments (McCarthy *et al* 1974, Dixon *et al* 1976, Cook *et al* 1984) were concerned with structure studies, using momentum distributions derived from non-coplanar (e, 2e) measurements to discriminate between different theoretical correlated wavefunctions of the helium ground state. More recently, high energy coplanar experiments (Stefani *et al* 1990, Dupré *et al* 1990, Lahmam-Bennani *et al* 1992a) have probed the dynamics of the simultaneous ionization and excitation process. These experiments have been of the glancing type, with one of the outgoing electrons carrying away most of the energy and being deflected in the forward direction. The measurements show a marked contrast to those for direct ionization, with the backscatter peak being larger than the forward scatter peak. Theoretical models for these asymmetric geometries are only beginning to be developed (Lahmam-Bennani *et al* 1992b, Robaux *et al* 1991, Franz and Altick 1992), and these models indicate the importance of initial state correlations in the atom and final state correlations between the ejected electron in the continuum and the excited electron in the residual ion.

Results are presented here for a coplanar non-glancing experiment at a much lower incident energy. The excitation energy of the excited ($n = 2$) electron in the He^+ ion

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core is comparable to the kinetic energy of the detected electrons in this experiment, and so strong correlations between all three electrons in the final state might be expected. Measurements are also presented for direct ionization to the ionic ground state, where the energy of the detected electrons was selected to be the same as for ionization with excitation. This allows a direct comparison to be made between the two processes, since the analyser efficiencies remained unchanged. Additionally, the cross sections have been placed on an absolute scale by comparison with the absolute coplanar symmetric measurements of Gélébart and Tweed (1990) for direct ionization.

Labelling the ingoing and outgoing two electrons as e_0, e_a and e_b respectively, the energy equation for this reaction may be written:

$$E_0 = \mathrm{IP} + E_{ex} + E_a + E_b \tag{2}$$

where for helium the ionization energy $\mathrm{IP} = 24.6$ eV and the ionic excitation energy $E_{ex} = 0$ eV and 40.7 eV for $n = 1$ and $n = 2$ respectively. In the present experiments the electrons e_a and e_b were chosen to have equal energy, $E_a = E_b = 40$ eV, and were detected at equal azimuthal angles $\theta_a = \theta_b = \theta$ (see figure 1). The incident electron energy E_0 was therefore 104.6 eV for direct ionization and 145.3 eV for ionization with excitation. The doubly-symmetric differential cross section (DCS) was obtained by varying the angle θ and measuring the (e, 2e) coincidence signal as a function of this angle. A particular 'slice' of the fivefold differential cross section $d^5\sigma/d\Omega_a\, d\Omega_b\, dE_a$ was thus obtained, the polar coordinate $\phi = (\phi_a - \phi_b)$ ($=0°$ for coplanar geometry) and the energy $E_a = E_b$ being held constant as $\theta_a = \theta_b = \theta$ was varied.

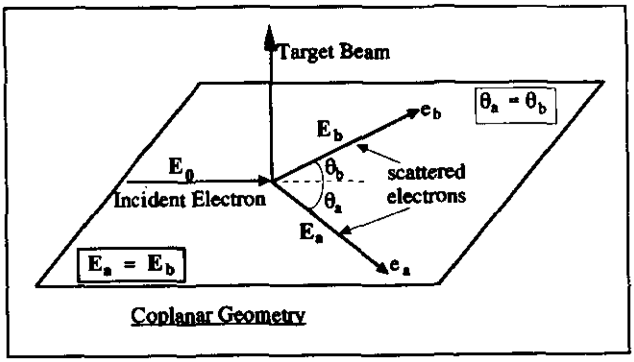

Figure 1. The coplanar doubly-symmetric experimental geometry.

No attempt has been made to distinguish between the 2^2S and 2^2P states. In principle the differential cross section arising from the $2^2P_{1/2,3/2}$ states could be separated from that for the $2^2S_{1/2}$ state with a triple coincidence between the outgoing electrons together with detection of the decay emission from the 2^2P states. The ionic 2^2P substate population and coherences could additionally be determined by measuring the angular distribution or polarization of the emitted photons. Such an experiment would, however, be very difficult in practice due to the extremely low triple coincidence yields that would be obtained.

The spectrometer used to collect these results is a fully computer controlled and real-time computer optimized (e, 2e) coincidence spectrometer (Murray *et al* 1992a). The optimization software monitors and controls seventeen lens and deflector voltages, the electron beam current, high voltage supplies and vacuum pressure. The spectrometer is maintained at its optimum during data accumulation, with frequent adjustment for any long term drifts. This is essential in experiments which require long data accumulation times such as the one described here.

Briefly, the spectrometer is mounted in a vacuum chamber at a background pressure of typically 10^{-8} Torr. The incident electron energy is selectable from 20 eV to 300 eV with a resolution of approximately 600 meV, the beam current being focused at the interaction region to a 1 mm diameter beam with zero beam angle and a pencil angle of approximately 2°. 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 pre-amplified and noise discriminated. The discriminators feed a time to amplitude converter via appropriate delay lines, resulting in an 8 ns FWHM coincidence signal which accumulates in a multichannel analyser located on the IBM 80286 PC computer bus. The computer software optimizes the spectrometer at regular intervals using a modified simplex technique (Nelder and Mead 1965). Full details of the spectrometer and the computer interface may be found in Murray *et al* (1992a).

The direct ionization experiments were interleaved with the experiments on the ionic excited state. The background vacuum pressure was maintained at 1.0×10^{-5} Torr during data collection, and the typical electron beam current was 0.9 μA. The average coincidence counting rate for data accumulation to the ground state varied from 18 counts per second to approximately 1 count every 30 seconds, and the total run time was 4.8×10^{5} s. By contrast, for ionization with excitation, the average coincidence count rates varied from 1 count every 5 seconds to as low as 1 count every 400 seconds, and the total run time was 5×10^{6} s (i.e. approximately 60 days).

The data were normalized as described by Murray *et al* (1992b). The coincidence count rates $\dot{N}_{\mathrm{C}}(E_0, E_{\mathrm{a}})$ are given by

$$\dot{N}_{\mathrm{C}}(E_0, E_{\mathrm{a}}) = \frac{I_{\mathrm{F}}\rho V_{\mathrm{o/lap}}}{e\pi r^2}\frac{\mathrm{d}^5\sigma}{\mathrm{d}\Omega_{\mathrm{a}}\,\mathrm{d}\Omega_{\mathrm{b}}\,\mathrm{d}E_{\mathrm{a}}}\varepsilon_{\mathrm{a}}(E_{\mathrm{a}})\varepsilon_{\mathrm{b}}(E_{\mathrm{b}})\,\delta\Omega_{\mathrm{a}}\,\delta\Omega_{\mathrm{b}}\,\delta E_{\mathrm{coinc}} \qquad (3)$$

where I_{F} is the current in the incident electron beam of radius r, ρ is the target gas density in the interaction region, $V_{\mathrm{o/lap}}$ is the overlap volume of the gas and electron beam as viewed by the analysers, $\varepsilon_{\mathrm{a}}(E_{\mathrm{a}})$ and $\varepsilon_{\mathrm{b}}(E_{\mathrm{b}})$ are the efficiencies of analysers a and b at the energy $E_{\mathrm{a}} = E_{\mathrm{b}} = 40$ eV, $\delta\Omega_{\mathrm{a}}$ and $\delta\Omega_{\mathrm{b}}$ are the input solid angles of the analysers and $\delta E_{\mathrm{coinc}}$ is the coincidence energy resolution. In these experiments, I_{F}, ρ, $\varepsilon_{\mathrm{a}}(E_{\mathrm{a}})$, $\varepsilon_{\mathrm{b}}(E_{\mathrm{b}})$, $\delta\Omega_{\mathrm{a}}$, $\delta\Omega_{\mathrm{b}}$ and $\delta E_{\mathrm{coinc}}$ were held constant for ionization with and without excitation, and the electron beam diameter was focused to a smaller diameter than viewed by the analysers (Murray *et al* 1992b). The ratio of differential cross sections for the two processes is therefore given by the ratio of observed coincidence count rates. The data for direct ionization were then placed on an absolute scale by comparison with the 100 eV absolute coplanar symmetric data of Gélébart and Tweed (1990).

Figures 2 and 3 show the normalized differential cross sections plotted on linear and logarithmic scales in order to highlight the differences in the forward and backward scattering directions. The estimated uncertainty in the direct ionization data is ±44% (Murray *et al* 1992b), whereas the uncertainty estimated in the excited state result is ±60%. The ratio of cross sections is approximately 100:1 and so separate scales have been used for the two sets of measurements. The forward scattering cross sections are qualitatively similar in form, in contrast to the results for the high energy asymmetric

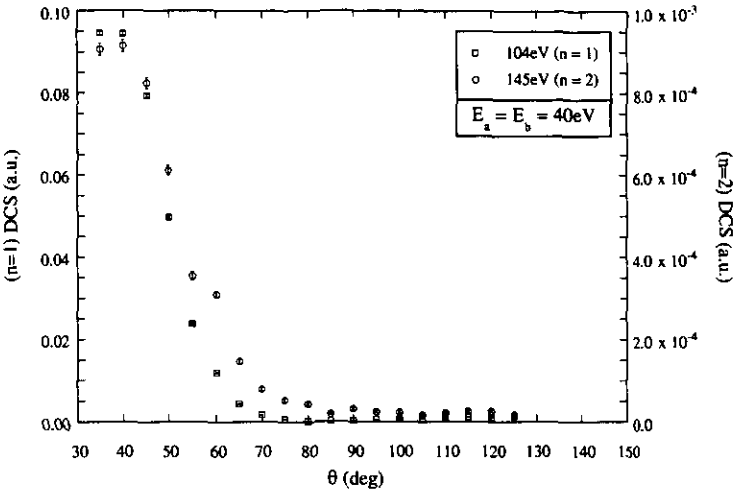

Figure 2. The doubly-symmetric differential cross section for ionization with and without ionization, plotted on a linear scale.

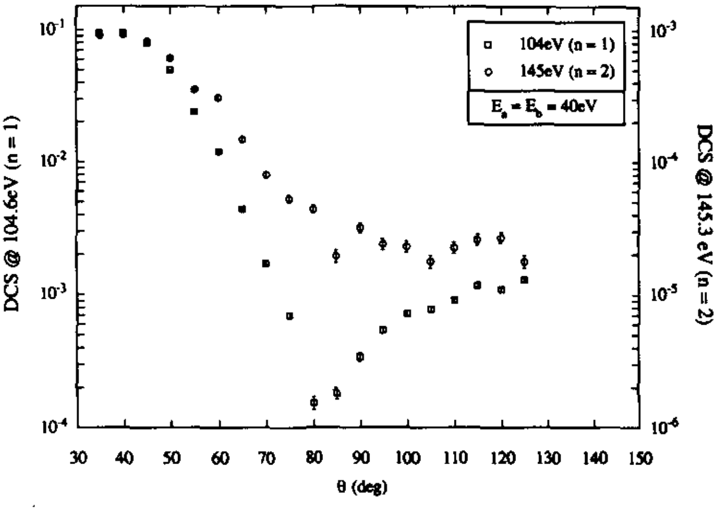

Figure 3. The doubly-symmetric differential cross section for ionization with and without ionization, plotted on a logarithmic scale.

geometry (Stefani *et al* 1990, Dupré *et al* 1990, Lahmam-Bennani *et al* 1992a). The direct ionization result is identical in structure to that of Gélébart and Tweed (1990) at 100 eV as expected, although the magnitude differs slightly because the incident energy is different. A deep minimum is seen around 80°, followed by a backscatter peak around 135°. Whelan and Walters (1990) suggest this results from elastic scattering of the incident electron through 180° from the atomic core followed by a quasi-free binary collision. By contrast, the result for ionization with excitation does not appear to exhibit this deep minimum, although the very low measured coincidence counts at these angles preclude any definite conclusion.

There is a slight structure observed at $\theta \approx 60°$ for ionization with excitation which does not appear for direct ionization, and since these results were taken at the same time, this is not considered to be an instrumental effect. Direct ionization from a p orbital exhibits structure in the cross section with a splitting of the binary and backscatter peaks, a secondary peak appearing roughly at 50-60° in the forward lobe (Rösel *et al* 1990, Whelan and Walters 1990). It is perhaps not unreasonable to assume that analogously, excitation to the excited 2^2P state might exhibit similar structure. The cross section for excitation to the 2^2S ionic state would be expected to forward peak at approximately $\theta = 45°$, as in the direct ionization process. A similar structure might be expected in a backscatter peak at approximately 120°, where the incident electron is initially scattered elastically by the atom prior to ionization and excitation, and a suggestion of such a peak can be seen in figure 3.

In conclusion, experimental (e, 2e) differential cross sections at low incident energy have been presented for ionization with excitation to the 2^2S and 2^2P valence states. No other low energy experiments of this type have been performed with which to compare these results. All previous experiments where the ion is left in an excited state have been conducted at high energy and at glancing angles, and theoretical models for these results have only recently been attempted. No theory is available at present at either this energy or for this doubly-symmetric coplanar geometry.

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