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LETTER TO THE EDITOR

Low energy (e, 2e) differential cross section measurements on neon from the coplanar to the perpendicular plane geometry

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Abstract. Experimental results are reported for the (e, 2e) differential ionization cross section of neon at an incident electron energy 20 eV above the ionization potential. The measurements have been carried out from the coplanar to the perpendicular plane geometry, the electrons being detected at equal scattering angles in the detection plane and with equal energies. The differential cross section displays trends that are very different from those seen for helium.

Understanding the complex interactions that are involved when atoms or molecules are ionized by electron impact remains one of the major challenges facing atomic physics at the present time. These interactions have been studied for many years, and significant advances in both theoretical understanding and experimental techniques have been made (see for example Byron and Joachain 1989, Ehrhardt 1983, McCarthy and Weigold 1995 and references therein).

The most sophisticated of the past experiments have studied the ionization reaction by measuring the resulting products in coincidence. For single ionization by electron impact, the (e, 2e) coincidence experiment probes the scattered and ejected electron momenta that result from the ionization events. By selecting different momenta at which the outgoing electrons are observed, a complete description of the ionization process can be obtained in principle.

In the experiments reported here, spin effects are neglected and so the only constraints placed upon the reaction are the requirements that momentum and energy be conserved, which therefore allows the scattered and ejected electrons to have a range of different directions and a range of different energies. A differential cross section is thus required to fully characterize the reaction for any given incident energy E_{inc}. This cross section is differential in two solid angles defined by the direction of the correlated electrons, $\mathrm{d}\Omega_a$, $\mathrm{d}\Omega_b$, and is differential in the energy of one of the outgoing electrons (since the energies of the two outgoing electrons are related by energy conservation). The differential cross section may therefore be written :

$$\sigma = \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_a \mathrm{d}\Omega_b \mathrm{d}E_a}.$$

It has been necessary in practice to restrict the measurements by holding one or more of the parameters constant, and observing the cross section while varying the remaining parameters. As an example, in coplanar geometry the incident electron momentum $\boldsymbol{k}_0$ and the outgoing electron momenta $\boldsymbol{k}_a$ and $\boldsymbol{k}_b$ are restricted to a single plane. This reduces the number of independent parameters to three, comprising two angles and one energy. At any given incident energy, measurements are usually conducted by selecting a set of fixed energies and directions for the electrons, and scanning over the direction of the other outgoing electron (Ehrhardt *et al* 1969, Ehrhardt and Frost 1993, Röder *et al* 1996).

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An alternative type of coplanar measurement is that in which both detectors rotate at equal angles with respect to the incident electron trajectory but on opposite sides of that trajectory (Pochat *et al* 1983). Yet another type is that in which the outgoing electrons share the available energy equally (Bray *et al* 1998, Rioual *et al* 1997, 1998, Rouvellou *et al* 1998, Chen *et al* 1998). In these experiments the measurements are very sensitive to dynamical and correlation effects, and considerable theoretical effort has been made to understand these processes. Distorted wave Born approximations prove successful at higher impact energies (Whelan *et al* 1993), however, as the impact energy decreases other effects such as polarization of the target and post collisional interactions become important, and the interplay between these effects can cause large discrepancies between theory and experiment. In particular, Rioual *et al* (1997) have found that the inclusion of polarization effects leads to significant differences in the theoretical predictions for neon and argon at energies 100 eV and below, with this effect increasing as the incident energy decreases. It is therefore expected that these effects will play a significant role in the measurements presented here.

Whereas coplanar measurements are the most common type of experiment performed, it is also possible to make measurements in a *non-coplanar* geometry (Cvejanovic and Read 1974, Hawley-Jones *et al* 1992, Murray and Read 1992, 1993a, b, Bowring *et al* 1997). In this case, a plane is defined by either $\mathbf{k}_0 \times \mathbf{k}_a$, $\mathbf{k}_0 \times \mathbf{k}_b$ or $\mathbf{k}_a \times \mathbf{k}_b$, where $\mathbf{k}_0$, $\mathbf{k}_a$ and $\mathbf{k}_b$ are the momentum vectors of the incident and two outgoing electrons respectively. The maximum number of free parameters is then four, comprising three angles and one energy.

In the experiments described here, the $\mathbf{k}_a \times \mathbf{k}_b$ plane is chosen as a reference plane, which will hereafter be called the *detection plane*. The incident electron momentum $\mathbf{k}_0$ is then varied with respect to this plane as shown in figure 1. The most symmetric geometry is used, in which the outgoing electrons emerge from the reaction with equal angles $\xi_a = \xi_b$ and equal energies $E_a = E_b$. The electron gun is moved from $\psi = 0^\circ$ (coplanar geometry) through to $\psi = 90^\circ$ (the perpendicular plane geometry), with a common point between all measurements occurring when $\xi_a = \xi_b = 90^\circ$. This allows all measurements to be related and normalized to this common point. A comprehensive study of the reaction dynamics can thus be conducted over the full three-dimensional surface which describes the ionization process (Murray *et al* 1994, 1997). A full description of the experimental apparatus which is used for these experiments is given in Murray *et al* (1992).

The measurements reported here have not been placed on an absolute scale, although the existence of the common normalization point at $\xi_a = \xi_b = 90^\circ$ implies that only a *single*, later absolute measurement need be used to place the data onto an absolute scale. Once this point is chosen, any theoretical calculation can be matched against *all* measurements, for all angles

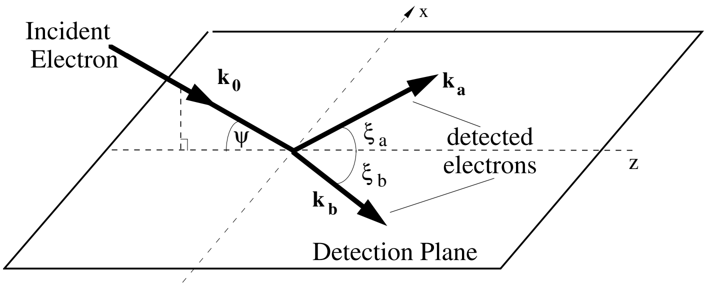

Figure 1. The experimental geometry which defines a detection plane $\mathbf{k}_a \times \mathbf{k}_b$. The incident electron momentum vector $\mathbf{k}_0$ is at an angle ψ with respect to this plane as shown.

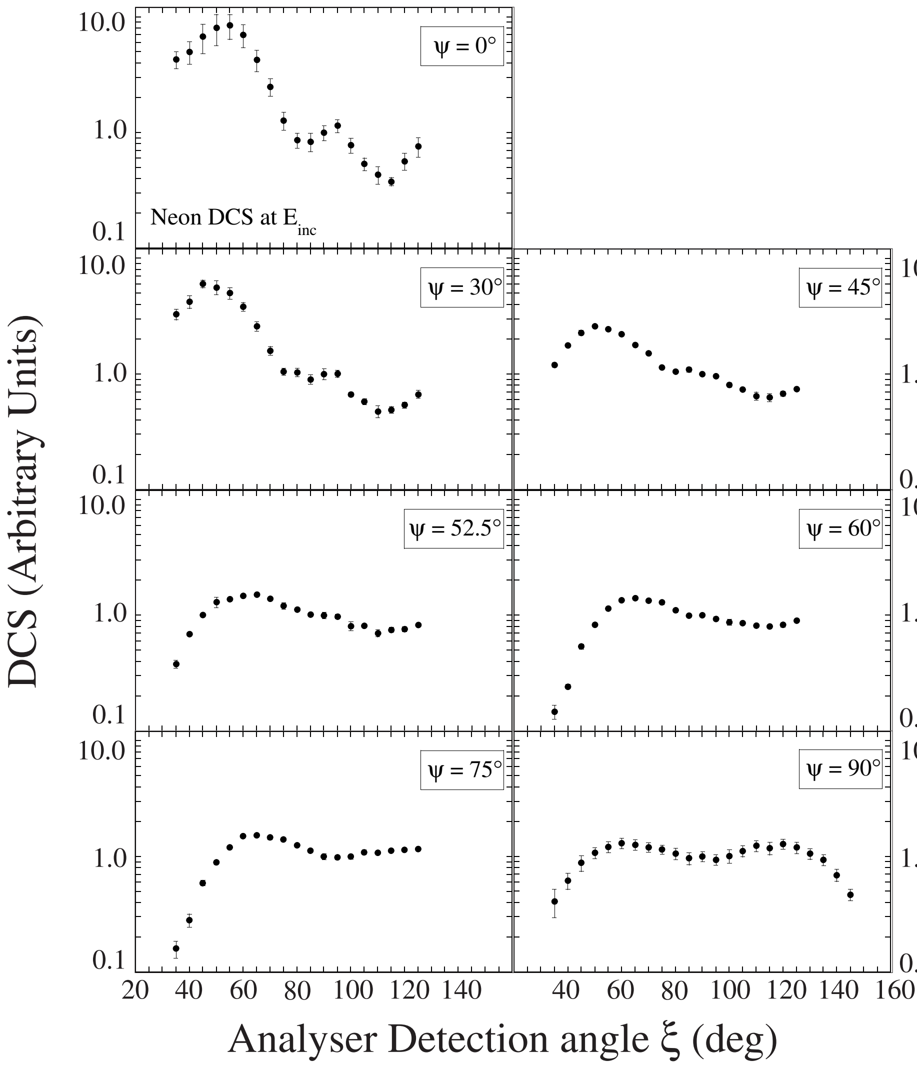

Figure 2. The set of differential cross section measurements for ionizing neon at an incident energy of 41.6 eV shown on a logarithmic scale. Seven gun angles were selected from $\psi = 0°$ to $\psi = 90°$ as shown, the results being normalized to unity at $\xi = 90°$.

ψ, ξ_a and ξ_b, since all the data are related via the common point. These constraints present a significant challenge to theoretical models of the interaction.

Figure 2 shows the results obtained ionizing from the $2p^6$ orbital of neon at an incident energy of 41.6 eV (i.e. 20 eV above the ionization threshold). Seven gun angles, $\psi = 0°, 30°, 45°, 52.5°, 60°, 75°$ and $90°$ were used, the measurements being normalized to unity at $\xi = 90°$. The angles ξ_a and ξ_b were restricted to the range from 35° to 125° for all gun angles up to $\psi = 75°$, whereas for $\psi = 90°$ the results could be extended to $\xi = 155°$ as shown.

It can be seen that the behaviour of the ionization differential cross section of neon is significantly different from that of helium, which is shown in figure 3 for eight gun angles,

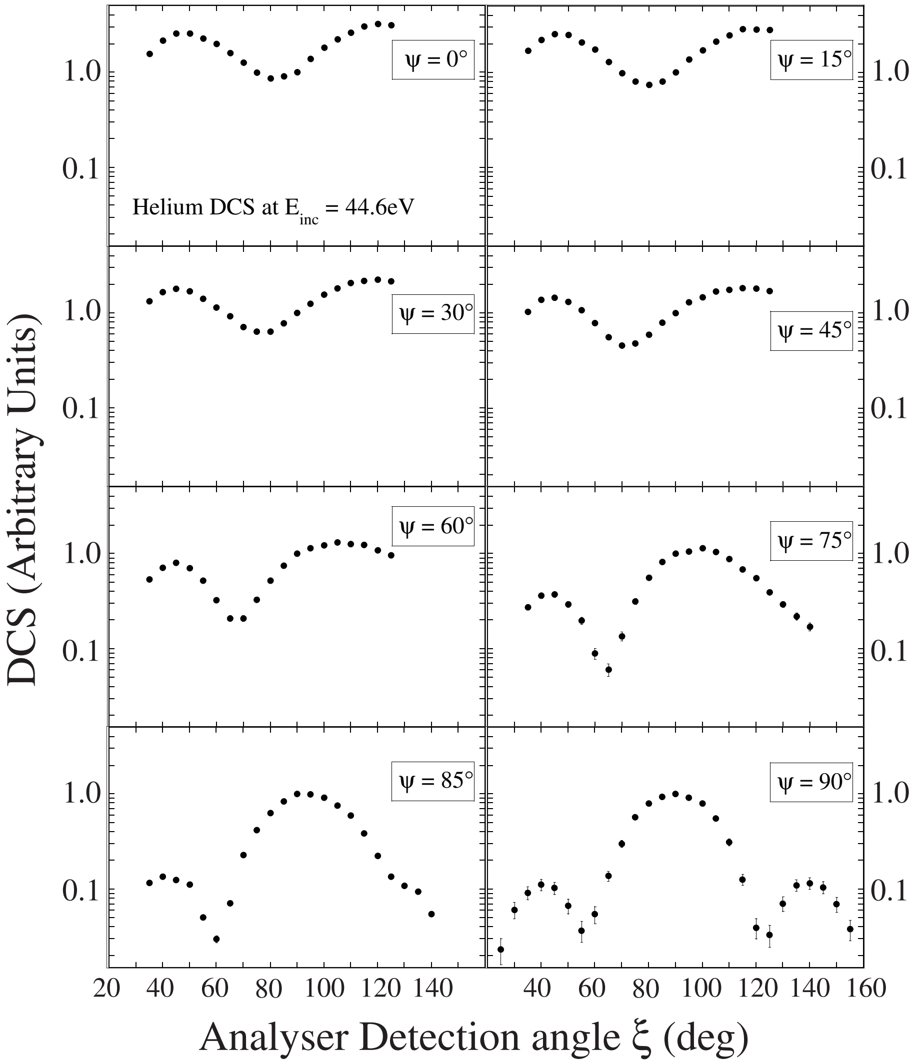

Figure 3. Differential cross section measurements for ionizing helium at an incident energy of 44.6 eV shown on a logarithmic scale. Eight gun angles were selected from $\psi = 0°$ to $\psi = 90°$ as shown, the results being normalized to unity at $\xi = 90°$.

$\psi = 0°$, 15°, 30°, 45°, 60°, 75°, 85° and 90°. The cross section is again normalized to unity at $\xi = 90°$ (Murray and Read 1992).

In coplanar geometry ($\psi = 0°$) the forward-scatter peak dominates in neon, with a minimum in the cross section being observed at $\xi = 115°$. The main backward-scatter peak is at an angle $\xi > 125°$, and is outside the measurable range of the apparatus. A second minimum occurs at an angle $\xi \approx 85°$ and a corresponding small peak appears at an angle $\xi \approx 95°$. This secondary minimum is a result of the momentum of the bound valence p-electron which has zero probability of being equal to zero, and which peaks at 0.85 au. This has been observed to produce a dip in the differential cross section in coplanar geometry when ionizing a valence p-electron from other targets (Avaldi *et al* 1989, McCarthy and Weigold 1995, Bell *et al* 1995, Rioual *et al* 1997). These coplanar results are qualitatively similar to the results of Rioual *et al* (1995, 1997) who studied coplanar symmetric ionization of neon at 50 eV and between 65 eV and 500 eV. The dip seen at the angle $\xi \approx 85^\circ$ is deeper at the lower energy used in this study compared to the results at higher energies.

As the gun angle ψ is increased, a number of different phenomena are observed. The forward-scatter peak steadily reduces while the backward-scatter minimum increases, until at $\psi = 52.5^\circ$ there is almost no change in the cross section from $\xi = 55^\circ$ through to $\xi = 125^\circ$. The cross section remains fairly flat for all higher gun angles from $\psi = 52.5^\circ$ to $\psi = 90^\circ$.

At detection angles in the range from $\xi = 35^\circ$ to $\xi = 55^\circ$ the differential cross section decreases rapidly as the gun angle increases from $\psi = 0^\circ$, reaching a minimum at $\psi \approx 60^\circ$, and then increases again as the gun angle moves from $\psi = 75^\circ$ through to $\psi = 90^\circ$. At these higher gun angles the observed minimum at $\xi \approx 90^\circ$ also deepens slightly, although it remains quite shallow. The results for $\psi = 90^\circ$ are symmetric around $\xi = 90^\circ$ as expected due to symmetry, with only two peaks being observed. This contrasts with the perpendicular plane results for helium where three peaks are observed, the peak at $\xi = 90^\circ$ dominating the reaction for helium in this geometry.

In the backward direction in the detection plane ($\xi > 90^\circ$), the cross section is smallest for coplanar geometry and monotonically increases until reaching a maximum in the perpendicular plane. This is completely opposite to the observations for helium, where the cross section in the backward direction is a maximum in coplanar geometry and proceeds monotonically to a minimum in the perpendicular plane, as shown from the series of results presented.

The contrast between the neon and helium results is interesting given that the outgoing electron energy is relatively low and is the same for both targets. At these energies, post collisional interactions between the outgoing electrons in the final channel following the reaction are expected to contribute significantly to the observed cross section. As noted by Rioual *et al* (1997) for coplanar symmetric experiments, the effect of target polarization is also significant for neon. The non-coplanar experiments described here require a double or higher scattering mechanism for the outgoing electrons to emerge into the detection plane and so it might be expected that the polarizability of the target also plays a role in this double scattering mechanism for neon. Post collisional interactions in the final channel are clearly not dominating the reaction at this energy (apart from at $\xi = 0^\circ$ and $\xi = 180^\circ$ where the cross section must be zero), or the data would be similar for both targets. Although theoretical analysis of these reactions is proving to be reasonably successful in coplanar geometry, these theories have yet to adequately explain the non-coplanar measurements in helium. The results presented here for neon provide further data for these theories to consider.

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