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Triple-differential cross section for electron-impact ionization of argon in a coplanar symmetric geometry at intermediate energies

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We have measured experimental triple-differential cross sections for electron-impact ionization of the outer shell of argon at incident energies of 115.8 and 215.8 eV. The experiments have been performed in coplanar symmetric geometry with $E_a = E_b = 50$ eV and $E_a = E_b = 100$ eV. The results are compared with recent distorted-wave Born-approximation calculations.

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The $(e,2e)$ technique, in which an ejected and scattered electron are detected in coincidence after electron-impact ionization of a target, has been applied to a wide range of targets and kinematical arrangements. The cross section measured in such experiments is called the triple-differential cross section (TDCS). Differing elements of the scattering process may be explored, depending on the choice of kinematics; for example, the noncoplanar symmetric geometry yields information on the momentum probability distribution of the bound electron, while the highly asymmetric geometry simulates photoionization [for more details of various aspects of the $(e,2e)$ process, see, for example, the extensive reviews of Brion [1], Ehrhardt *et al.* [2], McCarthy and Weigold [3], and Lahmam-Bennani [4], as well as recent conference proceedings [5,6]]. In the experiments described here, the coplanar symmetric geometry has been employed, in which the incident, ejected, and scattered electrons are detected in the same plane and the ejected and scattered electrons are detected with equal energies and equal polar angles (see Fig. 1). This geometry maximizes the probability of close electron-electron collisions. A number of recent measurements of the TDCS, both relative and absolute, have been performed on helium using this geometry [7–9]. For intermediate energies (incident energies in the range 100–500 eV), recent distorted-wave Born-approximation (DWBA) calculations performed by Whelan and co-workers [10] exhibit good agreement with the helium data, although at 100 eV the agreement is noticeably poorer at backward angles, where the theory underestimates considerably the magnitude of the TDCS relative to experiment. However, coplanar symmetric measurements of the TDCS for neon and xenon [9,11] indicate that at 100 and 200 eV the agreement between experiment and theory is not as good as for helium, although at higher energies (500 eV) the theory again appears to perform well. Thus further measurements of the TDCS for the noble gases at intermediate energies may be useful in further elucidating the range of validity of the latest theories.

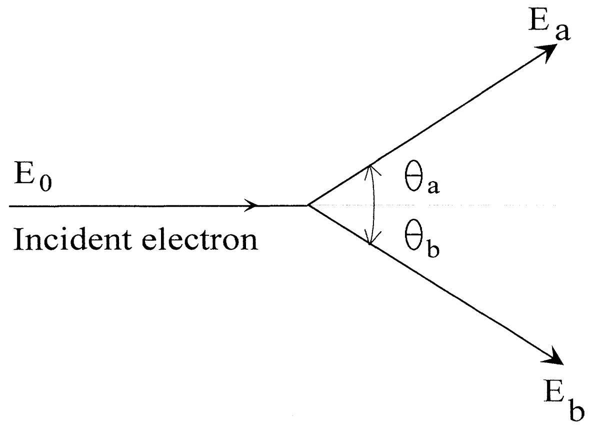

FIG. 1. Coplanar geometry for $(e,2e)$ collisions. In the coplanar symmetric case, $E_a = E_b$ and $\theta_a = \theta_b$.

We present here measurements of the TDCS for argon measured in coplanar symmetric kinematics at sum energies of $E_a + E_b = 100$ eV and $E_a + E_b = 200$ eV. The incident energy in each case is then $E_0 = E_a + E_b + 15.8$ eV. The measurements have been performed using a coincidence electron spectrometer that has been designed for electron–Auger-electron coincidence experiments, in which the Auger electron emitted after inner-shell electron-impact ionization of a target atom is detected in coincidence with the scattered electron. The apparatus has been described in detail elsewhere [12]. Briefly, it comprises a commercial electron gun (with a thoriated tungsten filament), two identical hemispherical analyzers mounted on turntables, and a gas jet produced from a stainless-steel capillary. The spectrometer is contained within a vacuum chamber lined with μ metal and pumped by a turbomolecular pump; the chamber itself is enclosed within three orthogonal pairs of large, square Helmholtz coils. We have recently replaced the channeltron detector in one of the analyzers with a position-sensitive detector incorporating a pair of microchannel plates with a resistive anode, and the associated modifications to the data acquisition system have been discussed elsewhere [13].

The gas is admitted to the interaction region by a single stainless-steel capillary 1 mm in diameter, and using the results of Buckman *et al.* [14] we estimate that the gas jet has a diameter of approximately 2 mm at the interaction region. Measurements of the electron-beam profile using a narrow Faraday cup indicate that the diameter of the beam is around 1 mm. The angular accep-

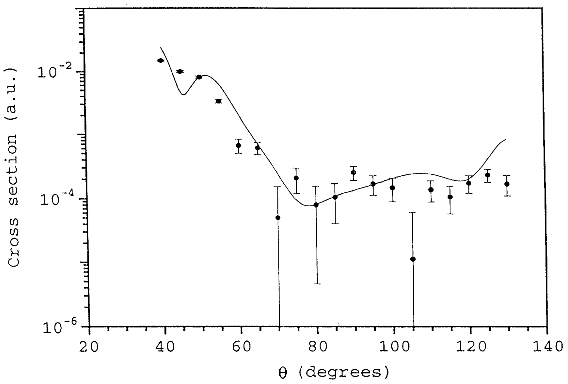

FIG. 2. Triple-differential cross section for $3p$ ionization of argon at an incident energy of 215.8 eV with $\theta=\theta_a=\theta_b$ and $E_a=E_b=100$ eV. The measured data (●) have been normalized to the DWBA calculation (——) at 50°.

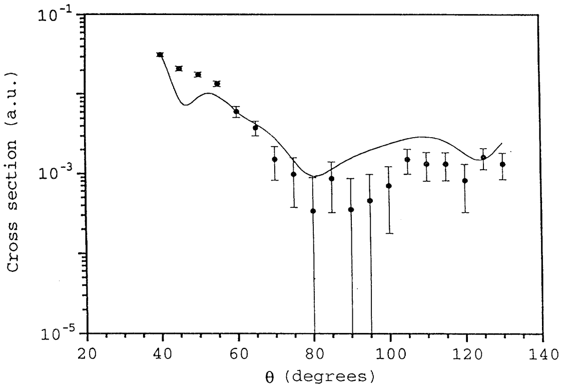

FIG. 3. Triple-differential cross section for an incident energy of 115.8 eV. In this case $E_a=E_b=50$ eV. The symbols are as for Fig. 2, and the measured data have been normalized to the theory at 60°.

tances of the analyzers are quite large (±3.5°), as they were designed for electron-Auger coincidence measurements where the count rates are very low. Hence the angular resolution in these measurements is rather poor. In order to check the angular calibration and to ensure that the analyzers view the whole interaction region at all angles, our measured differential cross section for elastic scattering from argon at 100 eV was compared with previous measurements and calculations [15]. The total coincidence energy resolution in these measurements was 1.5 eV.

The experiments are under computer control and the incident energy, detection energies, and angular positions of the analyzers may all be controlled via the computer. The data acquisition is performed using a custom-made analog-to-digital converter card in conjunction with a 486 PC. During a run, the analyzers are repeatedly scanned over the region from 40 to 130° in 5° steps, and spend only a short time at each angle in order to minimize the effects of any drifts in experimental parameters over the course of a scan. In previous measurements on helium in this energy regime, Frost, Freienstein, and Wagner [7] and Gélébart and Tweed [8] measured the cross section separately over two different angular ranges. This was done in order to allow them to vary the conditions of the experiment between the two sets of measurements, which was necessitated by the fact that the cross section drops by three to four orders of magnitude between forward angles and backward angles. In contrast, we scan the whole angular range in each run, without changing any of the experimental conditions. As the cross section for argon also drops by several orders of magnitude over this range, this means that the data points at larger angles have very large error bars. However, this procedure means that we do not have to use a normalization procedure to match sets of data that have been accumulated under different conditions, which is more important in our case as we do not measure absolute cross sections.

The measured TDCS results are shown in Figs. 2 and 3, where they are compared with the DWBA calculations of McCarthy [16]. In Fig. 2 the data have been normalized to the theory at 50°, in order to give the best visual fit. At 200 eV, the cross section drops by two to three orders of magnitude over the range 40°–130°. The agreement between theory and experiment is quite good for this case, with the theory agreeing well with the relative magnitude of the cross section at backward and forward angles. Note that the experimental measurements do not resolve the dip at 45°, and in fact measurements of the cross section in this region at 2° intervals indicate that we measure more of a "shelf" than a dip, which we attribute largely to the poor angular resolution of the system. The dip in the cross section near 45° is characteristic of ionization for a p orbital.

In Fig. 3, the 100-eV cross-section measurements have been normalized to the DWBA calculation at 60°. Again, there is reasonable agreement between theory and experiment, although in this case the theory does not predict the relative magnitude of the cross section at forward and backward angles quite as well. The experimental results also appear to verify the double bump structure predicted at backward angles, although further measurements at larger angles would help to confirm this. Whelan and Walters [17] and Zhang, Whelan, and Walters [18] have suggested that the double bump structure in the backward direction is a rough mirror image of the split peak in the forward direction, and the calculations predict that the dip in the backward direction should become more pronounced as the incident energy increases (as does the dip in the forward direction).

The present measurements of the TDCS in argon confirm that recent DWBA calculations give a good representation of the cross section for sum energies as low as 100 eV. The agreement between theory and experiment at these energies appears to be somewhat better for argon than for neon and xenon.

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