Large Angle Elastic Scattering of Electrons from Ar^+

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Absolute angular differential cross sections have been experimentally determined for large angle scattering of a free electron by a positive ion for the first time. Data are presented for elastic scattering over the range 120°–170° from Ar^+ at 3.3 eV. Interference effects are observed due to the competing short-range and Coulomb interactions. The importance of interference and correlation effects is demonstrated, and the consequent sensitivity of such measurements as a test of theoretical approximations is discussed.

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The elastic scattering of electrons from neutral atoms has been extensively investigated both experimentally and theoretically. Interference structure is typically evident in the angular differential cross sections (DCS) [1]. While there is still a common perception that elastic scattering from positive ions is simply described by the classical Rutherford formula, interference structure has been theoretically predicted for electrons elastically scattered from partially stripped ions [2]. Evidence to support this has come from fast ion-atom or ion-molecule ionization studies, where the binary encounter (BE) peak has been interpreted as the elastic scattering of a quasifree target electron in the field of the projectile ion [3]. BE peak anomalies such as multipeaks and energy shifts have been attributed to being the result of minima in the corresponding electron-ion elastic DCS [4]. However, these studies are restricted to high effective electron-ion collision energies, and are complicated by the role of the host atom, via momentum distribution of the quasifree electron [3] and in postcollision interactions [5]. More direct evidence for interference structure may be expected through the scattering of free electrons from positive ions.

At low collision energies, describing the elastic scattering process is further complicated by enhancement of electron-electron correlations as the velocity of the free electron reduces below the velocity of the electrons dressing the ionic core. A recent many-body calculation at 10 eV predicts strong variation in large angle DCS for Cs^+ due to the inclusion of polarization, as well as illustrating the quite different nature of the scattering to that observed from the isoelectronic neutral atom Xe [6]. In order to investigate these effects, we have developed a novel experimental technique, which we have used to measure absolute angular DCS for the elastic scattering of free electrons from Ar^+ ions at an impact energy of 3.3 eV. These constitute the first measurement of large angle scattering by a free electron, and the first to probe below the inelastic threshold of an ion. The only previous experiment on the elastic scattering of free electrons was restricted to forward scattering angles, and involved multiply charged ions at higher energies [7].

The instrument used for the current investigation has been briefly described previously [8,9], and a more detailed account will appear elsewhere [10]. Hence, only the salient features will be summarized here. The instrument, shown schematically in Fig. 1, is immersed in a uniform axial magnetic field of about 50 G. Magnetically confined electrons are extracted from an indirectly heated cathode and pass through small, 0.3 mm, apertures in a three-element lens system. To eliminate the low intensity halo of low energy electrons surrounding the primary beam, it is decelerated close to zero axial energy at the exit of the gun. By application of a radial electric field across the curved deflection plates, the primary beam is trochoidally deflected to the axis of intersection with the ion beam. At the point of interaction, a narrow slit driven across the beam allows monitoring of the electron beam profile. Typical beam diameters are 0.3 mm (FWHM). A further slit 10 mm downstream of the point of interaction is used to diagnose scalloping and spiralling of the beam. By careful tuning of the gun lens elements, and playoff between the main and small trochoidal plates, both effects may be minimized or eliminated. On traversing the interaction region, the primary electron beam is deflected out of the plane containing the beams, and into a deep, baffled Faraday cup. The Ar^+ ion beam traverses the point of interaction perpendicular to the direction of the electron beam. It enters from, and exits to, differentially pumped chambers, so that the interaction region is maintained at a pressure below 5×10^{-10} mbar with both beams running. Both beams are electrostatically modulated to allow extraction of small signal rates against large backgrounds.

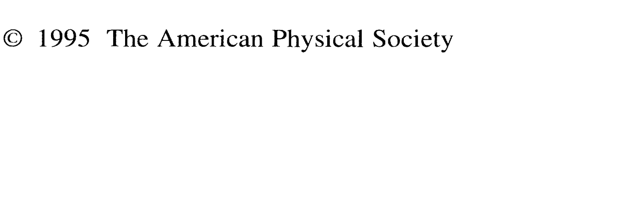

FIG. 1. Schematic diagram of the instrument.

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Electrons that are elastically scattered from the ions remain confined by the magnetic field, and hence spiral along the primary beam axis with a cyclotron radius determined by the collision energy and the angle through which the electron is scattered. Those scattered in the angular range $\{0, \pi/2\}$ travel along with the primary beam, and are collected by the Faraday cup. Electrons that are scattered in the angular range $\{\pi/2, \pi\}$, however, travel in the opposite direction and hence reenter the main deflection plates. Here they are trochoidally deflected away from the primary beam and detected by a channel electron multiplier detector with a 10 mm diameter entrance cone. Using this arrangement we have recently reported on absolute partial elastic cross sections in the angular range $\{\pi/2, \pi\}$ for Ar^+ over the energy range 3.5–6.5 eV [9].

In the present study we have extended our technique so as to extract angular differential information from the scattering process. To achieve this, the instrument has been modified by inserting high transmission grids between the deflectors and the channel electron multiplier detector. By applying a variable negative bias to the central grid, a retarding potential difference (RPD) analysis was carried out on the backscattered elastic signal. In this way data are obtained that are a function of axial velocity, and hence scattering angle. Accurate collision energy calibration was attained by replacing the ion beam with a thermal molecular beam of CO_2, and mapping the well-known elastic resonance at 3.8 eV [11]. Furthermore, the effect of contact potentials at the RPD analyzer was accounted for by reflecting a low intensity beam of electrons onto the detector, and noting the cutoff point as voltage was applied to the analyzer.

It should be noted that the kinematics requires a transformation of scattering energy and angle from laboratory (lab) to center of mass (c.m.) frame of reference. It can readily be shown that a particular axial velocity component in the c.m. frame results in a range of observed axial components in the lab frame, due to scattering through all azimuthal angles. Thus corrections were carried out over the full range of azimuthal angles, using standard transformation equations [12]. In the present case, where the beams intersect at right angles and the electron velocity is greater than 10 times the ion velocity, the resulting correction is small within the angular range studied. At all angles the spread in axial energy is significantly smaller than the energy spread in the beam. A full account of kinematic effects and corrections will appear elsewhere [10].

A partial wave analysis has also been carried out in order to test the accuracy of semiempirical potentials sometimes used in electron-ion scattering calculations. Manson [2] has derived short-range phase shifts for electron scattering from a singly charged positive ion using a Herman-Skillman potential. Szydlik, Kutcher, and Green [13] have similarly derived phase shifts using the independent particle model potential of Green, Sellin, and Zachor [14]. For both cases it is found that only the first three partial waves contribute significantly to the scattering at low energy. We have used both sets of short-range phase shifts, coupled with the Coulomb phase shifts, to calculate the differential cross section for elastic scattering from Ar^+ at 3.3 eV. The results are displayed in Fig. 2. Interference effects between the Coulomb and short-range interactions are clearly observable, with a strong peak predicted to occur at 180°.

In order to facilitate a direct comparison of the theory with experiment, it is necessary to fold the calculated data with an instrumental angular profile. In the present experiment there are two sources of angular broadening. The primary electron beam has been measured to have an energy spread of 250 meV (FWHM). This has the effect of smearing the resolution of the RPD analyzer, and in particular can be shown to be responsible for the fall in the measured cross section at angles greater than 160° (see Fig. 4). Secondly, the deflector used to separate the backscattered beam from the primary electron beam together with a small lens effect at the RPD analyzer also induces a spread in the axial velocity. This has been simulated using the SIMION particle trajectory code [15], which shows an effective angular spread decreasing almost linearly from 15° ± 3° at $\theta_0 = 120°$ to 5° ± 1° at $\theta_0 = 170°$. A convolution was thus performed of the theoretical differential cross section with Gaussian functions representing the instrumental profile.

Experimental data for the elastic scattering of electrons through large angles from Ar^+, at a center of mass energy of 3.3 eV, are shown in Fig. 3. These data

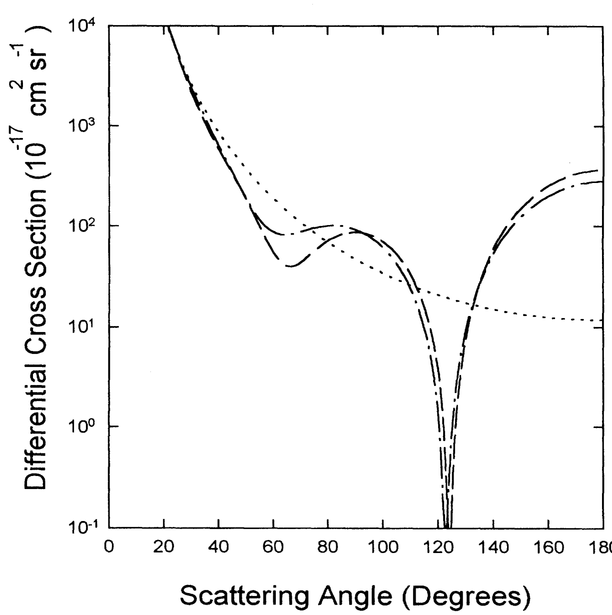

FIG. 2. Differential cross sections for the elastic scattering of electrons from Ar^+ at 3.3 eV. Partial wave calculations: Manson potential (—·—·), Szydlik, Kutcher, and Green potential (———), Rutherford formula (······).

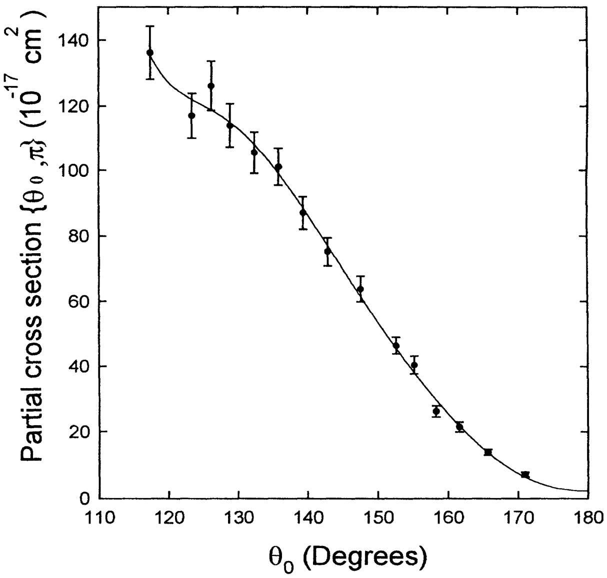

FIG. 3. Absolute partial cross sections for the elastic scattering of electrons from Ar^+ in the angular range $\{\theta_0, \pi\}$ at 3.3 eV. (●) Experimental results. (———) Best fit to the data.

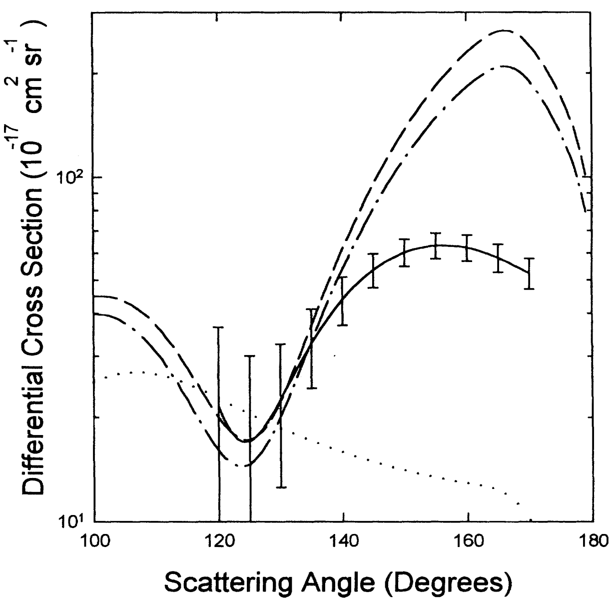

FIG. 4. Differential cross sections for the elastic scattering of electrons from Ar^+ at 3.3 eV, convoluted with instrumental profile: Experimental results (———); Rutherford formula (········); Partial wave calculations: Manson potential (—·—·), Szydlik *et al.* potential (— — —). The error bars denote the maximum uncertainty involved in the fitting procedure at representative points.

represent the partial cross section in the range $\{\theta_0, \pi\}$ as a function of θ_0. These partial cross sections are absolute, since the velocities and current intensities of the two primary beams, the detection efficiency, and the degree of overlap of the beams at the point of intersection were all experimentally determined. A description of these procedures has been given previously [9]. The error bars in Fig. 3 represent the statistical reproducibility at the 1.7σ or 90% confidence level. There is a further systematic error of 7% due to uncertainties in measuring the above parameters.

To extract angular differential cross sections, a curve was fitted to the experimental data, and the derivative calculated as a function of θ_0. The resulting angular differential cross sections are depicted in Fig. 4, where the error bars denote the maximum uncertainty involved in the fitting procedure at representative points. Interference effects are clearly observable. Also shown in Fig. 4 is the prediction of the classical Rutherford formula. As expected, this does not predict the observed peak at large angles, and in fact is seen to underestimate the cross section over most of the observed range.

To gain further insight into the scattering process, the experimental results are also compared with partial wave analysis calculations in Fig. 4. Both calculations are found to predict strong interference effects, and are in reasonable agreement with measurements over the angular range 120°–140°. Although uncertainties near 120° are large, there is clear evidence that the cross section is close to zero at this point when the angular spreading due to the trochoidal plates is taken into account. Above this range, qualitative agreement in terms of a monotonically increasing cross section is achieved. However, the calculations are clearly seen to grossly overestimate the measured values at the highest angles.

Hence, there are large discrepancies between experimental data, the predictions of the Rutherford formula, and partial wave calculations at large scattering angles. In this regime of low energy and large scattering angle we might expect dynamic effects to be of major importance. Manson's potential includes a local exchange term, allowing for interchange of the primary electron with a bound electron from the target ion. Szydlik, Kutcher, and Green argue that in defining parameters through fitting to Hartree-Fock energy levels exchange effects are inherently incorporated in their potential. However, electron exchange effects are more accurately represented by nonlocal exchange contributions, as described by Bhalla and Shingal [16].

Neither Szydlik, Kutcher, and Green nor Manson, either explicitly or implicitly, take account of the dynamic perturbation of the electronic charge cloud of the ion due to the electric field of the approaching electron. However, Johnson and Guet [6] in their treatment of elastic scattering from Cs^+ at 10 eV note major differences between calculations for backscattering, with and without the inclusion of polarization effects. It is apparent that accurate reproduction of the present measurements requires a consideration of polarization and/or exchange. The deviations observed at large angles in Fig. 4 suggest the measurements may prove a sensitive test of the application of these effects, and hence of the collision dynamics.

To summarize, we have experimentally determined absolute angular differential cross sections for large angle scattering of a free electron by a positive ion for the first time. This has been carried out at low impact energy for the singly charged ion Ar^+. The present measurements, when compared with the Rutherford formula, conclusively demonstrate the predicted interference between Coulombic and non-Coulombic interactions. This strongly supports the interpretation of the BE peak in hard ion-atom collisions in terms of the elastic scattering of a quasifree target electron in the field of the projectile ion. The short-range interaction leads to a major enhancement in the large angle scattering, but not to the extent predicted by essentially static scattering potentials. Hence we may conclude that polarization and/or exchange contributions play a major role in the collision dynamics.

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