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Differential Cross Section Measurements for Elastic Scattering of Electrons from Ar^{2+} and Xe^{2+}

P. McKenna and I. D. Williams*

The Queen's University of Belfast, Belfast BT7 1NN, UK

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Abstract

A crossed-beams energy-loss spectrometer has been used to investigate angular distributions for electron scattering from Ar^{2+} and Xe^{2+} ions, at a collision energy of 16 eV. For Ar^{2+} the measurements are compared with the predictions of a partial waves calculation based on a semi-empirical potential, where it is shown that the interference term governs the position of the observed minimum in the angular distribution.

1. Introduction

In the last decade experimental measurements of angular distributions for the elastic scattering of free electrons from beams of positive ions have been carried out for the first time [1–8]. During the same period indirect measurements of elastic scattering deduced from observations of collisions between high-energy ions and light atomic or molecular targets have also been pioneered [9,10]. This progress has been greatly facilitated by the advent of high intensity ion sources, in particular electron cyclotron resonance (ecr) sources, coupled with new sophisticated signal processing methods. Experiments have dramatically demonstrated the presence of interference features in the angular distributions, and that as a consequence the usual approach of plasma modellers in asuming a classical Rutherfordian distribution to the elastic scattering of electrons from ions is generally unsound [11].

A number of the studies to date have concentrated on ions of the Argon isonuclear sequence. Huber's group have used a technique whereby the kinematic shift in energy-loss of the scattered electrons due to the fast ion beam is used to advantage to investigate elastic sattering from Ar^{8+} at centre-of-mass collision energies of 12.98 eV and 22.46 eV, and over an angular range of 32–148° [5]. Most recently Kobayashi's group have studied Ar^{7+} and Ar^{8+} at a collision energy of 100 eV and over an angular range of 34–85°, using a newly developed spectrometer capable of simultaneous detection of all scattered electrons within a range of energy-loss and scattering angle [8]. Our group have previously reported on low energy back-scattering in Ar^{+} [2], and on a preliminary study of forward scattering in Ar^{2+} and Ar^{3+} at a collision energy of 16 eV [7]. Only Huber's group have so far carried out measurements on the elastic scattering of electrons from ions of the Xe isonuclear sequence, namely for Xe^{3+}, Xe^{4+} and Xe^{5+} at a collision enegy of 43 eV over the angular range 20–60° [5]; Xe^{6+} for energies and angles of 20.7 eV, 30–150° [5], 41.4 eV, 35–80° and 50 eV, 35–70° [1]; and Xe^{8+} at 50 eV, 35–80° [1].

In the present paper we report on measurements of the elastic scattering of free electrons at 16 eV from Ar^{2+} and Xe^{2+} ions. At such low collision energies, where the velocity of the free electron is of comparable magnitude to the velocities of the electrons dressing the ionic core, the effects of short-range interactions at small impact parameters are of increasing importance. In this regime, interference effects between the scattering amplitudes due to the short-range and Coulombic interactions can be manifested as sharp structures in the observed angular distributions.

2. Experimental method

The crossed-beams electron energy-loss spectrometer (see Fig. 1) has been described previously [4], and hence only a brief description is given here. Beams of Ar^{2+} and Xe^{2+} were extracted from a 5 GHz ecr ion source, momentum analysed in a 90° bending magnet, and focussed through a differentially pumped region into the interaction chamber. The ion beams, transported at an energy of 10 keV, were decelerated to an energy of 2 keV prior to crossing an electron beam at an angle of 90°. Great effort was made to maintain a parallel beam of electrons at the point of interaction to minimize the focussing effect of the space charge of the ion beam, which could otherwise result in modulation of the background signal rate. Electrons, elastically scattered by the target ions were analyzed by a 180° hemispherical analyzer which was free to rotate in a plane perpendicular to the plane containing the interacting beams. A microchannel plate position sensitive detector was used in the dispersion plane of the analyzer.

3. Results and Discussion

Figure 2 shows the measured angular distribution for the elastic scattering of free electrons from Ar^{2+} ions, at a centre-of-mass collision energy of 16 eV, and over the angular range 32.5–85°. Each datum shown in Fig. 2 typically represents the average of at least seven separate differential measurements carried out under different experimental conditions (i.e. beam intensities, ion-beam energy, and degree of overlap). The uncertainties are plotted at 1.7σ, i.e. at the 90% confidence level, and represent the statistical reproducibility of the data. Also shown in Fig. 2 is the prediction

*e-mail: i.williams@qub.ac.uk

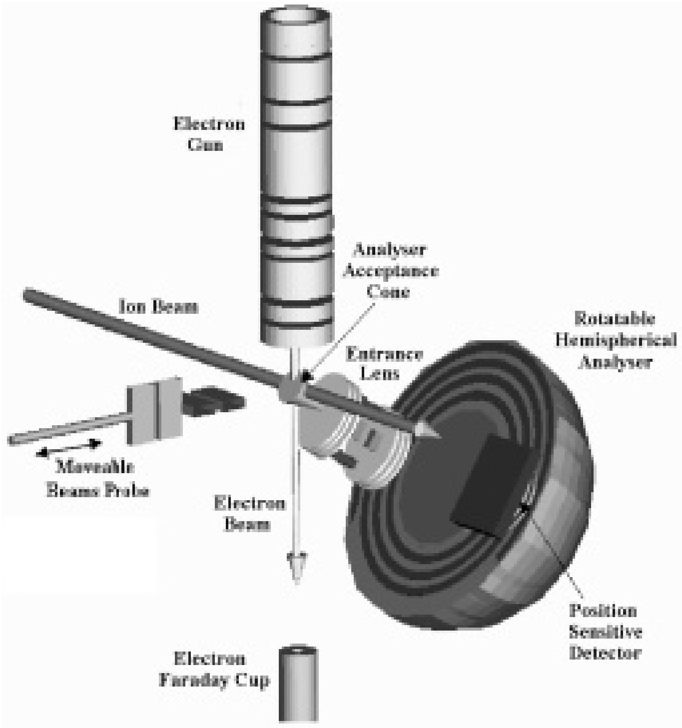

Fig. 1. Schematic diagram of the electron spectrometer.

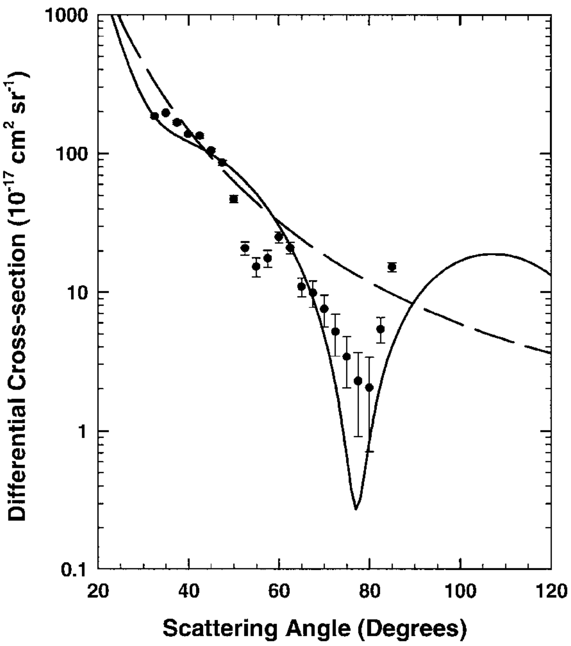

Fig. 2. Angular distribution for the elastic scattering of electrons from Ar^{2+} at 16 eV collision energy. The error bars denote the statistical reproducibility of the experimental data at the 90% confidence level. Present experimental data (●), partial waves calculation (———), Rutherford formula (— — —).

of the classical Rutherford formula

$$\frac{d\sigma}{d\Omega} = \frac{q^2}{4k^4 \sin^4(\theta/2)} \tag{1}$$

where q is the ionic charge and k is momentum.

As expected, the approximation of a pure Coulombic interaction, only valid if the ion could essentially be considered as a structureless point positive charge, is not appropriate for an ion of low charge state at such low collision energy. It is well known that a more complete description can be given by:

$$\frac{d\sigma}{d\Omega} = | f_c(k, \theta) + f_s(k, \theta) |^2 \tag{2}$$

$$= | f_c(k, \theta) |^2 + | f_s(k, \theta) |^2 + 2\mathrm{Re} \, | f_c(k, \theta) \cdot f_s(k, \theta) | \tag{3}$$

where f_c and f_s are the scattering amplitudes for scattering from Coulombic and short-range potentials respectively. The first term in Eq. (3) is simply the Rutherford formula (as given by Eq. (1)), a Coulomb term. The second term represents a short-range term, analogous to the differential cross section for a neutral target, where only short-range interactions apply. The third term is an interference term, representing interference between the scattering amplitudes.

The short-range scattering amplitude, f_s, is given by:

$$f_s(k, \theta) = \frac{1}{2ik} \sum_{l=0}^{l=\infty} \left\{ (2l+1) e^{2i\sigma_l(k)} [e^{2i\delta_l(k)} - 1] P_l(\cos\theta) \right\} \tag{4}$$

where $P_l(\cos\theta)$ are the Legendre polynomials, σ_l are the well known Coulombic phase shifts and δ_l are short-range phase shifts. For Ar^{2+} ions short-range phase shifts, δ_l, have been calculated by Manson and Turner [12] using a Hartree–Fock–Slater short-range potential of the form:

$$V(r) = -\frac{2Z}{r} + \frac{2}{r} \int_0^r \sigma(t) dt + 2 \int_r^\infty \frac{\sigma(t)}{t} dt - 6 \left(\frac{3}{8\pi} \rho(r) \right)^{1/3} \tag{5}$$

where Z is the atomic number, $\rho(r) = (\sigma(r)/4\pi r^2)$ is the spherically averaged total electron charge density and the final term is the free electron exchange potential .

The full curve in Fig. 2 shows the results of a calculation where the short-range phase shifts of Manson and Turner have been included. The measured angular distribution has been put on an absolute scale by normalizing the low angle points to the Rutherford curve, so that the comparison of the experimental data to the partial waves calculation is independent of the method of normalization.

It can be seen from Fig. 2 that the main structure observed in the experimental data with a minimum near 80° is well described by the partial waves calculation. A shallower minimum in the measured angular distribution near 55°, also observed in our previous preliminary measurements [7], is however not reproduced by the calculation.

In Fig. 3 we have replotted the data shown in Fig. 2 on a linear scale, and include the three terms, Coulomb, short-range and interference, that contribute to the calculated differential cross section (Eq. (3)). It is interesting that the minimum in the calculation near 80° is in fact governed by the interference term and not by the short-range term. Thus the position and depth of the feature are more sensitive to the form of the potential used in the calculation than is normally the case in scattering from a neutral target where the angular form of the Legendre polynomials dominate. This suggests the possibility of predicting ionic targets and collision energies where a dominant interference term leads to structure in the angular distribution that is extremely sensitive to the collision dynamics. Such a possibility will be explored further in a forthcoming article.

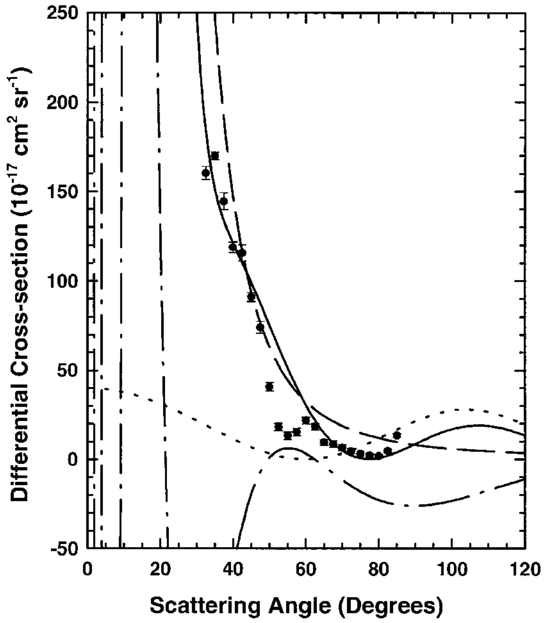

Fig. 3. Same as for Fig. 2. In addition the components of the calculated differential cross section are plotted: Coulomb term (— — —), short-range term (- - -), interference term (— - — - —).

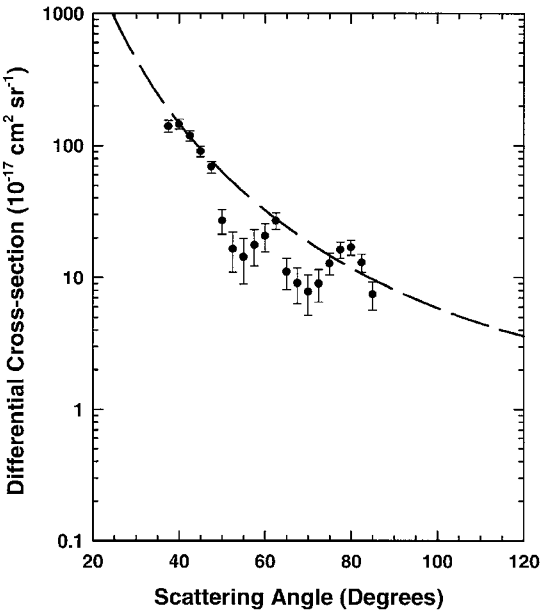

Fig. 4. Angular distribution for the elastic scattering of electrons from Xe^{2+} at 16 eV collision energy. Legend as for Fig. 2.

Figure 4 shows experimental angular distributions for the elastic scattering of electrons from Xe^{2+} ions, again at a collision energy of 16 eV. The data is once more compared to the prediction of the Rutherford formula, and is normalized to the theory at low angles. No short-range phase shifts are available for Xe^{2+}, so that direct comparison to a partial waves calculation, similar to that carried out for Ar^{2+}, is not possible. However it is worth noting the comparison between the Xe^{2+} and Ar^{2+} measurements. In particular, partial waves calculations for Ar^{+} and Ar^{2+} at this energy demonstrate a quite similar angular distribution with the position of the minimum for each ion coinciding to within a few degrees. Using short-range phase shifts, δ_l, calculated by Manson [13] for elastic scattering from Xe^{+} at 16 eV, and assuming a similar trend for Xe as witnessed for Ar, it can be predicted that a minimum should occur within a few degrees of 68°. The minimum observed in the Xe^{2+} measurements at 70° agrees extremely well with this prediction.

A feature with a minimum near 55° is also observed in the Xe^{2+} angular distribution, similar to that previously described for Ar^{2+}. Thorough, meticulous checks of possible sources of error, such as space charge, modulation and background effects, conspicuously fail to explain these features. Full details of these checks will appear with a detailed account of the spectrometer in a forthcoming publication. Furthermore, confidence in the action of the spectrometer is heightened by the fact that the second more pronounced minima for Ar^{2+} and Xe^{2+} are observed at different angles, both in agreement with predictions.

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