Angular distribution for the elastic scattering of electrons from Na^+ ions

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A spectrometer has been designed and built for the study of electron-ion scattering. The angular distribution obtained with this instrument for the elastic scattering of electrons from Na^+ ions at 10 eV is presented. The measurements clearly demonstrate interference effects, deviating markedly from the Rutherford formula, and are in good agreement with the results of phase-shift calculations based on semiempirical potentials. [S1050-2947(96)51010-3]

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Electron-scattering studies have proven remarkably successful in the understanding of atomic structure. From the early work of Ramsauer [1] to recent sophisticated correlated measurements [2], the experimental study of electrons scattered from neutral atomic targets has provided a foundation upon which much of our theoretical understanding has been built. The extension of such studies to charged ionic targets will yield insight into the atomic structure of ionized matter. In addition, and in contrast to direct atomic scattering, there is a plethora of compound states that may be accessed due to resonant capture of the incident electron. Analysis and detection of electrons subsequently ejected due to Auger emission can provide information on the structure of multiexcited states of the intermediate ion or atom, and on the collective behavior of two or more excited electrons. However, experimental measurements of angular distributions of electrons scattered from ions are extremely scarce. Excitation measurements at low scattering angles and energies between 35 and 75 eV in Mg^+, Zn^+, and Cd^+ were reported by Williams *et al.* [3]. Some distributions for large-angle elastic scattering have been deduced from binary-encounter peak studies in high-energy multiply charged ion collisions with atoms [4]; these have typically been for collisions in the 100–200-eV center-of-mass energy range. Huber *et al.* have measured angular distributions for elastic scattering in the angular range 30°–80° at 50 eV, for Ba^{2+}, Xe^{6+}, and Xe^{8+} [5], and most recently our own group has deduced high-angle elastic-scattering distributions for Ar^+ at 3.3 eV using a magnetically confined trochodial spectrometer [6].

In the present Rapid Communication we present an angular distribution obtained from an electrostatic spectrometer, designed specifically for electron-ion–scattering studies. Results have been obtained for the elastic scattering of electrons from Na^+ ions at 10-eV impact energy, and over the angular range 25°–95°. These are the first low-angle measurements for scattering from an ion at an energy below the threshold for inelastic scattering.

The electron spectrometer, shown schematically in Fig. 1, has been described in a previous publication [7], and hence only a brief description is given here. Electrons from an electrostatically focused gun intersected a target ion beam at 90°. A combination of lenses on the front end of the gun ensured an almost parallel electron beam of spot size 1–2 mm at the intersection region. Electrons scattered during the interaction were analyzed by a 180° hemispherical analyzer that was free to rotate in a plane perpendicular to the plane containing the electron and ion beams. A microchannel plate position-sensitive detector utilizing an integrated chip with 128 discrete anode-preamp-discriminator-counter units was used in the dispersion plane of the analyzer. The ion beam was produced by thermionic emission in a universal ion source [8]. It has been shown [9] that after a few hours of operation the ions emitted from the source are almost entirely Na^+. The ion beam was electrostatically focused into a spot size of approximately 4–5 mm at the interaction region. In order to minimize any neutral flux from the ion source reaching the interaction region, the ion beam was deflected prior to entering the target chamber, hence ensuring no direct line of sight between the source and interaction region.

Initially the spectrometer was tested with a gas target, accurately reproducing known angular distributions for both elastic and inelastic scattering from He and Xe at low target densities. The linearity of the elastic scattering signal from Na^+ was determined by varying the ion- and electron-beam currents, and the ion energy, which was varied between 500 eV and 2 keV. At these low-ion-beam energies, the noise due to 10-eV secondary electrons produced by ionization of the background gas was very low, typically of the order of 0.1 s^{-1}. A low rate was to be expected since the analyzer was

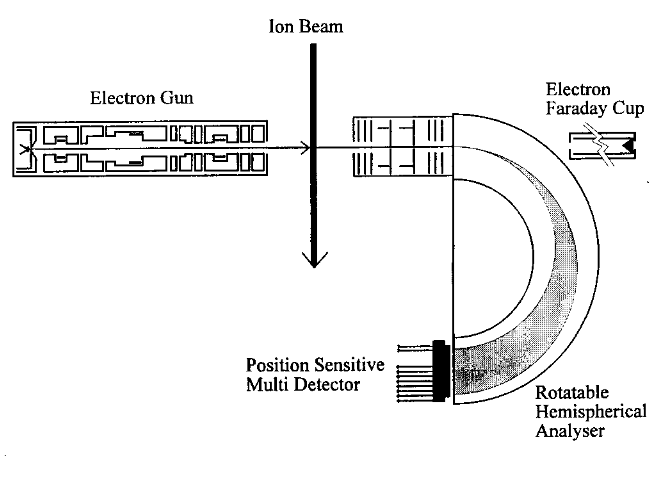

FIG. 1. Schematic diagram of the electron spectrometer.

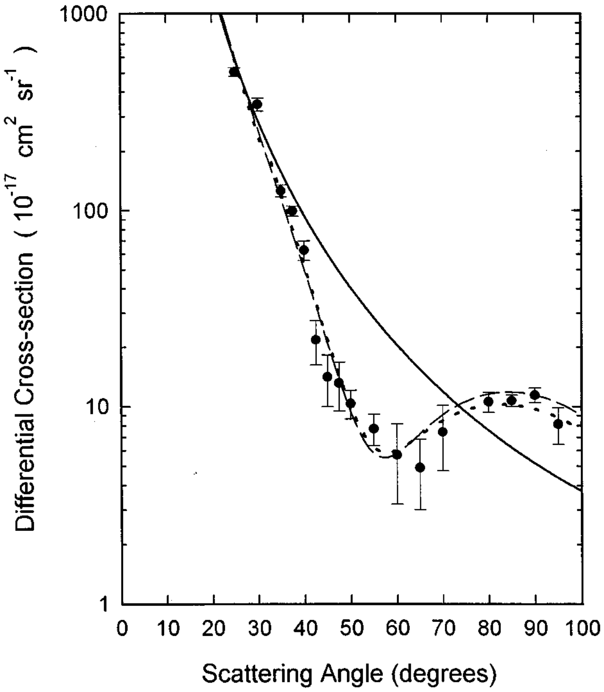

FIG. 2. Differential cross sections for the elastic scattering of electrons from Na^+ at 10 eV. ●, present experimental data; ____, Rutherford formula; partial waves calculations: · · · , Manson potential; – – –, Szydlik *et al.* potential. The error bars denote the statistical reproducibility of the experimental data at the 90% confidence level.

mounted such that it always detects electrons ejected at 90° from the ion-background gas interaction [10]. Noise due to 10-eV electrons elastically scattered from the background gas, at an operating pressure of 2×10^{-9} torr, was typically 250 s^{-1} at low angles and 30 s^{-1} at high angles. Corresponding signal rates from the Na^+ ions were typically 50 and 5 s^{-1}. Given the above rates, only the ion beam was modulated, permitting the signal to be extracted from the electron-background gas noise. The velocity of the Na^+ ions was sufficiently low that kinematic corrections were less than 0.5° in laboratory scattering angle, and less than 0.5 eV in scattered electron energy.

Results taken with the spectrometer for the elastic scattering of electrons from Na^+ at 10-eV center-of-mass collision energy are shown in Fig. 2. Measurements cover the range 25°–95°, and represent angular measurements for forward angle scattering at an energy below the inelastic threshold of an ion. Each datum shown in Fig. 2 represents the average of four or five separate differential measurements made under different experimental conditions (i.e., beam intensities, ion-beam energy, and degree of overlap). Each set of differential measurements was normalized at the 30° scattering angle point. At this angle, the signal strength was strong, and the signal-to-noise ratio was sufficient to allow real-time tuning of the spectrometer. The data thus form a self-consistent relative set, but with no absolute cross-section value. Error bars are plotted at 1.7σ, i.e., at the 90% confidence level, and represent the statistical reproducibility of the data.

It is immediately apparent that structure, due to interference effects between the Coulomb and short-range interactions, is manifested in the angular distribution, contrary to the prediction of the Rutherford formula of a monotonically decreasing cross section. Short-range phase shifts for the elastic scattering of electrons from various singly charged ions have been calculated by Manson [11] and Szydlik *et al.* [12], using semiempirical potentials. Manson obtained phase shifts for the $l=0$, 1, 2, and 3 partial waves, using a Herman-Skillman potential of the form

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

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. Szydlik *et al.* have similarly calculated $l=0$, 1, and 2 phase shifts using the independent-particle model potential of Green *et al.* [13], viz.,

$$V(r)=-\frac{2}{r}\left(\frac{Z-q}{H(e^{r/d}-1)+1}+q\right), \tag{2}$$

where q is the degree of ionization, and H and d are adjustable parameters selected for a particular ion by (i) minimizing the total energy of the neutral atom, and (ii) fitting the single-electron energies for the neutral atom.

Coupling these short-range phase shifts with the Coulomb phase shifts, we have calculated angular differential cross sections for the elastic scattering of electrons from Na^+ at 10 eV. The two calculations are seen to be in good mutual agreement, particularly over the lower angular range, and below 30° also follow the Rutherford formula.

The present experimentally measured angular distribution has been put on an absolute scale by normalizing to the calculations of Manson and of Szydlik *et al.* by fitting the low-angle experimental points to the calculations. It may be concluded that for low-energy elastic scattering of electrons from a closed-shell, light, singly charged ion, the semiempirical potentials of the form adopted by Manson and Szydlik *et al.* accurately describe the forward angle scattering.

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