Angular Distribution for Electron Excitation of the $4\,^2S \rightarrow 4\,^2P$ Transition in Zn II: Comparison of Experiment and Theory

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Differential electron-scattering cross sections for inelastic excitation of an ion have been measured for the first time. Experiments were carried out in a crossed electron-ion–beam geometry for the $4\,^2S \rightarrow 4\,^2P$ transition in Zn II at 75 eV. In addition, differential cross sections were calculated at energies between 15 and 100 eV in a five-state close-coupling approximation in which $4s$, $4p$, $3d^9 4s^2$, $5s$, and $4d$ states were included. Agreement in shape between theory and experiment at 75 eV is excellent.

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The phenomenon of electron scattering in positive ions is one that has assumed increasing importance in the last decade. Electron-impact excitation of ions is observed in solar and stellar spectra by earth-orbiting satellites such as Skylab[1] and the International Ultraviolet Explorer.[2] The Voyager 1 and 2 spacecrafts have detected rich emissions in the Io-Jupiter torus from a range of charge states in sulfur and oxygen ions.[3] The attainment of "break-even" plasmas in fusion reactors such as the Joint European Torus[4] and the Princeton TFTR[5] will bring with it a variety of ionic emission spectra excited by the electron component of these stellarlike laboratory plasmas. For example, resonance lines of one-electron, alkalilike systems such as Li-, Na-, and Cu-like systems are easily identified in tokamak-type discharges.[6]

Experimental measurements of inelastic electron-ion scattering are a fundamental part of the basis for understanding this broad range of plasma environments. Such measurements are difficult and tedious because of the low target ion densities (less than 10^8 cm^{-3}) involved. Several recent developments, however, have added to the repertoire of techniques available for carrying out measurements of cross sections and phenomena. Observations of inelastic electron scattering in Zn II by Chutjian and Newell,[7] and of dielectronic recombination in Mg II by Belić *et al.*,[8] have provided new, exciting approaches to the study of electron-ion scattering phenomena. These latest advances are in addition to a very extensive literature dealing with excitation and ionization of ions by electrons.[9] In Zn II measurements of absolute emission cross sections for the $^2S \rightarrow {}^2P$ transition have been recently reported by Rogers *et al.*[10] and calculations of these same cross sections, both with and without cascade, by Mzezane and Henry.[11]

In this Letter we report measurements and calculations of the angular distribution for inelastic excitation of the $4\,^2S \rightarrow 4\,^2P^\circ$ resonance transition in Zn II. Measurements were made at an electron energy $E_0 = 75$ eV and over the range of scattering angles $4^\circ \leq \theta \leq 16^\circ$. This impact energy corresponded to the peak of the excitation function reported by us previously.[7] A crossed (90°) electron beam–ion beam geometry was used in an apparatus similar to that of the earlier measurements. A beam of Zn II was generated from a dc discharge in Zn vapor produced in a heated boron-nitride oven. The ions were velocity selected in a Wien filter, electrostatically focused by several sets of cylinder lenses, and magnetically deflected prior to the collision region. The last deflection served to eliminate ionizing photons from the ion-source plasma, and to eliminate any neutral Zn effusing from the source crucible. Fast neutral Zn atoms, produced by charge exchange of Zn II with the background gas, were also removed by this deflection. After the collision region the ions were electrostatically deflected and collected in a deep Faraday cup.

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A beam of electrons of low angular divergence was electrostatically focused onto the ion beam. Inelastically scattered electrons were detected over a range of angles in the forward scattering direction with a hemispherical electrostatic analyzer and lens system which were rotated relative to the electron gun. Electron pulses from a channel-type electron multiplier were amplified and stored in a multichannel scalar as a function of energy loss at each scattering angle.

Design principles for the various lens systems (ion beam, electron gun, and analyzer) were given earlier[12] and will be discussed in more detail elsewhere, as will other details of the apparatus in connection with inelastic results in Cd II.[13] Electron and ion currents, overall resolution in the energy-loss spectra, and typical gun and analyzer focusing procedures were the same as given in Ref. 7.

Energy-loss spectra were measured at 1° intervals over the range of scattering angles $4° \leq \theta \leq 16°$. The spectra corresponded to the unresolved $4\,^2S_{1/2} \rightarrow 4\,^2P^\circ{}_{1/2,3/2}$ fine-structure transitions at 6.01 eV ($j = \frac{1}{2}$) and 6.12 eV ($j = \frac{3}{2}$). Peak areas were measured at each angle, and normalized to unity at $\theta = 14°$. The observed spectra were similar to those shown in Fig. 1 of Ref. 7. The zero-angle position of the rotatable analyzer was measured by detecting the maximum current to the outer sphere of the hemispherical analyzer as the analyzer view cone was rotated into the electron gun. This was confirmed by measuring the nominal angle about which inelastic scattering in argon (11.828-eV feature) was symmetric. These two determinations of the zero-degree position agreed to 0.5°. The low-angle limit ($\theta < 4°$) to the scattering was established by interference of the scattered signal by the parent electron beam; the high-angle limit ($\theta > 16°$) by overlap with the Vegard-Kaplan bands of N_2 (background gas). The former problem can be alleviated by use of a double hemispherical analyzer system, and the latter by better vacuum ($\leq 1 \times 10^{-7}$ Pa) in the collision region. Both efforts are currently under way.

From two to five measurements of the relative cross section were made at each angle and the results averaged. A small systematic correction to the data was applied to compensate for the angular "smearing" of the differential cross sections arising from the finite angular resolution of the electron analyzer.[14] This correction amounted to a 2% increase in the data for θ less than 10°, with no correction for data at $\theta > 10°$.

The mean of the measurements, and errors representing two standard deviations of the mean, are given in Fig. 1 at each scattering angle. For purposes of comparing the shape of the differential measurements to theory, the measurements were normalized to theoretical results at $\theta = 14°$.

From the theoretical standpoint, Msezane and Henry[11] had previously calculated cross sections for excitation of Zn II from the $4s$ ground state to the resonance $4p$ state in a close-coupling approximation in which the $4s, 4p$, $3d^9 4s^2$, $5s$, and $4d$ states were retained. Very good agreement with measurements of the absolute emission cross sections of Rogers *et al.*[10] was obtained for the energy range $15 < E_0 < 100$ eV when cascade contributions were included. We used the reactance matrices obtained by Msezane and Henry[11] in a program developed by Brandt, Truhlar, and Smith[15] to calculate angular differential cross sections in the same energy range.

In Fig. 1 we show the calculated differential cross section for excitation from $4s$ to $4p$ in Zn II at an incident electron energy of 75 eV. These results were interpolated from our calculations at 60 and 100 eV. There is excellent agreement in shape between the present measurements and calculations. Agreement in magnitude at the normalization point is also good. An experimental

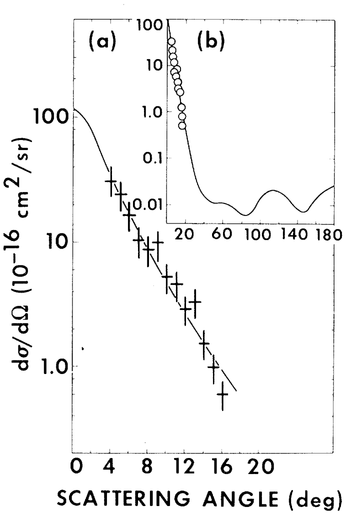

FIG. 1. Differential cross sections $d\sigma/d\Omega$ for excitation of the $4\,^2S \rightarrow 4\,^2P^\circ$ transitions in Zn II at 75-eV electron energy. (a) Detailed comparisons of experimental results normalized to theory at $\theta = 14°$ (crosses) and theoretical calculations (solid lines) for the angular range $4° \leq \theta \leq 16°$. (b) Calculated results over the range $0° \leq \theta \leq 180°$ and experimental measurements in the smaller angular range.

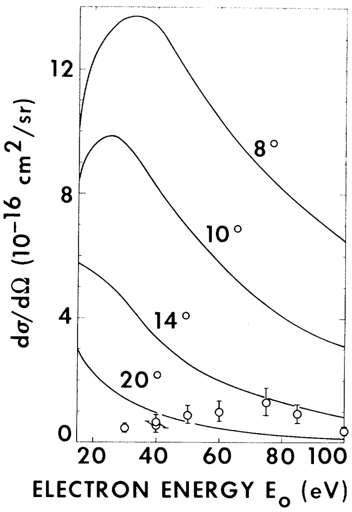

FIG. 2. Differential cross sections $d\sigma/d\Omega$ for the $4\,^2S \to 4\,^2P^\circ$ excitation in Zn II in the electron energy range $15 < E_0 < 100$ eV and at the indicated scattering angles. Calculated results are indicated by solid curves, and experimental data at $\theta = 14°$ are shown as open circles.

cross section of 1.30×10^{-16} cm^2/sr at $\theta = 14°$ was reported earlier,[7] whereas the theoretical value is 1.57×10^{-16} cm^2/sr. However, this experimental value is uncertain since the form factor, which varies with incident energy, was estimated rather than measured. Thus the shape of the measured values in Ref. 7 may be incorrect, and the agreement between experiment and theory at 75 eV is probably fortuitous.

One notes in Fig. 1 that at small angles the scattering intensity falls very rapidly with angle. For example, present measurements for the extended range $0° \leq \theta \leq 20°$ account for 92% of the integral inelastic cross section. This rapid falloff is also characteristic of observed angular distributions for neutral atoms[16] in which the fractional energy loss is not too great. At large angles, theoretical diffraction maxima and minima are noted. The same qualitative behavior was observed in a five-state close-coupling calculation for e-Mg II scattering[17] at an electron energy (50 eV) corresponding to a fractional energy loss comparable to Zn II. Also, these diffraction patterns closely resemble those appearing in the corresponding distributions of elastically scattered electrons. A similar pattern exists for electrons that have suffered small energy losses in elastic collisions with heavy atoms.[16]

Theoretical differential cross sections at various scattering angles are given as a function of incident electron energy for the $^2S \to {}^2P^\circ$ transitions in Zn II in Fig. 2. One finds a peak in the cross section which decreases both in magnitude and in energy position with increasing scattering angle. Similar trends were also calculated in Mg II.[17] The magnitude of the cross section for Mg II at the peak is about three times that for Zn II which is consistent with the ratios of total cross sections. Experimental results of Chutjian and Newell[7] at $\theta = 14°$ are given by circles. One finds reasonable agreement between experiment and theory at incident energies $E_0 \geq 60$ eV. For example, an error of one degree in scattering angle in the earlier measurements (data at 15° rather than 14°) would place experiment 10% below theory at 60 and 100 eV, and in agreement at 75 and 85 eV. However, because of the larger differences at energies below 60 eV, comparison to an absolute cross section in which detector efficiency, scattering volume, and beam overlap are measured directly would be more meaningful. Such work is being planned, especially in light of the encouraging agreement between experiment and theory for the shape of the differential cross sections.

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