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Experimental electron energy-loss spectra and cross sections for the $4^2S \rightarrow 4^2P$ transition in Zn II

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Electron energy-loss spectra and differential cross sections are reported for inelastic scattering from Zn II. Measurements were carried out in a crossed electron-beam–ion-beam apparatus, at incident electron energies of 30, 40, 50, 60, 75, 85, and 100 eV, and at a scattering angle of 14°. The present results are the first reported measurements of inelastic electron scattering from an ion.

The need for electron scattering measurements from ions is well known to the plasma physics community.[1] The abundance of stellar observational data from the International Ultraviolet Explorer (IUE),[2] the attainment of "break-even" plasmas in fusion reactors,[3] and the detection of sulfur and oxygen-ion emissions in the Io-Jupiter torus[4] are all recent examples which highlight the need for a study of electron scattering from ions.

Recent experimental measurements of absolute emission cross sections in the e–Zn II system have been reported by Rogers *et al.*,[5] and theoretical close-coupling calculations by Msezane and Henry[6] in the same system. In this Communication we report the first measurements of inelastic differential scattering of electrons from ions. In addition to the applications mentioned above, this type of measurement is of direct use to theoreticians for testing theories and models of electron-ion scattering. An angular differential cross section is a more stringent test of theory than an integral one, thus a higher level of confidence can be established in theoretical approximations. The best theory can then, for example, be used to calculate cross sections in highly stripped ions for which measurements are even more difficult.

The present experiments were carried out in a crossed (90°) electron-beam–ion-beam geometry. The apparatus was the same as one used in an earlier measurement of ion-neutral scattering[7] and will be described in more detail elsewhere.[8] Briefly, a beam of Zn II was generated by heating metallic Zn in a crucible, and extracting the Zn II from a dc discharge in the vapor. Results were obtained both with and without argon carrier gas in the source. The ions were velocity selected in a Wien filter, and magnetically deflected prior to the collision region to eliminate photons and any neutral components from the ion source, as well as fast neutrals produced by charge exchange with the background gas. After the collision region, the ions were electrostatically deflected and collected in a deep faraday cup. Ion currents into the scattering volume were in the range 2.5–5 μA at 6 keV, and were focused to a spot diameter of 1.9 mm which corresponded to ion densities of $(4-8)\times 10^7$ cm^{-3}.

A beam of highly collimated, low-energy electrons was electrostatically focused onto the ion beam. Inelastic electrons were detected at a scattering angle of 14° relative to the incident electron beam using a hemispherical electrostatic analyzer, channel-type electron multiplier, and associated electron lens systems. Design principles for the ion beam, electron gun, and electron analyzer were similar to those discussed earlier.[9] The electron pulses were amplified, shaped, and stored in a multichannel scalar as a function of energy loss. Electron currents at the scattering center were 2–4 μA in the energy range 30–100 eV, respectively. The overall resolution of the electron gun and analyzer system was 0.45 eV [full width at half maximum (FWHM)], which was almost entirely due to the primary electron energy spread in the gun.

The typical experimental procedure employed was to focus the gun and analyzer using a beam of neutral argon gas, and detecting the 11.828-eV inelastic transition [excitation to the $4s'(\frac{1}{2})_1^o$ level]. Then, with no further adjustments to the gun and analyzer focusing voltages, the argon was pumped away, and the inelastic spectrum of Zn II accumulated in the energy-loss range 4.2–9.2 eV. The step size in the measurements was 0.020 eV/channel, and the recording time 20–60 min depending on the strength of the feature. Pressure in the collision region during operation of both beams was in the range $(1-5)\times 10^{-8}$ torr.

Energy-loss spectra obtained at electron energies of 30, 75, and 100 eV at the 14° scattering angle[10] are shown in Fig. 1. Prominent in these spectra are

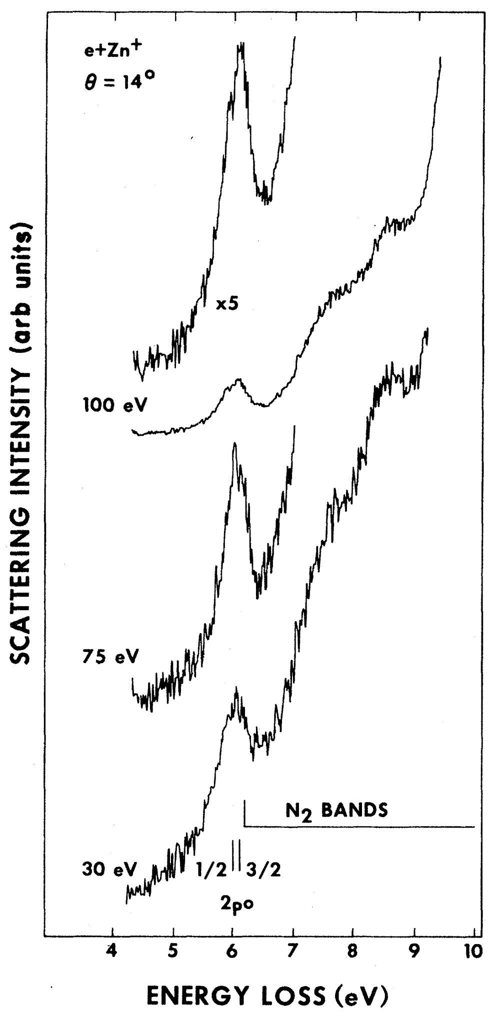

FIG. 1. Experimental energy-loss spectra of the $^2S_{1/2} \rightarrow {}^2P^o_{1/2,3/2}$ resonance transition in Zn II at $\theta = 14°$ scattering angle, 6-keV ion energy, and at the indicated electron energies. Energy-loss transitions in molecular N_2 are responsible for the rising background. The onset of these transitions [the (0,0) band of the $X \rightarrow A$ Vegard-Kaplan system] is shown.

the unresolved fine-structure Zn II transitions $(3d^{10}4s)^2S_{1/2} \rightarrow (3d^{10}4p)^2P^o_{1/2,3/2}$ at 6.01 eV ($j=\frac{1}{2}$) and 6.12 eV ($j=\frac{3}{2}$).[11] The rising background at higher-energy losses is due to unresolved vibrational bands in several electronic transitions of molecular nitrogen, and arises by inelastic electron scattering from the background gas.[12] These features have an onset at 6.17 eV (shown in Fig. 1) corresponding to the (0,0) band of the $X\,^1\Sigma_g^+ \rightarrow A\,^3\Sigma_u^+$ Vegard-Kaplan system.

Various experimental checks were made of the Zn II feature. The feature disappeared when either the ion or electron beam was turned off; in the former case the rising N_2 background was still detected. In addition, both beams were modulated by one of the schemes suggested by Molyneux *et al.*,[13] with the signal plus background, and background counts stored in individual scalars. Statistically significant signals were observed with the electron analyzer tuned to the $^2S_{1/2} \rightarrow {}^2P_{1/2,3/2}$ transition. It was by this method, in fact, that the inelastic signal was first detected. Finally, a somewhat remote possibility was considered wherein the observed transition could be the $^1S_0 \rightarrow {}^1P_1^o$ resonance transition in *neutral* Zn. This could arise by charge-exchange of Zn II with the background gas, coupled with some error in the energy-loss scale of the order 0.2 eV. This possibility was excluded since, under present experimental conditions, the fraction of ions undergoing charge exchange was calculated to be less than 1.2×10^{-3}.

Spectra such as those in Fig. 1 were obtained at seven electron energies between 30 and 100 eV. Cross sections relative to the 100-eV scattering were obtained at each energy by measuring ratios of peak areas. These relative cross sections are given in Table I and plotted in Fig. 2. The error in these measurements includes that in obtaining the area under the inelastic feature, and is estimated conser-

TABLE I. Relative and absolute differential cross sections for excitation of the resonance transition $^2S_{1/2} \rightarrow {}^2P^o_{1/2,3/2}$ in Zn II at $\theta = 14°$.

Electron energy (eV)	Relative cross section	Absolute cross section (10^{-17} cm^2/sr)[a]
30	1.32 ± 0.24	4.63
40	1.89 ± 0.34	6.63
	1.46 ± 0.26	5.13
50	2.53 ± 0.40	8.88
60	2.83 ± 0.31	9.93
75	3.69 ± 0.37	13.0
85	2.58 ± 0.21	9.05
100	1.00 ± 0.13	3.51

[a]With an error estimate of 33%.

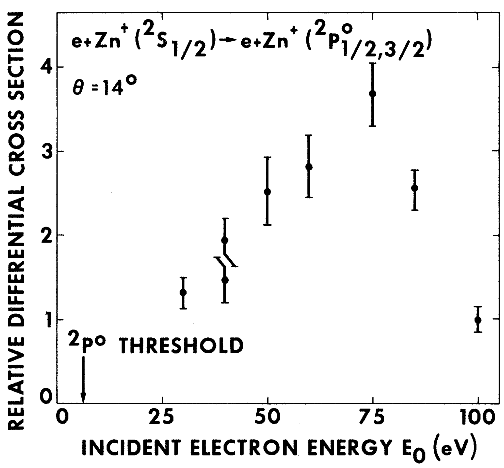

FIG. 2. Relative differential cross sections at $\theta = 14°$ for the $^2S_{1/2} \rightarrow {}^2P^o_{1/2,3/2}$ transition in Zn II relative to scattering at 100 eV (see also Table I).

vatively as 14% over all the spectra. The error in the reproducibility of the data, as shown by the 40-eV data, is 13% giving an overall (root-mean-square) error of 19% in the relative data. With these error estimates, one observes a real maximum in the $\theta = 14°$ cross section near 75 eV. Unfortunately, there are no theoretical calculations in the literature with which to make direct comparisons. Close-coupling calculations on this system are currently in progress.[14]

To obtain an absolute differential cross section we use the expression for the count rate in terms of our experimental parameters. This rate R (sec^{-1}) of inelastic signal is given as

$$R = \sigma \frac{I_i I_e}{e^2} \frac{(v_i^2 + v_e^2)^{1/2}}{v_i v_e} \frac{d\Omega}{F} \quad ,$$

where σ is the differential cross section, I_i and I_e are the Zn II and electron currents, respectively, v_i and v_e are the corresponding velocities, and e is the electron charge. The quantity $d\Omega$ is the effective solid angle subtended by the electron analyzer at the scattering center and F is an integral defining the overlap of the ion and electron beams.

An average R value was obtained from three separate measurements at 100 eV, $\theta = 14°$. Appropriate values of v_i ($v_e >> v_i$) and $d\Omega$ (product of analyzer geometric solid angle and detection efficiency) were used, and the overlap F was approximated as the average height of the electron beam at the target, as given by ray-tracing calculations.[9] In all cases the acceptance cone of the analyzer optics viewed the total overlap of the electron and ion beams. Consistent with the design specifications of the analyzer the detection efficiency was taken as 0.9; i.e., 90% of electrons which entered the view cone of the analyzer were ultimately counted. With these values and assumptions, σ (100 eV, $\theta = 14°$) was calculated to be 3.51×10^{-17} cm^2/sr, with an estimated error of 27%. Absolute cross sections at the lower energies are given in Table I.

It is hoped that the present technique and approach to electron-ion scattering can complement the information provided by integral, photon-emission studies such as thoses recently reported[5] in Zn II, and can provide another source of data to aid theoretical studies,[6] again in the Zn II system. This latter study, in fact, is already under way.[14]

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