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International Journal of Mass Spectrometry 233 (2004) 253–257

International Journal of Mass Spectrometry
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The ^1S–^1P electron excitations of Zn at small scattering angles

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Received 17 November 2003; accepted 21 December 2003

Abstract

Electron impact excitation from the 4^1S ground state to the 4^1P and 5^1P states of zinc has been experimentally investigated at incident energies from 15 to 100 eV and scattering angles up to 12°. The absolute generalized oscillator strengths and differential cross-sections are determined through normalization to the optical oscillator strengths. The present values are compared with limited number of available data.
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PACS: 34.80.Dp; 32.70.Cs

Keywords: Electron excitation; Zinc atom; Differential cross-section

1. Introduction

Zinc is an atom that has been driving a lot of interest recently, starting from investigations of collisional cross-sections [1,2], ionization phenomena [3–5] to isotope abundances and the concentrations in humans [6]. There are number of theoretical studies of optical oscillator strengths [7,8] and very few electron excitation cross-section calculations [9]. Experimental studies of differential cross-section (DCS) for the excitation are limited to early measurements of Williams and Bozinis [10] at single incident electron energy of 40 eV. Electron excitation functions have been recently obtained by Shpenik et al. [1] from threshold to 15 eV and these are complemented by earlier optical excitation cross-section measurements at low electron energies [11–13].

In the present study, we have employed an electron spectrometer in crossed electron–atom beam arrangement to derive absolute values of DCSs at small scattering angles for electron impact excitation of the 4^1P and 5^1P states of zinc from the 4^1S ground state. In such an arrangement, it is difficult to determine directly all measuring values in absolute way, i.e., target beam density and its profile, electron beam profile and its intersection with atomic beam, transmission of the analyzer and scattered electron detection efficiency. Instead, a theoretical approach of Msezane's group [14] has been adopted in order to normalize relative DCS to absolute scale. Their method of forward scattering function (FSF) [15], which uses only the optical oscillator strength (OOS) as input and describes the loci of the 0° generalized oscillator strengths (GOS) and determines the normalization constant. Absolute GOSs and DCSs have been obtained in intermediate electron energy range from 15 to 100 eV.

2. Experimental

The apparatus consists of conventional crossed-beam electron spectrometer described elsewhere [16]. In brief, the hemispherical selectors in monochromator and analyzer are made of molybdenum, while all cylindrical lenses are made of gold plated OFHC copper. In Fig. 1 a schematic overview of electron spectrometer is shown and the operating conditions are summarized in Table 1.

The energy scale was calibrated by measuring the position of the feature in the elastic scattering attributed to the threshold energy of the 4^3P excitation of Zn at 4.03 eV. In order to observe the resonance structure, it was necessary to achieve the energy resolution to 40 meV. The position of true zero was determined before each run and angular distribution measurement by checking the symmetry of scattered electron signal at positive and negative angles.

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doi:10.1016/j.ijms.2003.12.025

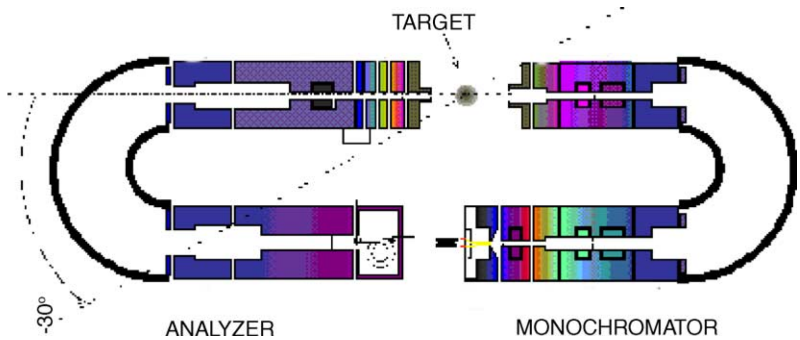

Fig. 1. Schematic overview of hemispherical electron spectrometer.

Table 1
The experimental conditions of electron spectrometer

Parameters	Condition
Impact energy range (eV)	15–100
Energy resolution (meV)	40–100
Uncertainty in energy scale (meV)	300
Angular range (°)	−30 to 150
Angular resolution (°)	1.5
Uncertainty in angular scale (°)	0.5
Oven temperature (K)	670
Metal-vapour pressure (Pa)	10
Oven nozzle aspect ratio	0.075
Primary electron current (nA)	10–50
Residual magnetic field in the interaction region (double μ metal shield) (μT)	<0.1
Background pressure (mPa)	<5

Measurements at zero degree were not reliable due to two reasons: firstly, there was some access noise originated from primary beam electrons although the energy selection of analyzer was very efficient, secondly, the present angular resolution was not sufficient to record true intensity of strongly forward peaked angular distribution.

3. Results and discussion

We have measured the differential cross-sections for the excitation of the resonant 4^1P and 5^1P states of zinc. Incident electron energies were 15, 20, 25, 40, 60, 80 and 100 eV for the 4^1P state and 20, 25 and 40 eV for the 5^1P state. Scattering angles ranged from 1 to 12°. In Fig. 2a–c are shown the GOS values with corresponding fitting curves, terminating to forward scattering function determined by minimum of K^2 momentum transfer. FSF tends to the OOSs for these states with the values of 1.47 ± 0.03 [17], and 0.122 [18], respectively.

The minimal values of squared momentum transfer are determined by incident electron energy and energy of observed transition and are achieved for zero scattering angle. For the 4^1P excitation it ranges from 0.052 to 0.0064 when the incident energy spans from 15 to 100 eV. In Fig. 2a the minimal value of 0.0166 for 40 eV incident energy is indicated. The declination of the lines that correspond to the linear fit of the log(GOS) as a function of log(K^2) become smaller with the increase of the incident electron energy and, also, the value of the minimal momentum transfer slides down the forward scattering function curve as the incident electron energy decreases. That seems to be a behaviour predicted by the theoretical assumptions incorporated in this approach. But for higher energies above 40 eV, GOS values do not follow straight line in the logarithmic fit. Instead, the higher K^2, there is faster decline GOS values.

Once the absolute values of GOS are obtained, differential cross-sections could be easily calculated by the Eq. (1). The GOS, denoted as $f(K,E)$, and the DCS, denoted as $\mathrm{d}\sigma/\mathrm{d}\Omega$, values for atomic excitation by an electron impact are related by

$$f(K, E) = \frac{\omega k_\mathrm{i}}{2k_\mathrm{f}} K^2 \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right) \tag{1}$$

where k_i and k_f are the electron momenta before and after the collision, K is the momentum transfer,

$$K^2 = 2E\left[2 - \frac{\omega}{E} - 2\sqrt{1 - \frac{\omega}{E}}\cos(\theta)\right] \tag{2}$$

where ω and E are the excitation and impact energies, respectively (in atomic units). Determined absolute DCS for the 4^1P and 5^1P states are shown in Fig. 3a–c and in Tables 2 and 3.

There are two main sources that contribute to the total error for absolute DCS values: the uncertainties in experimental quantities and the uncertainties in normalization procedure. The contributions to the first source of errors arise from statistical errors (0.10), uncertainty of energy scale (0.05), uncertainty of angular scale (0.10) and uncertainty of applied path-length correction factor (0.06). For each incident energy that were performed between 15 and 20 independent runs in order to get average angular distributions and to improve statistics. The other source of error includes uncertainty in OOS values (0.02) and fitting procedure (0.15). The overall absolute error is obtained as a square root of sum of squared errors. In our experiment it is of the order of 0.22 for the 4^1P state and 0.25 for the 5^1P state.

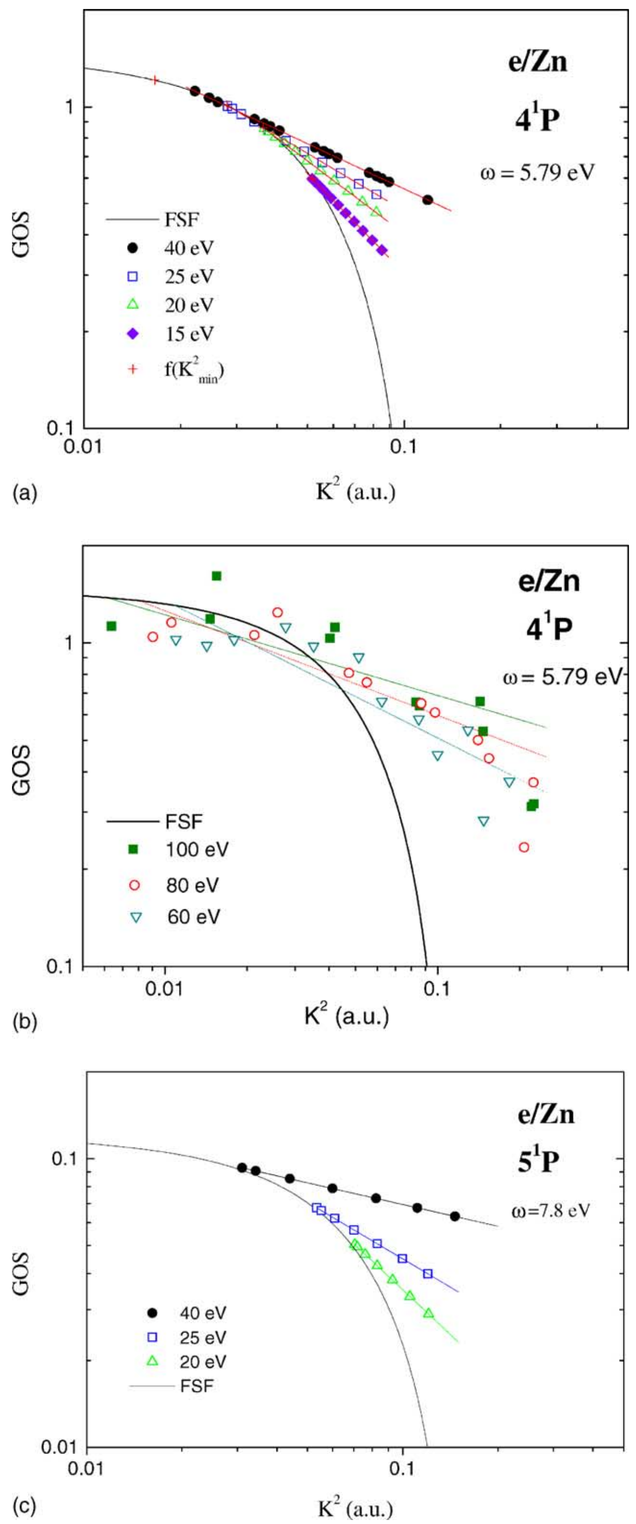

Fig. 2. Generalized oscillator strengths (GOS) vs. squared momentum transfer (K^2): (a) the 4^1P state excited by 15, 20, 25 and 50 eV electrons; (b) the 4^1P state excited by 40, 60 and 100 eV electrons; (c) the 5^1P state excited by 20, 25 and 40 eV electrons.

Table 2
Differential cross-sections (in units of 10^{-20} m^2/sr) for electron impact excitation of the 4^1P state of zinc atom

Angle (°)	15 eV	20 Ev	25 eV	40 eV	60 eV	80 eV	100 eV
1	23.6	51.8	81.0	172	205	292	
2	22.9	49.1	74.9	144	159	200	204
3	21.8	45.1	66.0	109	118	121	
4	20.4	40.3	56.2	79.4	82.9	71.4	66.8
5	18.7	35.2	46.7	57.3	52.4	42.1	
6	17.0	30.2	38.2	41.6	37.4	25.2	19.6
7	15.2	25.7	31.0	30.7	24.4	15.8	
8	13.5	21.6	25.1	23.0	15.8	10.8	10.2
9	11.9	18.1	20.4	17.6	10.2	7.92	
10	10.4	15.2	16.6	13.7	6.69	5.92	3.61
11	9.05	12.7	13.6	10.8	4.47	3.85	
12	7.87		11.2	8.66	3.08	1.11	

The comparison could be made with experiment of Williams and Bozinis [10] at 40 eV for both transitions. Their DCS absolute values are higher for a factor of 2 for the 4^1P state and for a factor of 3 for the 5^1P state at scattering angle of 5°. One of causes of disagreement is believed to be in our better angular and energy resolution. Especially better angular resolution is crucial for measuring strongly forward peaked DCSs. In our experiment it is 1.5°, while in the previous experiment it was between 1.7 and 3.2°.

Calculated data points of Kaur et al. [9] for 40 eV lay between two experimental sets of data, but closer to data of Williams and Bozinis [10]. At 20 eV calculated data [9] are for a factor 1.5 larger than present experimental value at 5°, but the present angular distribution is more forward peaked than calculated one. Both present experimental and calculated DCS curves for 20 and 40 eV intersect at angles between 8 and 9°. Carried calculation is based on a relativistic distorted-wave approximation. The effect of correlation on the ground states where explored by performing relativistic multi-configuration Dirac–Fock calculations for both ground and excited states. It was found [9] that the configuration mixing lowers the cross-sections. Also, it is known effect from calculations by Clark et al. [19] that adding more configurations results in lowering the cross-sections by a constant factor at most scattering angles. It would be interesting to perform the same type of calculations by using more than two configurations to represent excited

Table 3
Differential cross-sections (in units of 10^{-20} m^2/sr) for electron impact excitation of the 5^1P state of zinc atom

Angle (°)	20 eV	25 eV	40 eV
2	1.05	1.94	4.64
4	0.935	1.65	3.40
6	0.782	1.31	2.31
8	0.624	0.989	1.55
10	0.482	0.732	1.07
12	0.366	0.539	0.756

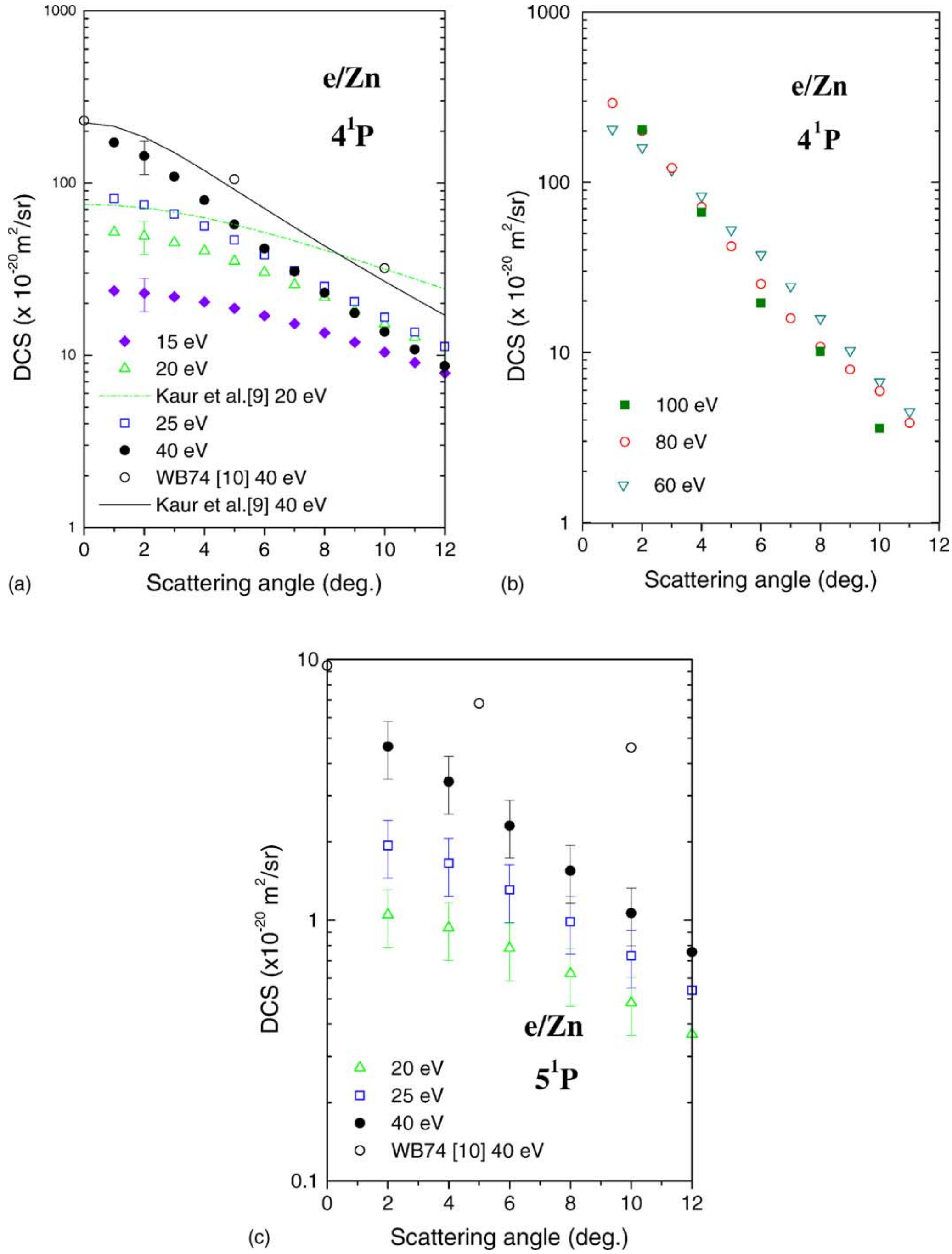

Fig. 3. Differential cross-sections (DCS) vs. scattering angle: (a) the 4^1P state excited by 15, 20, 25 and 40 eV electrons, solid line and dash–dot line represent calculations by Kaur et al. [9] at 40 and 20 eV, respectively, open circles are experimental points by Williams and Bozinis [10] at 40 eV; (b) the 4^1P state excited by 40, 60 and 100 eV electrons; (c) the 5^1P state excited by 20, 25 and 40 eV electrons, open circles are experimental points by Williams and Bozinis [10] at 40 eV.

state, on the same manner as it was done for magnesium [9].

In summary, we have obtained absolute values for generalized oscillator strengths and differential cross-sections for the excitation from the ground 4^1S to the 4^1P and 5^1P states of zinc atom by electron impact at the intermediate energy range. Except for the single energy of 40 eV, there were no other experimental data available. Also, there exist calculations for the 4^1P state at 20 and 40 eV. The agreement with this previous work is rather poor. That suggests performing more extensive relativistic calculations with inclusions of several mixing configurations. Also it would be interesting to experimentally obtain DCSs in broader angular range in order to make a comparison with already available theory.

Acknowledgements

We are grateful to Prof. Dr. Rajesh Srivastava and Dr. Saviner Kaur for supplying us with tabulated data of their calculations. This work has been carried out within MSTD project No. 1424 of Republic of Serbia.

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