Spin-polarised Stokes parameters of open and closed shell transitions and their resonances in zinc atoms.

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Abstract. The formation and decay processes of negative ion resonances are explored for zinc atoms using spin-polarised incident electrons with observation of visible photons from the resonance decay into the 6s 1S, 4d 1,3D and 4p 1,3P states. For Fano resonances, near singly and doubly excited neutral atom states and two ionic states, the Stokes parameters of the radiation indicate markedly different effects of electron exchange and spin-orbit interactions as well as the angular momentum effects of closed and open 3d10 core states.

1. Introduction
The advances with atomic clock technology [1], quantum information processing [2], the production of ultracold molecules [3] and quantum phase transitions [4] have aroused new interest in Feshbach resonances with possibilities for control of the interaction strength between atoms [5] and consequently for the study of quantum many-body phenomena. An understanding of the formation and decay of resonances in such applications has followed from the fundamental descriptions [6, 7] and led to more detailed studies of the decisive role played by multi-electron correlations in a wide variety of atoms and collision processes. Photons, rather than electron or other probes, have fewer degrees of freedom and frequently lead to more specific information such as multielectron correlations. For example, in the photo detachment of a 1s electron from a lithium negative ion [8, 9], the rearrangement of the core electrons with various relaxation effects, a strong polarisation interaction between the core and the photoelectron, and a double excitation process in which the post-collision interaction has a dominant role, have been identified in the formation of shape resonances. More detail of angular momentum phenomena has emerged from the photo-absorption studies in Ca and Sr where [10] showed how the spin-dependent interaction affects the mixing of different states and the breakdown of LS-coupling in various auto-ionising series affects the resonance structures. Electron impact studies have extended the observed interactions to include non-dipole, electron exchange and dynamical correlation effects on the formation and decay of auto-ionising resonances [11].

The present paper extends the above knowledge using incident spin-polarised electrons to explore orbital and spin angular momentum through electron exchange and spin-orbit interactions involving negative ion resonances near auto-ionising levels and on their formation and decay processes. The study has approached such phenomena by observing resonance radiative decays, specifically into the 4d, 5d, 6d 1,3D and 4p 1,3P states of neutral zinc atoms in threshold regions using spin-polarised and non-polarized incident electrons [12-19]. Figure 1 shows the studied energy levels and the observed negative ion resonance levels above the ionization threshold which were detected through their decay into the 1,3D and 4p 1,3P states and the subsequent fluorescence with 636.2, 328.2 to 334.6, 277.1 to 280.1, 257.0 to 260.9 ranges and 213.4 nm photons. In this way information could be deduced about the neutral atom radiation with closed shell transitions while the negative ion resonance decays were
observable via open 3d⁹-shell formation with subsequent decays via open-to-closed shell paths. These transitions were seeking more tightly bound 3d¹⁰ core states as expected since there are no ground state atomic states, or singly excited states, with a 3d⁹ electronic configuration. In that way we were able to explore a variety of near threshold excitation processes and their associated negative ion resonance states.

**Figure 1.** Energy level diagram of zinc atoms, showing the studied levels and transitions of (i) the neutral atom (left hand side) and (ii) the doubly–excited neutral atom, the negative ion and the singly charged positive ion (right hand side).

An underlying approach for this work was the earlier success of deducing the angular momentum exchange from the mixed state electronic configurations of transitions within the neon 3P 3/2,1/2 transitions after excitation using spin-polarised incident electrons and observing the Stokes parameters. It was shown [18], for example, that the polarization of the decay photons depends on the different LS-mixing properties of the intermediately coupled states; the triplet components may make exchange and spin-orbit interaction important while for states with a large singlet component the spin-orbit interaction may be dominant. In particular, to highlight the strength of the technique, it is noted that the 703.3 nm transition (2p⁵3p[1/2] → 2p⁵3s[3/2]) contained the most striking feature of a strong resonance observed in the polarised excitation functions at about 18.7 ± 0.2 eV. While the overall magnitude of the linear polarization was quite small, it was the practically zero values of P₁ and P₂ which clearly indicated the influence of the dominant (98.2%) ¹S component of its superposition of LS-based wavefunctions in a P-state. The circular polarisation P₃ was about 0.45 and attributable to the electron exchange process as the dominant excitation mechanism for the state. The small non-zero negative values near -0.002 of the P₂ parameter were attributed most probably to the effects of the negative ion resonances since the spin-orbit coupling effects within the atom is expected to be small for this state. We aimed to see the applicability of aspects of these results to other atoms.

Those experiments led to a number of significant conclusions that in turn indicated the direction for future studies and a subset was selected for study in the present paper.
1) For transitions coming from a common upper state, those with $\Delta J = 1$ had larger linear polarizations than those with $\Delta J = 0$ and $-1$.

2) For the transitions coming from upper states with a different core state, those with a $^2P_{1/2}$ core had a larger linear polarization than those with a $^2P_{3/2}$ core.

3) The normalized integrated state multipoles $\text{Im} T(J)_{11}$, reflecting the electron exchange process, and the $\text{Re} T(J)_{21}$ indicating the strength of spin–orbit interaction within the atom, are consistent with calculated LS compositions [20] (Luke 1986).

4) The breakdown of LS-coupling for the $J = 1$ states in the neon 3p manifold was confirmed and hence the spin–orbit interaction within the atom plays a significant role in the electron impact excitation collisions.

5) The negative ion resonances had a significant influence on the polarizations which depended on the different LS mixing properties of the intermediately coupled states.

6) The effect of the core on the alignment of the excited states indicated the resonances have a more significant influence on the alignment of the excited states with $a j = 1/2$ core than for states with $a j = 3/2$ core. The state multipoles indicated the distribution of the integrated charge cloud of the excited states and the angular momentum transferred during the collision.

Results 1) and 2) indicated the need for consideration of the angular momentum coupling in the excitation processes. Results 3) and 4) indicated the advantages of modeling to indicate probable correlated wave functions and their mixing coefficients. Results 5) and 6) indicated the angular momentum coupling in the excitation process, the importance of observing the polarization of the transition radiation as well as the need for modeling and for angular correlation measurements.

Questions remain about the propensity for similar transitions which we pursue here for zinc atoms with observations of closed and open shell transitions. Information of the angular momentum transfer and its association with the multiple moments of the excited state will be pursued with the observation of the “integrated” (over the angular distribution of the scattered electrons) Stokes parameters $P_i$ ($i = 1, 2, 3$) of the excited states. We report the Stokes parameters for the $6s\ ^1S$ to $4p\ ^1P$ transition to establish the precision of the technique and to verify its applicability to zinc. Then we report the $P_i$ for the $4d\ ^3D$ transitions to establish the closed shell behaviour below the first ionisation level, then explore the excitation of the ionic closed shell $3d^{10}5d\ ^2D$ to $3d^{10}5p\ ^2P$ 602.1 nm transition and the open shell $3d^{9}4s\ ^2D$ to $3d^{10}4p\ ^2P$ 589.4 nm transition to explore the spin-orbit and exchange interactions. Finally the observations of open and closed shell transitions in the vicinity of the resonances in the autoionizing states near 11 eV are explored to complement the energy loss electron studies [15].

2. Apparatus and techniques

The observations follow from the use of incident low energy spin-polarised electrons to control the spin angular momentum; a beam of thermal energy zinc atoms to define the initial ground state; scattered electron energy loss and radiated photon detection to identify the scattering state and polarization detection to identify the angular momentum transfer in the scattering process as well to identify electron exchange and spin-orbit interaction effects.

The apparatus is described in detail elsewhere [13] and briefly here. The intersection of crossed electron and zinc atom beams is observed by photon polarization detectors and electron energy analysers. Either unpolarized or polarized incident electron beams may be used, the latter produced via 830 nm photo emission from a GaAs surface after oxygen and cesium treatment and energy selected by an electrostatic 180° hemispherical monochromator. The incident electron beam was about 100nA with 30% polarization. Base pressures are about $4 \times 10^{-11}$ Torr in the spin-polarised source region and about $5 \times 10^{-8}$ in the zinc interaction chamber. Optical interference filters preceded the photomultiplier detectors and, for example, selected the 518.2 nm photons from the $6s\ ^1S$ state with a 518.3 nm central wavelength filter with a FWHM of 0.3 nm. The zinc oven reached a stable operating mode when its temperature reached about 410 °C after 1 hour working time when the 468.1 nm photon
count rate was about 6000/sec. For these conditions there was no detectable instrumental or collisional depolarization. The observed Stokes parameters have been corrected for hyperfine depolarization arising from the natural abundances of 95.9% and 4.1% for the isotopes with nuclear spin of 0 and 5/2, resp. The scattered electron energy resolution was selected from 150 to 300 meV according to the need of the measurement.

The scattered electrons were detected after energy selection by a 127º cylindrical analyzer. Incident electron energy and also scattered electron residual energy (to maintain a constant energy loss) were scanned simultaneously so that energy dependence of angle differential scattered electron intensity was measured. The scattered electron energy analyser can rotate on both sides of the incident electron beam direction to verify symmetric scattering around the incident beam direction and enable left/right scattering asymmetries. Orientation of the electron spin vector perpendicular (up/down) to the electron scattering plane was changed by reversing the helicity of the laser light in the source.

3. Results and Discussion

3.1 The closed core 6s ^1S to 4p ^1P 518.2 nm transition

The precision of the technique was indicated by measuring the Stokes parameters P_{1,2,3} of the 6s ^1S to 4p ^1P 518.2 nm radiation as shown in figure 2.

![Figure 2. The Stokes parameters P_{1,2,3} of the 6s ^1S to 4p ^1P 518.2 nm radiation.](image-url)

Within about the first 0.6 eV from threshold all three integrated Stokes parameters (integrated over all electron scattering angles) are zero within the statistical uncertainties. This transition is very weak compared with the other transitions observed in this work and so its measurement established the precision of our technique for the present experimental conditions. Also the observation is consistent
with the state being a pure and well LS-coupled state, i.e. the electron charge cloud is spherical, both $P_1$ and $P_2$ should be zero and, since the upper state is a singlet state, $P_3$ is expected to be zero. Those observations indicate the applicability of the interpretation of the measurements to zinc, at least to those states. About 1 eV above threshold the three $P$ parameters are definitely non-zero, most likely by transfer of polarization through cascade from higher states, but the possibility of resonance phenomena can not be excluded for the present statistics and limiting electron energy resolution of about 0.3 eV.

3.2 The closed core $4d\,^1D_2$ to $4p\,^1P_1$ 636.2 nm transition
The measurements of the integrated Stokes parameters for the $4d\,^1D_2$ to $4p\,^1P_1$ 636.2 nm transition, shown in figure 3, also indicate very small (<0.002) values of $P_2$ within about 2 eV from the threshold at 7.74 eV and small, near zero, values of $P_3$. Again the statistical accuracy is sufficiently good to indicate the minimization and/or absence of most experimental uncertainties.

![Figure 3](image.png)

**Figure 3.** Integrated Stokes parameters $P_{1,2,3}$ for the $4d\,^1D_2$ to $4p\,^1P_1$ 636.2 nm transition. The vertical line indicates the threshold energy of 7.74 eV. The top left section shows $P_1$ (upper data) and the integral cross section (lower data, right hand side axis).

The integral cross section for the $4d\,^1D_2$ state indicates that cascade from the $5p$ level is evident from its threshold at 8.2 eV and it contributes significantly to $P_1$ and possibly with a very small contribution near 8.3 eV to $P_3$ values. The model of Bartschat and Blum [21] indicates that the spin-orbit interaction is negligible and that the state is well LS-coupled. If the small $P_3$ values are considered as zero within ± 0.005 the experimental and theoretical indications that electron exchange and spin-orbit interaction are negligible, are in agreement.
3.3 Open and closed shell transitions near 24 and 18 eV

The above data for closed core transitions indicate a consistent model for excitation of S and D states of low energy and near threshold. To explore the difference between open and closed shell transitions we choose the ionic $3d^{10}5d^{2}D_{3/2}$ closed–to-closed $3d^{10}5p^{2}P_{1/2}$ shell transition and the $3d^{9}4s^{2}^{2}D_{3/2}$ open–to-closed $3d^{10}4p^{2}P_{1/2}$ shell transition, i.e. with both parent states well above the first ionisation threshold. Wavelength filters of 589.6 nm and 602.2 nm with 0.6 and 1.0 nm FWHM bandwidths, resp. were used. By the nature of the open shell binding of electrons in zinc, all of the open shell states lie above the first ionisation potential and so there are competing auto-ionisation continua which influence the interpretations. Figure 4 indicates slight differences between open and closed shell transitions in all three Stokes parameters.

![Figure 4](image-url)

**Figure 4.** The Stokes parameters $P_1$ (lower section), $P_2$ and $P_3$ (upper sections) for the closed $3d^{10}5d^{2}D_{3/2}$ to closed $3d^{10}5p^{2}P$ shell 589.6 nm transition (closed circles) and open $3d^{9}4s^{2}^{2}D_{3/2}$ to closed $3d^{10}4p^{2}P$ shell 602.2 nm transition (open squares).

The top left section of figure 4 shows zero values of $P_2$ for an incident non-polarised electron beam because of the cylindrical symmetry of the scattering geometry when there is not a spin vector to define a plane. That result confirms a correct working of that aspect of the method as well as the size and spread of the uncertainties in the data points indicating the precision and accuracy of the measurements but only for that observed wavelength. Consequently even the three data points just above threshold indicate non-zero values of $P_2$. We see that the open shell transition with non-zero $P_1$ values indicated angular momentum transfer with combined exchange and spin-orbit interactions, at least as indicated by this technique, as well as the rearrangement of two electrons; clearly a consequence of the open $3d^9$ core. An interpretation may be that the $3d$ core-perturbed potential enhances the probability of capturing, albeit temporarily, an electron to form a resonance just above threshold. In contrast the closed shell radiating the 589.6 nm photons showed a zero value of $P_2$. Both
the open and closed shell transitions occur in the process of excitation-with-ionisation, the ejected
electron escaping with unknown angular momentum and limiting the present interpretation.

The Stokes $P_1$ parameters for the open and closed shell transitions within the zinc ion are rather
similar with the essential similarities of a sharp decrease in value near threshold presumably indicating
a rapid change of the electron exchange interaction shown for $P_3$, which also appears then in $P_1$.
Assuming in the limiting case at threshold, and at least below the onset of radiation cascade, that only
the $L = 0$ partial wave is dominant a finite polarization occurs at threshold, electron exchange is the
dominant excitation process and the decrease of the polarization with increasing energy occurs.

These measurements have shown how an open shell in the ionization-with-excitation process
caused a breakdown of LS-coupling while a closed shell process remained well LS-coupled. In both
processes the residual ions remained aligned and oriented. An analysis [13] using normalized state
multipole revealed much more information. For the closed shell transition the total and spin angular
momentum transfers, and hence the magnetic dipole moment of the spin angular momentum transfers
and the electric quadrupole moment of the orbital angular momentum, were separated. A positive
value of the spin magnetic dipole indicated positive angular momentum transfer from the incident
electron via exchange. The negative value of the total magnetic dipole indicated a negative angular
momentum transfer to the residual ion when the spin coupled to the orbital angular momentum. In that
way the $m = -1$ states were populated rather than the $m = +1$ states.

3.4 Open core resonances near 11 eV

To seek further evidence of electron correlations we looked with the sensitivity of the Stokes
parameters to the region where the 3d$^{10}$ core opens just above the first ionization threshold, as
indicated in figure 5.

![Figure 5.](image-url)

**Figure 5.** Stokes parameters $P_i$ fitted with Fano resonance profiles for the 4d $^1D_2$ state decay photons.
The bottom left section indicates the measured intensity of the linear polarization at an angle of zero
degrees. The dashed line indicates the fitted background for the extracted resonances.
In the excitation of the 4d $^1D_2$ state around 11 eV the intensity of the radiated 636.2 nm photons, for either spin-up or spin-down incident electrons, indicates only a localized rise as shown in figure 5, however their difference, i.e. the Stokes parameters, shows not one, but two, resonances.

The lower energy resonance with a significant P$_2$ value infers a strong spin-orbit interaction in contrast to the negligible (near zero P$_2$) spin-orbit interaction for the higher-energy resonance. By definition, these resonances are a measure of the configuration interaction between each resonance state and its accessible continuum states. For an isolated resonance the Fano profile shapes $\sigma(E)$ are described by

$$\sigma(E) = c(E) + \{2\sigma_s q (\Gamma/2) (E-E_r) + \sigma_b (q^2-1) (\Gamma/2)^2 \} / (E-E_r)^2 + (\Gamma/2)^2 \}$$

where $c(E)$ is the sum of the resonance $\sigma_s$ and other $\sigma_b$ backgrounds, q is the profile index and $\Gamma$ is the resonance width. In the usual fitting procedure, the two resonances were shown to have energies of 10.98 ± 0.02 eV and 11.33 ± 0.02 eV with widths of 0.25 ± 0.03 eV and 0.33 ± 0.05 eV respectively. Ideally an experiment must determine also the phases of the overlapping scattering matrix elements as well as the differential inelastic cross sections into the accessible channels in order to characterize a resonance completely but while this is not yet feasible some details may be deduced. It was assumed that the two resonances were coupled to different continua, their separate shapes just superposed and no interference between them occurs [22]. Given the width of the resonance, the q-parameter measures the ratio between the transition probabilities to the bound and continuum components of the final state from the initial state. The q value is large for resonances dominated by the contribution from the transition to the bound component of the final state. Here, the q-values are given as (a:P$_i$) for resonances (a) and (b) with Stokes parameter P$_i$(i = 1, 2, 3) are (a: 4.9, 4.4, 4.2) and (b: -2.6, -2.1, -2.4) respectively. Singly-excited closed-core-excitation channels have large q-values and generally reduce the background contributions to the double excitation resonances which, in turn, causes the raising of the q-parameters for the double excitation resonances and which become more symmetric. Here the main core excitations arise from the 3d electrons and the correlations for the 3p electrons are small; the q-values are small and the different signs indicate different phases of the continuum background. The observation is in accord with photo-ionization data which indicate that core-shielding effects on resonance energies and widths are small and in contrast core shielding effects on the q parameter of the resonance are large. Work is in progress to determine the cross sections for the background continua.

Further interpretation of the negative ion resonance data requires a configuration, a coupling scheme and consideration of the effects of electron exchange and the spin-orbit interaction, as follows. Assuming that the additional electron is bound with a negative electron affinity of up to 0.5 eV, as for a Feshbach resonance, then the observed negative ion resonances at 10.98 and 11.33 eV, can be associated with a parent configuration of 3d$^9$ 4s$^2$4p with a calculated [23] center-of-gravity energy of 11.459 eV rather than the lower 3d$^{10}$4p$^2$ configuration at 10.301 eV. A resonance configuration with two outer 4p electrons bound to the ionic grandparent 3d$^9$ 4s$^2$ with J = 5/2 and J = 3/2 ion cores, resp., is probable since most of the 3d$^{10}$4p$^2$ configurations have energies too low and the 3d$^{9}$ 4s$^2$5p etc energies are too high. The spin-orbit splitting in this grandparent ion core is 0.337 eV [24] in accord with the energy difference of 0.36 ± 0.02 eV for the two observed resonances.

3.5. Multi-configuration Hartree-Fock [MCHF] models

Further assistance with an interpretation of these results for excitation of the 4d $^1D_2$ state and the two $^2D$ states was sought in a multi-configuration Hartree-Fock [MCHF] type calculation [25]. The approach was to achieve an outcome similar to that for neon [18], that is, to treat the closed core with either selective inclusion of linear combinations of configurations or “switching off” different parts of the program to obtain an indication of the effects of the closed and open cores. Variations included (i) closing the 1s-3d shells to allow only the effects of correlation between valence electrons to contribute to the calculation, (ii) remove one 3d electron from the core to allow correlation between core and
valence electrons, (iii) remove a second 3d electron to allow for additional core-core correlations, and (iv) allow for relativistic (spin) effects.

The procedure was standard for an outer two-electron closed shell atom, i.e. diagonalise the non-relativistic $H_{\text{HF}} = T_1 + T_2 - 2/r_1 - 2/r_2 + 1/r_{12}$ to obtain eigenstates $|2S+1L\rangle = \sum a_n |\psi_{2S+1L}\rangle$ of appropriate symmetry. Add spin-orbit interaction $V_{\text{SO}} = \sum l_s^2 s_i / r^2$ and repeat diagonalisation since $V_{\text{SO}}$ may cause mixing of multiplets in the representation of the additional eigenstates. This procedure was simple when the 3d electrons were part of the core and the only possible states were 4d, 5d etc and the orbitals were spectroscopic i.e the diagonal energy is related closely to a binding energy and the orbital was basically Hartree-Fock. In contrast, the correlation orbitals can be considered as corrections to the wave function with a large diagonal energy parameter which effectively contracts the orbital and so modifies the wavefunction in the region of the spectroscopic orbitals of the main configurations. The calculations for the 4d 2D level in the MCHF package were continued until the length and velocity forms of the matrix elements agreed to within 1.3 % and the lifetime and energy agreed with standard values. At that point the core included $n = 1, 2, 3$ except when one 3d-electron was included in the configuration state functions (CSF) to model the core-valence correlation and $n = 7$ was the highest principal quantum number of the electron CSFs included.

A similar approach was used for the observed 2D ionic configurations. When the 3d$^{10}$ electrons were part of the core, the only possible states were 4d, 5d etc and the calculations were simple with a small number of CSFs. The correlation orbitals were considered as corrections to the total wave function, they usually had a large diagonal energy parameter which had the effect of contracting the orbital and so modify the wave function in the space occupied by the spectroscopic orbitals of the main configuration. However the lowest eigenvalue for the 2D ionic configuration is the open core 3d$^9$4s$^2$ state, which plays an important role for the higher 3d$^{10}$ 4d and 5d 2D states and so must have good radial functions for the same 3d$^{10}$ potential. This was achieved using a Hartree-Fock calculation with an average energy of the two states represented as the average configuration 3d$^{10}$ 4d$^{0.5}$ 5d$^{0.5}$ and then estimating the 4s from the lowest state 3d$^9$ 4s$^2$ by an MCHF calculation in which only the 4s-orbital was varied. A reasonable estimate of the core-orbitals (1s-3p) and of the 3d, 4s, 4d and 5d orbitals was obtained. The state 3d$^9$4s$^2$ 2D$^{3/2}$ was represented by a single configuration wave function composed, for example, of fixed orbitals 1s, 2s, 3s, 4s; 2p, 3p, 4p and 3d, 4d, 5d [26]. Iterative processes, such as indicated above, enabled accurate energies for the 4d and 5d 2D states while the 3d$^9$4s$^2$ 2D energy varied depending upon the iterative procedure.

The results of these procedures determined that the valence correlations were limited to the correlations between only a few CSFs. Inclusion of the core-valence correlations made a significant difference and brought the calculated energies to less than 1% to the experimental values and the length and velocity values were almost identical with only a 0.1% difference. For example, the core-valence correlation improved the calculated values of wavelengths by 15% and 8% for the 4d 2D$^2$ and closed shell 2D transitions respectively showing its significance. However, the calculations did not show any significant configuration mixing of the 2D and 2D with the non 1D and 2D configurations, respectively.

It is interesting to note that the lifetime of the open-shell 3d$^9$4s$^2$ 2D$^{3/2}$ state via 589 nm decay is 1870 nsec and it involves the transition of two electrons after the ionisation i.e. of 4s$^2$ to 3d and 4p and hence expected to be weak. On the other hand, the closed shell transition involves electrons in the n=5 orbital which is expected to be weaker than the similar n = 4 transitions. The NIST database indicates equal line strengths, previous measurements indicated that at 50 eV the closed shell transition is about fifty times stronger whereas the present measurements [27] indicate, close to the threshold of the two states is about three times stronger. The differences arises from the different excitation functions for the 3d$^9$ 4s$^2$ 2D and 3d$^{10}$ 4d 2D transitions for which it appears that the 3d$^9$ 4s$^2$ 2D state is formed by the
removal of a single inner-shell electron while the $3d^{10} 4d^2 2D$ state is formed by ionization of one electron and excitation of another electron.

Consequently, the non-zero values of $P_2$ for the open-shell transition may be attributed to configuration mixing in the 3d orbital combined with spin-orbit interaction effects. This result is consistent with findings for ejected electron spectra [28] and photo-ionisation [29]. However it is the spin-polarised effects that are the more sensitive test of the interplay of correlation effects with exchange and spin-orbit interactions because of the observations when the strength of those interactions is not so small compared with the Coulomb interaction and the relative (unknown) phases of the interfering wavefunctions. Similar effects are found in various electron scattering phenomena to occur when the Coulomb dominated cross section is minimal and their spin effects become observable. Further work is needed to quantify the wavefunctions and their phases for the open and closed channel resonance formation in the open- and closed-core states in the region above the first ionization threshold, particularly for overlapping resonances.

5 The spin-dependent angle differential scattering asymmetries for resonance states

Further details and confirmation of the electronic configurations of the above resonances in section 3.4 observed in the 4d 2D photon decay channel near 11 eV await measurements of their spin asymmetries. However experimental considerations have limited observation of spin asymmetries to the 4s4p 3P electron energy loss channel which are reported here. Figure 6 shows the spin dependent

Figure 6. Electron excitation functions (top) and spin asymmetry (bottom) measured at an electron scattering angle of 54° (left hand side) and 30° (right hand side) for the 4s4p 3P 0,1,2 states of zinc atoms. The data for the excitation functions indicate spin-up (triangle) and spin-down (squares) and their difference, normalized to their sum and the incident electron beam spin polarization, is the spin asymmetry. The short vertical lines and the labels a, a’ etc indicate the energies and identify the resonances from other measurements (see text).
angular differential scattering intensities for the 4s4p $^3P_{0,1,2}$ states, and their corresponding spin asymmetry functions, for electron scattering angles of 30 deg and 54 degrees over the energy range from 10 to 12.2 eV. The spin asymmetry is defined as the difference of the scattered electron intensities for incident electron spin-up and spin-down, normalized to their sum and the incident electron beam spin polarization. An initial understanding of the features in figure 6 is derived from various sources.

The present measured electron energy scale was determined to within ± 0.030eV from the onset of radiation from the 4d $^1D$ state at 7.740 eV. The present electron energy resolution was not sufficient to separate the resonance energies. However their identification with configurations 3d$^8$ 4s$^2$4p4d was obtained from further observations of photon emission from the 4p $^1P$ states [17], the 4d,5d and 6d $^1D$ states [16] and of elastic electron scattering [19]. The negative-ion resonance structures are indicated by the labels a, a’, b, b’, c; c’ and c”’ and d with their (energies and, where available, widths) in brackets, as follows: a(10.74), a’(10.82), b(11.01, 0.25), b’(11.10), c(11.22), c’(11.33, 0.33), c”’(11.46) and d(11.61) eV. The energies for resonances labeled a, a’ and b, b’ are determined from the derivative of transmitted current [19], the energies of c, c’ and c”’ are the average of peak energies observed in photon emission [16], and the energy of the structure labeled d comes from differential elastic scattering [19]. The differential elastic scattering [19] indicated that all negative ions in the 3d$^8$4s$^2$4p$^2$ manifold are formed from, and decay by, emission of a d-wave electron. The two lowest energy structures labeled a, a’ and b, b’ were clearly doublets.

The energy dependence of the spin asymmetries shows marked differences between 30 and 54 degrees electron scattering angles. Both above and below the resonance region, the 30 deg data show a small but statistically significant non-zero asymmetry in contrast to the zero values for the 54 degree data which suggests a d-wave nature of the 4s4p direct excitation process and then presumably also through the resonance regions. A similar behaviour exists for the angle integrated Stokes parameters $P_1$, $P_2$ and $P_3$ of the singlet 3d$^{10}$ 4s4d $^1D_2$ and 3d$^{10}$ 4s4d $^1P_1$ decay photons [16] that both spin-orbit and exchange are active in the observed 3d$^8$ 4s$^2$ 4p$^2$ negative ion resonances. Through the resonance regions there are significant interferences between the resonant process and the direct excitation processes.

Further interpretation is restricted by the difficulty of the measurements and the lack of data from other sources. A relationship between resonance decay width and spin alignment may be inferred, for instance from helium-like systems [30] where the widths of the singlet resonances are larger than those of the corresponding triplet resonances. Also for triply excited states, the spin alignment determines the relative branching ratios of the decay channels. For example, the branching ratios of the 2s2s2p$^3P_0$ state of lithium, the two 2s electrons are most likely to interact strongly and the 2s electron with spin anti-parallel to that of 2p is most likely to escape and a similar conclusion can be drawn from the decay of other triply excited states in three-electron or four-electron systems. The present data indicate real expectations of resolving the resonances and their spin asymmetries with achievable electron energy resolutions. However there are insufficient data presently to extract the direct excitation phase shifts. Further measurements are in progress.

4. Conclusions
A wide variety of measurements have been made of the zinc excitation processes. Observations of the “integrated” Stokes parameters $P_i$, i.e. integrated over the angular distribution of the scattered electrons, of the photons radiated from polarized electron excited closed 3d$^{10}$5d $^2D_{3,2}$ and open 3d$^8$4s$^2$ $^2D_{3,2}$ shell ionic states of zinc, as well as the 6s $^1S$ and 4d $^1D$ state of neutral zinc atoms, have been made. The data describe resonance and non-resonance behaviour as well as the effects of electron exchange and spin-orbit interactions on the excitation and excitation-with-ionisation processes.
The measurements have shown how an open-core in the ionization-with-excitation process caused a breakdown of LS-coupling while the closed-core process remained well LS-coupled. For the latter case using state multipole analysis it was possible to separate orbital and spin angular momentum transfers to be separated and show the sign of the angular momentum transfer to the residual ion and then the preference for populating different magnetic sublevels. Measurements of the spin up / down asymmetries for inelastically scattered electrons indicated relatively large effects from the resonances observed in the $4s4p \ ^3P_{0,1,2}$ differential excitation probability. Initial descriptions of the energies, widths and electronic configurations of the resonances have been made. The significant value of spin polarised studies of the 3d transition metal atom zinc in revealing quantum structure and scattering dynamics has been shown.

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