Spin dependence in resonance electron scattering from zinc atoms

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Abstract.
Spin effects in excitation of the $3d^{10}4s^24p^3P_0,1,2$ states of zinc via $3d$ core excited negative ion resonances were studied using a spin polarized electron beam. Energy dependence of the angle differential scattered electron intensity is reported for two scattering angles, $\theta = 30^\circ$ and $\theta = 54^\circ$. Observations indicate strong spin-up/down scattering asymmetries in the energy region where excitation proceeds via $3d^94s^24p^2$ negative ion resonances.

1. Introduction
Experiments with low energy electron scattering on zinc atoms have shown significant effects of electron correlation as soon as excitation of the inner $3d$ electron becomes energetically possible. Of special interest are negative ion resonances formed upon the excitation of the $3d$ core electrons. These were observed in excitation of valence states using detection of decay photons [1] or of energy selected scattered electrons [2, 3]. While photon studies include cascade effects and the intensity is summed over all scattering angles, the detection of an electron, scattered at a chosen scattering angle and with well-defined energy loss, is final state specific and the observed count rate is proportional to an angular differential cross section. When the cross section is expanded in angular-momentum dependent partial waves, the effects of resonance states may become more apparent and this is particularly so for elastic scattering [3]. The present study of excitation of the $3d^{10}4s^24p^3P_{0,1,2}$ state using spin polarized electrons extends that investigation to obtain spin-specific angular momentum information. Also the spin-dependent interactions in the formation and decay of the $3d$ core-excited negative ion resonances in zinc are probed.

The mechanisms responsible for spin dependence in electron-atom collisions and the unique information obtained with incident spin polarized electrons have been discussed [4, 5]. In zinc, with a closed $4s^2$ outer shell, spin effects in elastic scattering are caused by the spin-orbit interaction of a scattered electron in the field of an atom (Mott scattering). For the excitation process however, spin polarization phenomena can be introduced by both the exchange and the internal atomic spin-orbit interactions. If electron scattering proceeds via a short-lived, negative ion resonance, additional spin effects are possible and these characterize the spin-orbit interaction and electron exchange in a particular negative ion state. As the active electrons/holes have non-zero orbital momentum (4p and 3d), both the momentum coupling of the 3d core and the pair of outermost 4p electrons will influence resonance scattering.
The only previous measurement of the angular behavior of asymmetries (left/right) in low energy elastic scattering of spin polarized electrons on zinc [6], used a coarse energy mesh above the ionization threshold to report non-zero values and could not observe variations due to negative ion resonances. However, that investigation observed a strong effect on spin asymmetry for the 4.05 eV resonance in cadmium.

We observed previously the core-excited negative ion resonances in zinc [7] in the angle-integrated Stokes polarization parameters $P_1$, $P_2$ and $P_3$. That study used spin polarized electrons to probe exchange and spin-orbit interactions activated by promotion of one of the inner 3d electrons. Both the spin-orbit and exchange effects were observed and separated by measurement of the Stokes polarization parameters $P_1$, $P_2$ and $P_3$ of the $3d^{10}4s^24d^1D_2 \rightarrow 3d^{10}4s4p^1P_1$ decay photons. Here we report the spin dependence induced by the same group of core-excited resonances but now observed in angle differential scattering cross sections for excitation of the unresolved $3d^{10}4s^24p^3P_{0,1,2}$ states. The results are expressed in terms of spin up/down scattering asymmetries.

2. Experiment

The apparatus was based on crossed spin-polarized electron and unpolarized atom beams. The source of spin polarized electrons has been described in detail previously [8]. Briefly, photo-electrons are emitted from a GaAs crystal irradiated with circularly polarized laser light with spin vectors parallel or anti-parallel to the helicity of the laser light. This initially longitudinal spin polarization was changed to transverse by deflecting electrons through 90°. Orientation of the spin vector with respect to the scattering plane, up $\uparrow$, or down $\downarrow$, can be changed by switching the helicity of the laser light from left to right using a liquid crystal variable retarder. The initial energy spread of electrons was reduced using an electrostatic 180° hemispherical monochromator. Spin polarization in the incident electron beam was 28%.

Electrons scattered on zinc atoms at a variable angle $\theta$ were energy selected by a 127° cylindrical analyzer and those exciting the $4s4p^3P_{0,1,2}$ states were detected using a channel electron multiplier. The incident electron energy and the scattered electron residual energy were scanned simultaneously for each spin direction to observe resonance structure and its energy and spin dependence. The scanning of electron energies, electron counters and the control of spin orientation were done using a PC-based data acquisition system. Repeated energy scans, with a change of spin orientation at each incident energy point, were taken until the required statistical accuracy was achieved. The scattered electron analyser can rotate to both sides of the incident electron beam direction which defines the zero of the angular scale. In this way measurements can be repeated and data compared for left/right and spin up/down scattering asymmetries. The incident electron energy scale was calibrated on known positions of negative ion resonances in zinc [1]. The reported studies were conducted with an energy resolution of 120 meV.

3. Results and discussion

Previous electron impact $3d^{10}4s4p^3P_{0,1,2}$ excitation studies [1, 2] showed a strong influence of negative ion resonances above the ionization threshold. The observed negative ions are created upon promotion of an inner 3d electron into the first unoccupied 4p orbital accompanied by the temporary attachment of the incident electron into the same 4p orbital. The assignment of negative ion states was discussed in terms of momentum couplings and related to the spin-dependent effects within the 3d ion core and the pair of outer 4p electrons [1, 3]. Previous work also outlines a comparison with the iso-electronic atom, i.e. autoionizing states of gallium atom with the same $3d^{10}4s^24p^2$ electron configuration. This comparison gives an insight into the likely symmetry and also the energy ordering of different negative ion states. The three fine structure components of the $3d^{10}4s4p^3P_{0,1,2}$ decay channel are not resolved in the present experiment but
are well resolved from other scattering events at nearby energies, i.e. from elastic scattering and excitation of the $4s4p^1P_1$ state.

The results for spin-dependent angle differential electron scattering leading to the excitation of the $4s4p^3P_{0,1,2}$ states at scattering angles of $\theta = 30^\circ$ and $\theta = 54^\circ$ are shown in figures 1 and 2, respectively. For each scattering angle, the scattered electron intensities for the spin-up, $I^{\uparrow}(\theta)$, and spin-down, $I^{\downarrow}(\theta)$, are shown in parts 1(a) and 2(a). These intensities were used to evaluate the spin asymmetry function $S_A(\theta)$ using equation

$$S_A(\theta) = \frac{1}{P_e} \frac{I^{\uparrow}(\theta) - I^{\downarrow}(\theta)}{I^{\uparrow}(\theta) + I^{\downarrow}(\theta)},$$

where $P_e$ is the spin polarization of the incident electron beam. The spin asymmetry as a function of energy is shown in figures 1(b) and 2(b).

The energy positions of the $a, a', b, b', c, c', c''$ and $d$ negative-ion resonance structures, determined from the photon [1] and electron excitation functions and electron transmission measurements [3, 9], are also indicated. As can be seen from figures 1 and 2 the energy behavior of the asymmetry function $S_A$ shows a clear angle dependent, sharp variation in the vicinity of the indicated resonances. Also, a small, but statistically significant, non-zero asymmetry is measured outside the resonance region at some scattering angles. This is similar to the observation from angle integrated Stokes parameters $P_1$, $P_2$ and $P_3$ of the $3d^{10}4s4d^1D_2 \rightarrow 3d^{10}4s4d^1P_1$ decay photons that both spin-orbit and exchange were active in some of the $3d^94s^24p^2$ negative ion resonances [7].

Similar measurements to those presented here have been performed for mercury by Bartschat et al [10]. That study observed variations in the energy dependence of the asymmetry in excitation of the $6s6p^3P_{1,2}$ and $6s6p^1P_1$ at known resonance energies. However, important differences between mercury and zinc exist. The $6s6p^3P_{0,1,2}$ fine structure states were resolved in mercury, unlike the present study where the fine structure of the zinc $4s4p^3P_{0,1,2}$ states was not resolved. This is a consequence of the larger strength of the spin-orbit interaction in mercury.
which would have also a separate influence on momentum coupling and the multiplet structure
relevant for both the negative ion spectrum and decay channels in the two atoms. Also some of
the states with equivalent $5d^66s^26p$ electron configuration in mercury are bound ($^2D_{3/2}$) while
some ($^2D_{3/2}$) are autoionizing. In conjunction with the strong spin-orbit interaction, this makes
direct comparison of zinc and mercury not possible.

An explanation for the negative-ion induced asymmetries observed by Bartschat et al [10] was
provided by Kessler [4]. When picking out the electrons of the dominant partial wave, i.e. orbital
angular momentum $l$, we must take into account that transversely polarised electrons which are
scattered to the left have total angular momenta $j$ different from those of the electrons scattered
to the right, since the orbital angular momenta are opposite to each other. In conclusion, for
a given incident electron spin polarisation, either electrons scattered to the right or to the left,
but not both, may have $j$ suitable to form a compound state. Similar reasoning is applicable in
the present measurements where only electrons scattered to the left were detected, but electrons
in the incident electron beam have predominantly spin up or spin down. In compliance with
conservation of angular momentum and parity, the incident electrons with spin-up or spin-down,
but not both, may have $j$ suitable for formation of the negative-ion resonance.

To demonstrate the effect of a negative-ion resonance on the spin asymmetry, let us
consider a negative-ion resonance which enhances the cross section of the observed state, and
is formed by incident electrons with orbital angular momentum $l$. If the observation is made
at a positive scattering angle $\theta$, and if this negative-ion resonance produces a positive spin-
up/down asymmetry, it means that spin-up incident electrons are bound in the negative ion,
which therefore has a total angular momentum $J = l + 1/2$. Likewise, if a negative spin-
up/down asymmetry is observed, it means that spin-down incident electrons are bound and
the negative ion has a total angular momentum $J = l - 1/2$. Obviously a negative-ion
resonance generally will not enhance a cross section because it may interfere destructively, as
well as constructively, with the non-resonance cross section. Whether a particular negative-ion
resonance produces a positive or negative asymmetry will depend on its Fano profile, as well as its
parity and $J$. In principle, spin asymmetry measurements can resolve overlapping negative-ion
resonances with different $J$, even if because of their large natural width they cannot be resolved
in unpolarised electron excitation function experiments. Therefore, the high-resolution spin
asymmetry function measurements can also assist the assignments of negative-ion resonances in
the autoionizing region of zinc.

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4. References

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