Post collision interaction effects in the excitation of zinc atoms

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Abstract.
Post collision interaction of scattered and ejected electrons in the decay of the $3d^94s^24p$ autoionizing states was observed to contribute to the population of the $4snd^3D_{1,2,3}$ states of zinc. Energies of PCI structures and percentage contributions to the emission cross sections have been measured for the $n = 4, 5, 6$ states. Also, the effects of PCI were observed in an energy loss at 13.4 eV and affected both the positions and the width of the energy loss structures. In the energy loss study a strong excitation of the $3d^94s^24p^3P_1$ state was observed in the near threshold regime.

1. Introduction
Photon intensity measurements of the emission lines from the electron impact excited states of zinc show remarkable structures in the autoionizing region above 10 eV. Our experiments have shown that the two phenomena of formation of temporary negative ions and Post Collision Interaction (PCI), both governed by strong electron correlations, can significantly affect the cross section when excitation of an inner 3d electron becomes possible [1]. In particular we investigated the population of the $4snd^3D_{1,2,3}$ states of zinc via the decay of the $3d^94s^24p$ autoionizing states when excited near their excitation thresholds. That process is made possible by the post collision Coulomb interaction of the slow scattered and ejected electrons while still in field of the Zn$^+$ ion. The interaction, which involves the exchange of energy and momentum, can lead to the capture of one, usually the slower scattered, electron into a higher energy state.

Here we observe the electron capture into three different excited states of the same orbital and spin momentum, i.e. the $4snd^3D_{1,2,3}$ $n = 4, 5, 6$ states, by measuring the intensity of the decay photons. Also, in the presence of the PCI and depending on the amount of energy exchanged, an autoionizing state can decay by ejection of one electron but with a kinetic energy different from their spectroscopic values. Due to energy conservation, the scattered electron energy would be changed appropriately. This process we observe in the energy loss spectrum at incident energies close to the threshold of the $3d^94s^24p$ autoionizing states. The PCI effect was observed previously in electron impact excitation of noble gases [2, 3] for which different outcomes were discussed.
2. Experiment

The apparatus was based on crossed electron and atom beams. Briefly, an electrostatic 127° analyzer selected a portion of the energy spread of electrons emitted from a tungsten cathode. Using aperture lenses electrons were focused into the interaction region where they were crossed with a Zn atomic beam emanating from a thermally heated oven. Two types of measurements were performed to investigate the electron impact excitation of zinc. First, decay photons, emitted in the direction perpendicular to the incident electron beam, were wavelength selected using an interference filter and detected by a photomultiplier tube. The incident electron energy was scanned and the intensity of the detected photons recorded using a PC-based system. The energy scale was calibrated on known positions of negative ion resonances in zinc [1]. Photon intensities were corrected for background to separate those photons which were not related to the electron impact excitation of zinc. Also, using the same electron impact spectrometer, electrons scattered on zinc atoms at a variable angle \( \theta \) were energy analyzed using a 127° cylindrical analyzer and detected using a channel electron multiplier.

3. Results and discussion

Photon intensity measurements of the unresolved fine structure emission lines from the \( 4s nd^3D_{2,3,3} \) states of zinc show remarkable structures in the autoionizing region above 10 eV [1]. The structures, superimposed on a smoothly varying cross section, are identified on the basis of the specific energy dependence of negative ion resonances and of the PCI effects. To show the structures in more detail a smoothly varying cross section is subtracted and the percentage contributions of the remaining structures are shown in figure 1.

At the low energy end of the spectrum for each of the three \( 3D_{2,3,3} \) states, the sharp structures labeled a,b and c” appear at the same incident electron energy. These structures correspond to the \( 3d^94s^24p^2 \) negative ion resonances observed in the excitation of different neutral states of zinc, [4, 5, 1], in electron transmission and angle differential elastic scattering [6]. The broad structures observed at higher energies are associated with the PCI effect in the decay of the \( 3d^94s^24p \) autoionizing states excited close to their respective thresholds. They move on an energy scale with increase of the \( n \) quantum number of excited electron in observed channel, i.e. with decrease of neutral excited state binding energy, as can be seen in the three spectra in figure 1. In the decay of the autoionizing state the ejected electron and the slow scattered electron, while still in the field of the residual ion, interact and exchange energy and angular momentum. Various outcomes of this interaction were discussed [2] for the noble gasses He, Ne and Ar. Here we observe the situation where one of the outgoing electrons loses more energy than its kinetic energy leading to recapture in the \( 4s nd^3D_{1,2,3} \) states of the neutral Zn atom. PCI appears in the cross section as an interference of direct excitation and PCI mediated population of these states via excitation of one of the autoionizing states. In the excitation of the triplet D-states in zinc this leads to significant enhancement of the cross section as can be seen in figure 1.

It follows from the nature of the post collision interaction that the energies of autoionizing states associated with observed PCI effects have to be close to, but not higher than, the onset of the observed structures as indicated in figure 1(a)-(c). Of the many autoionizing states with the \( 3d^{10}4p^2 \) and \( 3d^94s^24p \) electron configurations situated in the energy region below the observed PCI structures, we consider as likely contributors to excitation of the \( 4s nd^3D_{1,2,3} \) states of zinc, those excited with the largest cross sections in the relevant energy region. Extensive spectroscopic information, including the energies and relative intensities of both the optically allowed and optically forbidden states, was obtained by Back et al [7]. We used here the ejected electron spectrum at an electron impact energy of 16 eV and ejected electron angle of 60° later interpreted by Mansfield [8]. This ejected electron spectrum at kinematical conditions close to our experiment indicates appreciable excitation of the states with \( 3d^94s^24p \) electron configuration. The only exception is the \( 3d^{10}4p^{2}1S \) state at an excitation energy of 11.50 eV.
We use observed ejected electron intensities to gain an insight into which states are most likely to contribute to the observed PCI. Below the onset of the first PCI structure at 11.64 eV, by far the strongest contribution comes from the $3d^94s^24p^3P_1$ (11.186 eV) autoionizing state decaying with the ejection of 1.793 eV electrons. At higher energies, but below the onset of the second PCI process at 12.68 eV, a group of five more autoionizing states was observed. Their spectroscopic energies and corresponding ejected electron energies are shown in figure 2 (b) and (c).

![Figure 1](image1.jpg)  
**Figure 1.** Resonance and PCI structures observed in photon excitation functions.

![Figure 2](image2.jpg)  
**Figure 2.** Electron energy loss at $\theta=40^\circ$ $E_i=20$, 15 and 13.4 eV.

Providing an adequate energy resolution is available, additional information on autoionizing states, their near threshold excitation and decay, and also their relative cross sections, can be obtained from energy loss spectra like those shown in figure 2. The three spectra were measured at the same scattering angle of 40°, but at three different electron impact energies, $E_i=20$, 15 and 13.4 eV. The choice of energy permits the separation or simultaneous detection of both the scattered and ejected electrons from the process of autoionization while approaching the excitation threshold. The three spectra in figure 2 include also the states below the ionization threshold and the energy resolution, low background signal and energy loss scale are indicated.
The 20 eV energy loss spectrum in figure 2(a) is measured far from excitation thresholds where the excitation of optically allowed transitions dominates the spectrum. At an incident electron energy of 15 eV, closer to excitation thresholds, the relative intensities of autoionizing states have changed, the optically forbidden 3d\(^9\)4s\(^2\)4p\(^3\)P\(_{0,1,2}\) states are strongly excited. The J=1 state is the most prominent in agreement with ejected electrons intensities from Back et al [7] and is almost certainly responsible for the lower PCI peak. The spectrum still displays well defined energy loss features in the autoionizing region. In contrast the energy loss spectrum at 13.4 eV, while being still of the same quality below the ionization threshold at 9.39 eV, shows an apparent fuzziness in the region of autoionizing states between 11 and 13 eV.

For interpretation of energy loss spectra in figure 2(a)-(c) we consider the kinetic energy of the detected electron (the residual energy of the scattered electron) and evaluate where ejected electrons may appear in our energy loss spectrum. The positions of ejected electron peaks, calculated using their spectroscopic energies, are shown also on spectra in figure 2(b) and (c). As can be seen, the energy loss peaks corresponding to scattered and ejected electrons will overlap at incident electron energy of 13.4 eV. The kinetic energy of ejected electrons has a fixed spectroscopic value at some distance from threshold, but not near the threshold due to PCI, and the same is true for the scattered electrons after excitation of an autoionizing states subsequently decaying by autoionization. For both types of structures, the energy loss and ejected electron peaks are shifted and broadened, and the spectrum appears substantially different and appears to have lower energy resolution.

In contrast to PCI observed in noble gases, where ejected electrons have considerable kinetic energy and gain energy, while scattered electron is slow and loses energy, a specific situation occurs in zinc. In zinc, both the scattered and the ejected electron have relatively small energies and spend a substantial time in the vicinity of the residual ion while interacting. As a consequence, high values of angular momentum can be transferred [9]. An order of magnitude estimate [1, 3, 9] shows that for electron energies in zinc a transfer of \(\Delta J \leq 2.6\ h\) is possible explaining the strong effect on excitation of the D states. Also due to similar energies electrons are expected to be more correlated both in the escape and in re-capture processes.

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4. References
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