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Absolute differential cross sections for electron excitation of silver at small scattering angles

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ABSTRACT

We present results of our experimental and theoretical investigations of the electron excitation of the ground $4d^{10}5s$ state of silver. Differential cross sections (DCSs) for the excitation of the first combined resonant $4d^{10}5p$ state (two fine-structure levels with total angular momentum $J = 1/2$ and $3/2$ which cannot be distinguished in the present experiment) were measured at electron-impact energies (E_0) of 10, 20, 40, 60, 80 and 100 eV and for a range of scattering angles (θ) from 3° up to 15°. Absolute DCSs were obtained by the normalization of relative differential cross sections to the optical oscillator strengths. The relativistic distorted wave (RDW) method was used to calculate DCSs and generalized oscillator strengths for each level separately and the combined results are compared with the measurements.

1. Introduction

Besides being of fundamental importance, information about electron inelastic collisions with silver atoms and the results of both experimental and theoretical studies of this process are of significant interest for many applications such as laser techniques [1], development of new generations of atomic frequency standards [2–5] and astrophysics [6–8]. Similar to the alkali metals, silver has one valence electron in an outer (5s) orbital resulting in a $^2S_{1/2}$ ground configuration. On the other hand, electron excitation of silver requires higher excitation energies than for the alkalis because the last closed-shell in silver consists of ten *d* electrons while in the alkalis there are six *p* electrons in this shell.

Differential cross sections (DCSs) are widely used experimental tools in the study of electron interactions with different atoms. In electron–atom scattering processes, DCSs are used to describe the strength of interactions among atomic particles, i.e. to relate the impact parameter to the scattering angle of a particle that has experienced a collision with the force field of another particle. Generally, this observable gives the probability of a specific interaction at a certain electron energy and scattering angle. To determine the absolute DCS experimentally, it is necessary to know the absolute atom target density and its spatial distribution, the energy and angular distribution of the electron beam and its current density, as well as the effective scattering volume [9] and response function of the detection system.

There are only a few experimental and theoretical investigations related to the electron excitation of silver. To the best of our knowledge, there are no results on differential cross sections for the energies and scattering angles which we used in our experiment. Smirnov used the method of extended crossed beams to measure excitation cross sections of atomic silver in order to obtain the dependence of the cross sections on the principal quantum number of the upper level for a few spectral series and to calculate the contribution of cascade to the population levels of various states [10]. Theoretical studies are restricted to only one calculation by Zeman et al. [11]. Using the relativistic distorted wave (RDW) method, these authors calculated differential and integrated cross sections, Stokes parameters and generalized STU parameters for excitation of the $5p\ ^2P_{1/2,3/2}$ levels of Ag in the energy range from 30 to 100 eV.

There are both experimental and theoretical reasons for the lack of investigation of this atom. Experimental investigations are limited by the high working temperature (1300 K) which is necessary to vaporize the silver sample and to produce a well collimated effusive atomic beam while theoretical methods must take into account relativistic effects for this heavy atom with nuclear charge $Z = 47$.

We have investigated the excitation of the ground $4d^{10}5s$ state of Ag to its first excited $4d^{10}5p$ state both experimentally and theoretically. The ground state has a total angular momentum $J = 1/2$ while the excited state is a fine-structure doublet with $J = 1/2$ and

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$J = 3/2$ and energies of 3.664 and 3.778 eV, respectively. These levels cannot be distinguished in the present experiment and measurements are presented for the excitation of the combined levels, while the RDW calculations produce separate results for these two levels with different energies.

DCS measurements were performed at electron impact energies of 10, 20, 40, 60, 80 and 100 eV and from 3° to 15° scattering angles. The RDW calculations were carried out for the same energies and over all scattering angles.

2. Experimental techniques and procedures

The experimental method as well as the apparatus is the same as in our previous experiments and detailed descriptions were presented in recent papers [12–14]. Therefore, only a brief description will be given here.

The experimental method used to determine DCSs is based on a crossed beam technique employed in the electron spectrometer ESMA. A monoenergetic electron beam was obtained by means of a hemispherical selector and is focused by cylindrical electrostatic lenses. The electron beam with energies from 10 to 100 eV was crossed perpendicularly by an effusive atomic beam formed by heating a Knudsen-type oven crucible containing silver metal. In order to prevent clogging, the oven was heated by two separate heaters. The working temperature was about 1300 K. The additional shields located near the crucible plus water-cooling ensures that there was no overheating of surrounding components. The experiment was conducted in a vacuum chamber, which was shielded by a double μ-metal shield so magnetic fields were below 2×10^{-7} T. Two oil diffusion pumps with liquid nitrogen traps provided differential pumping of the vacuum chamber and electron optics system. The background pressure was of the order of 10^{-5} Pa and the contamination of the chamber was prevented by a liquid-nitrogen cold trap placed above the oven and interaction region.

Inelastically scattered electrons were energy analyzed by the selector, and were detected by a single-channel electron multiplier. The analyzer can be positioned from −30° to 150° with respect to the incoming electron beam.

The angular resolution of the spectrometer was estimated to be 1.5°. The typical overall energy resolution (FWHM) was 160 meV. Since the fine-structure doublet of the excited state has an energy splitting of only 114 meV, it cannot be distinguished and we measured the excitation of the combined levels. Before each measurement, the angular distribution of scattered electrons was measured from −10° to +10° and the real zero scattering angle was determined according to the symmetry of the inelastic scattering at negative and positive scattering angles around the instrumental zero.

Measured scattered intensities were transformed to relative DCSs using the effective path length correction factors, V_{eff}, [15] determined for the present experimental conditions. Absolute DCS values were obtained by the normalization of relative differential cross sections using the forward scattering function (FSF) based on the generalized oscillator strength (GOS) [16–18]. A detailed description of the normalization procedure was presented previously [13,19], so we will mention only the details which are specifically relevant for silver atoms and the observed excitation process.

It is well known that DCSs for optically allowed transitions are generally strongly forward peaked which puts great emphasis for an accurate DCS measurement at small scattering angles. However, measurements near zero scattering angle are not reliable for several reasons. Firstly, there is the influence of the primary beam at these small scattering angles. Secondly, these measurements require high angular resolution while the angular resolution of the present experiment is 1.5°. Finally, since the appropriate correction factors depend on the experimental geometry, electron beam collimation and the nature of the atomic target, the transformation of the scattered signal intensities to relative DCSs is strongly affected by the fast variation of V_{eff} near zero.

3. Theory

As mentioned above, the ground state of silver has a configuration $4d^{10}5s$ with total angular momentum $J = 1/2$. The first excited $4d^{10}5p$ states is a fine-structure doublet with the lower level having $J = 1/2$ and the upper level $J = 3/2$. The energy splitting of 0.114 eV indicates that relativistic effects are important in the description of this atom. The RDW theory takes into account these effects by calculating both the atomic and continuum electron wave functions within the Dirac formalism. The atomic orbitals and wave functions for both the ground and excited states (fine-structures levels) were calculated using the multiconfiguration Dirac–Fock (MCDF) program [20]. We included the basic configurations for the initial and final states, $4d^{10}5s$, $4d^{10}5\bar{p}$ and $4d^{10}5p$. We also included four relativistic configurations represented by the non-relativistic notation $4d^8 5s5p^2$ to represent correlation. There was almost no coupling between the basic configurations and the correlation configurations so that the initial and final wave functions used to calculate cross sections represented single configurations. The dipole polarization potential of Ag^+ was included in the calculations. The relativistic distorted wave (RDW) method formulated by Zuo et al. [21] is used to calculate the DCS for excitation of these two levels separately. Since our calculations are carried out in the relativistic j–j coupling scheme the wave functions have a definite total angular momentum and the spin of the projectile electron is specified. The distorted wave T-matrix can be written as

$$T_{i\to f}^{\text{DW}} = \left\langle J_f M_f \mu_f | V - U | J_i M_i \mu_i \right\rangle \tag{1}$$

where J and M represent the total angular momentum of the atomic state and μ is the spin projection of the free electron. V is the full interaction potential and U is the distortion potential in the final channel. In order to calculate the distorted waves, the distortion potential was chosen as the static potential of the ground state in the initial channel (i) and the spherically averaged static potential of the excited state in final channel (f). The DCS for the excitation of the atom from the initial state with angular momentum J_i to a higher lying level J_f is given by

$$\text{DCS} = (4\pi)^4 \frac{k_f}{2(2J_i+1)k_i} \sum_{M_i M_f \mu_i \mu_f} \left| \left\langle J_f M_f \mu_f \middle| V - U \middle| J_i M_i \mu_i \right\rangle \right|^2 \tag{2}$$

where we have summed over the spins of the incident and scattered electron. The momentum of the scattered electron is k_i in the incident channel and k_f in the final channel. More details concerning the RDW method can be found in [19,22] where we used a similar approximation to calculate DCSs for electron-lead excitation.

4. Results and discussion

As mentioned above, we normalized relative DCSs by using the FSF method which relies on the fact that the GOS tends to the optical oscillator strength (OOS) as the momentum transfer K tends to zero [16,17]. The FSF procedure is used for the normalization at all measured impact energies except at 10 eV where the necessary condition $E > 2.5\omega$ is barely satisfied and ω is the excitation energy of the transition. At this energy we normalized our experimental results to the calculated RDW data at 5°.

The above procedure is defined for the single excitation process where the excitation peak in an energy loss spectrum is fully resolved. The question raised here is how to deal with two unre-