Measurements of differential cross sections for elastic electron scattering and electronic excitation of silver and lead atoms

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Abstract. This paper presents absolute differential cross sections (DCSs) and integrated cross sections (ICSs) for both elastic and inelastic electron scattering by lead and silver atoms in the energy range from 10 to 100 eV. The DCSs were measured as a function of scattering angle. Scattering angles are from 1° to 150° for the excitations of the unresolved $4d^{10}5p \, ^2P_{1/2, 3/2}$ silver line and $6p7s \, ^1P_{0,1}$ lead line, while for the elastic scattering they span from 10° to 150°. The measurements utilize crossed beam technique with effusive atomic beam being perpendicularly crossed by electron beam. Monoenergetic electron beam is obtained by means of hemispherical selector and it is focused by cylindrical electrostatic lenses while effusive atomic beam is formed by heating of Knudsen type oven. Absolute values for the resonance states are obtained by normalization of relative differential cross sections to the optical oscillator strengths, while the absolute values for the elastic scattering are obtained from the intensity ratios at particular scattering angles. Obtained absolute DCSs were extrapolated to 0° and 180° and numerically integrated to yield integral, momentum transfer and viscosity cross sections. The experimental results have been compared with the corresponding calculations.

1. Introduction
Electron interaction with metal atom vapours provides fundamental information on the structure and collisional dynamics of atomic system, as well as information on basic interaction between particles in scattering process. The main observable in these processes is differential cross section (DCS) which indicates the probability of specific interaction at certain electron energy and scattering angle and it is given by:

$$DCS = \frac{k_f}{k_i} |A_\beta|^2$$

where $A_\beta$ is a scattering amplitude and $k_f$ and $k_i$ are wave vectors of scattered and incident particles, respectively. Beside the general importance of both experimental and theoretical collisional electron cross section data for understanding and explanation of fundamental electron interaction with isolated metal atoms, there is also a particular relevance of these results for the biomedical radiation research as well as for many plasma diagnostic and modeling techniques which require electron impact cross sections as input data for the calculation of plasma parameters [1, 2]. Besides this, detailed electron-metal atom collision data are very important in astrophysics for spectra’s analysis, for chemical composition determination of various astrophysical objects and also for its abundance analysis [3-12].
They are essential for determination of transport properties in astrophysical plasmas of some stellar atmospheres and also for modeling of some metal rich stellar atmospheres (atmospheres of some DZ white dwarfs) [13].

In metal atoms, DCS for resonant electron excitation is more pronounced than DCS for elastic scattering. To determine the absolute DCS experimentally, it is necessary to know several parameters [14]. Generally, experimental investigations are often limited by the high working temperature which is necessary to vaporize the metal sample in order to produce a well collimated effusive atomic beam. At the same time, at these temperatures, metal deposition can make contacts between electron lenses, which can induce difficulties during the measurements.

Here we present experimentally obtained absolute differential cross sections (DCSs) for both elastic and inelastic electron scattering by lead and silver atoms as well as corresponding integrated cross sections. The DCSs were measured at intermediate electron impact energies from 10 eV to 100 eV and scattering angles are from 1° to 150° for the combined excitations of the unresolved 4d105p 2P1/2,3/2 silver line and 6p7s 3P0,1 lead line, while for the elastic scattering they span from 10° to 150°. The experimental results have been compared with the corresponding calculations.

2. Experimental technique and procedure

In the crossed beam arrangement where an electron beam has been perpendicularly crossed by the effusive atomic beam, the scattered electrons have been analyzed in the high resolution electron spectrometer ESMA which has been described in our previous papers dealing with electron scattering by other metal targets [15-20].

A hairpin thermod-electron source was used and electron beam was formed by the electron monochromator which consists of systems of cylindrical electrostatic lenses and hemispherical electrostatic energy selector. Scattered electrons were analyzed by the hemispherical electron energy analyzer which is of the same type as the monochromator. It can rotate around the atomic beam axis so we could analyze and detect scattered electrons in the scattering angle range from -30° to 150°. A channel electron multiplier was used as a detector.

A metal vapor beam was produced by heating an oven crucible containing metal by two separate heaters. In this way we separately heated the top and bottom of the oven and provided a variable temperature difference at approximately 100 K. The working temperature was about 1170 K for Pb and 1300 K for Ag and background pressure was of the order of 10⁻⁵ Pa. The overall energy resolution (FWHM) was typically 120 meV for Pb and 160 meV for Ag while the angular resolution was 1.5°.

The position of true zero scattering angle was determined before each angular distribution measurement by checking the symmetry of the inelastically scattered electrons at negative and positive scattering angles (usually from -10° to +10°). The measured angular distributions were converted into relative DCSs by using the appropriate effective length correction factors [21]. The absolute values of differential cross sections for excitation are obtained through the normalization procedure to the optical oscillator strengths (OOS) for the observed transition. Following the method described by Fellli and Msezane [22], we normalized the relative DCSs by using the forward scattering function (FSF) introduced by Avdonina et al. [23]. Due to this procedure which is based on Lassettre limiting theorem and the fact that GOS tends to OOS as momentum transfer squared (K²) tends to zero, relative DCSs were converted to the generalized oscillator strengths according to formula:

\[
GOS(K,E) = \frac{\omega}{2K^2} \frac{k_i}{k_f} DCS(K,\theta)
\]

where \(\omega\) is the excitation energy, \(k_i\) and \(k_f\) are the electron momenta before and after the collision, respectively, and the momentum transfer \(K\) is defined by:
where $E$ is the impact energy. The obtained GOS values were fitted and extrapolated from the small values of $K^2$ obtained from zero scattering angle at each electron impact energy (Eq. 3) and normalized to the FSF. These normalization factors were then used to obtain absolute DCS values. FSF procedure was applied at all energies except at 10 eV for electron silver excitation where the necessary condition $E > 2.5\omega$ is not satisfied ($\omega$ is the excitation energy of the transition). A more detailed description of the normalization procedure has been described in details in our previous papers [15, 24]. Briefly, in the case of lead we generate FSF using the OOS value of 0.21 for the $6p^7s^3P_0,1$ state ($6p^7s^3P_0$ is optically forbidden). In the case of silver, contrary to the case of lead, both unresolved states are optically allowed and have appropriate OOS values so we used the OOS values of 0.452 for the $2P_{3/2}$ level and 0.223 for the $2P_{1/2}$ level. The absolute values for the elastic scattering are obtained from the intensity ratios at particular scattering angles.

Obtained absolute DCSs were extrapolated to $0^\circ$ and $180^\circ$ using the measured values at small scattering angles and corresponding calculations, relativistic distorted wave calculations (RDW) for excitation processes [15, 16] and optical potential calculations for elastic electron scattering [17, 19]. After extrapolation, numerical integration was applied and integral, momentum transfer and viscosity cross sections were derived using formulas

$$ Q_I = 2\pi \int_0^\pi \sigma(\theta) \sin \theta \, d\theta $$

$$ Q_M = 2\pi \int_0^\pi \sigma(\theta) \left[ 1 - \left( 1 - \frac{\omega}{E_0} \cos \theta \right)^{1/2} \cos \theta \right] \sin \theta \, d\theta $$

$$ Q_V = 2\pi \int_0^\pi \sigma(\theta) \left[ 1 - \left( 1 - \frac{\omega}{E_0} \cos^2 \theta \right) \sin \theta \right] \, d\theta $$

where $\sigma$ is the differential cross section (DCS) and $\omega$ is the excitation energy.

### 3. Results

#### 3.1 Electron scattering by lead atom

Both the elastic electron scattering and electron-impact excitation of the unresolved $6p^7s^3P_{0,1}$ levels of Pb atom have been investigated. The measurements at small scattering angles for the resonant $6p^3P_0 \rightarrow 6p^7s^3P_1$ transition in Pb are shown in Figure 1. One can see the normalized generalized oscillator strengths (GOSs) determined through normalizations to the optical oscillator strength using the forward scattering function (FSF) method [24]. It is evident that absolute GOS values for zero scattering angles lie on the FSF curve and also that the normalized GOSs decrease with increasing momentum transfer. At 20 eV we have linear dependence of $K^2$ but this linearity decreases at higher energies.

The absolute DCS values for the $6p^7s^3P_{0,1}$ excitation at 60, 80 and 100 eV electron impact energies are presented in Figure 2 and compared with the relativistic distorted-wave (RDW) calculations using multi-configuration (MCGS) and single-configuration (SCGS) wave functions for the atomic states [16]. The comparison between our experimental data and theoretical results shows that there is excellent agreement in both the shape and magnitude except at 100 eV and scattering angles between
70° and 120° where the experiment gives somewhat smaller values. The good agreement is also evident at small scattering angles (see inset in Figure 2).

**Figure 1.** Generalized oscillator strengths (GOS) for the 6p7s $^3P_1$ state of lead atoms versus momentum transfer squared ($K^2$) at 20, 40, 60, 80 and 100 eV electron-impact energies. The stars show the appropriate minimal values of $K^2$ for zero scattering angle and the solid line represents the forward scattering function (FSF) generated using the optical oscillator strength (OOS) value of 0.21 [24].

**Figure 2.** Differential cross sections for the 6p7s $^3P_{0,1}$ excitation of lead at (a) 60 eV, (b) 80 eV and (c) 100 eV electron impact-energies. Filled circles with error bars denote the present experimental results. The solid line shows DCSs calculated by the MCGS approximation and the dashed line shows the results obtained using the SCGS approximation [16]. In the insets, the low angle parts of DCS are zoomed out.
Figure 3. Generalized oscillator strengths (GOS) for the $4d^{10}5p^2 \, ^2P_{1/2,3/2}$ state of silver atoms versus momentum transfer squared ($K^2$) at 20, 40, 60, 80 and 100 eV electron-impact energies. Labels are the same as for the Fig. 1. The colour solid lines represent corresponding RDW calculations [15].

Figure 4. (a) Integral $Q_I$, (b) momentum transfer $Q_M$, and (c) viscosity cross sections $Q_V$ for electron impact excitation of the $4d^{10}5p^2 \, ^2P_{1/2,3/2}$ state of silver atom. Filled circles with error bars denote the present experimental results while the solid line shows the combined ICSs calculated by the RDW method.
3.2 Electron scattering by silver atom

We have also investigated the electron excitation of the first combined resonant $4d^{10}5p$ state of silver atom as well as the elastic electron scattering by this target [15, 19]. The obtained results for generalized oscillator strengths (GOS) are presented in Figure 3 together with corresponding relativistic distorted wave (RDW) calculations [15] where 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 [25]. Since both unresolved states of silver are optically allowed and therefore they both have the OOS values, we generated FSF using OOS value of 0.675 which was obtained as a sum of the OOS values of the $2P_{1/2}$ (0.223) and $2P_{3/2}$ (0.452) levels of silver [19]. As expected [22], the region of linearity of the GOS values decreases as $E$ increases from threshold. Good agreement between experiment and theoretically obtained GOS results for combined the $4d^{10}5p^2P_{1/2,3/2}$ excitation using RDW calculations verify that our normalization is reliable. At 10 eV electron impact energy where the necessary condition for normalization defined as $E > 2.5\omega$ is not satisfied, we normalized our experimental results to the calculated RDW data.

In Figure 4 we present results for integrated cross sections. As one can see, both experiment and theory predict decreasing of $Q_I$, $Q_M$ and $Q_V$ with increasing incident electron energy and there is a good agreement in shape of ICS curves. At 10 eV and 20 eV theory gives slightly higher ICS values but since the calculated DCSs are higher than the measured ones over the whole angular range this is not surprising.

Figure 5 shows present measured DCSs for elastic electron scattering by silver together with optical potential calculations [19]. There are two sets of calculated results, with (SEPASo) and without (SEPSo) taking into account absorption effects (potential). It is evident that experimental data exhibit the same shape as the theories and that both approximations give very similar results.
4. Conclusion
The elastic and inelastic electron collisions with Pb and Ag atoms have been investigated. We have obtained absolute values for generalized oscillator strengths (GOS), differential cross sections (DCS) and integrated cross sections (ICS) for electron impact excitation of the $4d^{10}5p^2P_{1/2,3/2}$ silver line and the $6p^7s^2P_{0,1}$ lead line, as well as DCSs and ICSs for elastic electron scattering by these targets. Measurements were performed at electron energies of 10, 20, 40, 60, 80 and 100 eV and at scattering angles up to 150°. The measured results were put on the absolute scale using FSF method. Comparisons with corresponding relativistic distorted wave (RDW) calculations for excitation [15, 16, 24] and optical potential calculations for elastic scattering [17, 19] were made. We found reasonably good agreement between experiment and theory. It is known that the data about electron metal atom cross sections are of particularly interest for different applications in many fields such as the astrophysics, biomedicine, plasma physics, surface and material science etc. In order to contribute to research in these areas by getting new reliable results, our future work will be concentrated to the electron interaction with other metal atoms.

5. References

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