Excitation of the $6p7s\ ^3P_{0,1}$ states of Pb atoms by electron impact: Differential and integrated cross sections

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Experimental measurements of electron impact excitation of the $6p7s\ ^3P_{0,1}$ states of Pb atoms have been made at incident electron energies E_0=10, 20, 40, 60, 80, and 100 eV and scattering angles from 10° to 150°. In addition, relativistic distorted-wave calculations have been carried out at these energies. The data obtained include the differential (DCS), integral (Q_I), momentum transfer (Q_M), and viscosity (Q_V) cross sections. Absolute values for the differential cross sections have been obtained by normalizing the relative DCSs at 10° to the experimental DCS values of [S. Milisavljević, M. S. Rabasović, D. Šević, V. Pejčev, D. M. Filipović, L. Sharma, R. Srivastava, A. D. Stauffer, and B. P. Marinković, Phys. Rev. A **75**, 052713 (2007)]. The integrated cross sections were determined by numerical integration of the absolute DCSs. The experimental results have been compared with the corresponding calculations and good agreement is obtained.

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I. INTRODUCTION

Differential cross sections for electron-impact excitation of Pb atoms are of considerable interest in many fields ranging from astrophysics to plasma research. At the same time, these studies lead to insight into the properties of the Pb atomic system and its electronic structure and the mechanisms and basic interactions in the electron-lead scattering process. Studies of electron excitation of Pb atoms have been quite rare and restricted to only a few measurements and theoretical calculations (Ref. [1], and references therein). Recently, we have reported both experimental and theoretical results for the generalized oscillator strengths and differential cross sections for the excitation of the $6p7s\ ^3P_1$ state of lead at 4.375 eV in the intermediate impact electron energy range from 10 to 100 eV and small scattering angles up to 10° [1]. Very good agreement is obtained between measurement and theory especially at higher electron-impact energies. It should be mentioned that reliable data at small scattering angles are important for determining the uncertainty in the normalization procedure and are necessary for the determination of the absolute DCSs at larger scattering angles. In this context, we normalized our present results to the experimental DCS values at 10° from Ref. [1].

In order to obtain a complete set of data on the electron-impact excitation in Pb, we have extended our recent results [1] to intermediate and large scattering angles. We present results of both electron spectroscopy measurements and relativistic distorted-wave (RDW) calculations for the excitation of the $6p^2\ ^3P_0 \rightarrow 6p7s\ ^3P_{0,1}$ transition in Pb by electron impact at medium impact energies up to 100 eV. The measurements were made for scattering angles in the range of 10°–150°. We report absolute DCSs and integral (Q_I), momentum transfer (Q_M), and viscosity (Q_V) cross sections. The comparison between the experimental data and theoretical results are given in Sec. IV below.

II. EXPERIMENTAL TECHNIQUES AND PROCEDURES

The experimental apparatus and procedure used to obtain new inelastic DCS data in the present work are the same as in our previous experiment and they were described in detail in our recent paper [1] so, in the following, only a brief description will be presented. Also, we will emphasize the details relevant for the normalization and determination of absolute differential, integral, momentum transfer, and viscosity cross sections.

A lead vapor beam produced in a specially constructed atomic oven heated by two resistive bifilar heaters is crossed perpendicularly with a monoenergetic incident electron beam. Inelastically scattered electrons were analyzed and detected at fixed impact energies and scattering angles ranging from 10° to 150° by a hemispherical electron energy analyzer with a channel electron multiplier set up for single-electron counting. The angle of the analyzer can be changed from −30° to 150° around the atomic beam axis. Measured scattered intensities were transformed to relative DCSs using the effective path length correction factors [2] determined for the present experimental conditions. The energy scale was calibrated by measuring the position of the feature in the elastic cross section attributed to the threshold energy of the $6p7s\ ^3P_1$ state of Pb at 4.375 eV. The overall system energy resolution [defined as full width at half maximum (FWHM)] was typically 120 meV. The angular resolution was 1.5° and the true zero scattering angle was determined on the basis of the symmetry of the measured signal around the mechanical zero.

The present absolute DCSs were obtained by normalization to the absolute DCS values at 10° [1]. Then, these values were extrapolated to 0° and 180° and numerically integrated in order to determine experimental integrated, momentum

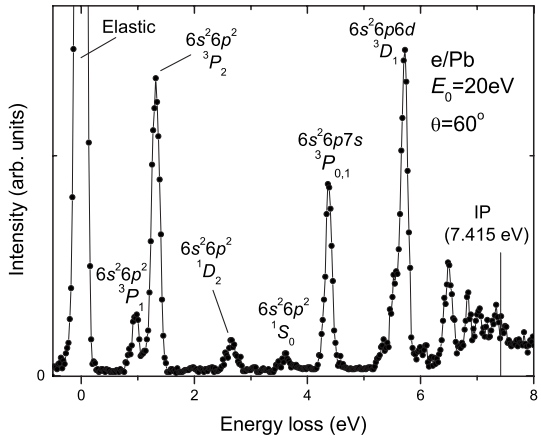

FIG. 1. Energy-loss spectrum of lead at 20 eV electron-impact energy and 60° scattering angle.

transfer and viscosity cross sections, defined as

$$Q_I = 2\pi \int_0^\pi \sigma(\theta) \sin\theta \, d\theta, \tag{1}$$

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

$$Q_V = 2\pi \int_0^\pi \sigma(\theta) \left[1 - \left(1 - \frac{\omega}{E_0} \right) \cos^2\theta \right] \sin\theta \, d\theta, \tag{3}$$

where ω is the excitation energy and σ is the differential cross section (DCS). Extrapolation to 0° was based on our small angle results while extrapolation to 180° was done by fitting the measured values using DCSs calculated in the multiconfiguration ground state approximation (MCGS).

III. CALCULATION METHOD

The details of the RDW calculation method were given in Ref. [1], and references therein. Two sets of wave functions were used in these calculations. The single-configuration ground state (SCGS) uses the minimum spectroscopic configurations containing the $6p$ and $7s$ orbitals in the j-j coupling scheme for the $6p^2\ ^3P_0$ initial state and the $6_p7s\ ^3P_{0,1}$ levels of the final state. In the multiconfiguration ground state (MCGS) calculation we added configurations including the $6d$ and $7p$ orbitals to obtain an accurate value for the optical oscillator strength for the allowed transition to the $J=1$ level. Since the excitation of the $J=0$ level is a forbidden transition, the cross section for this process will be much smaller than the allowed transition (see Discussion below).

IV. RESULTS AND DISCUSSION

Electron-impact excitation of the $6p7s\ ^3P_{0,1}$ levels of the Pb atom have been investigated both experimentally and theoretically. We have measured the angular distribution of electrons inelastically scattered by lead atoms at 10, 20, 40, 60, 80, and 100 eV incident electron energies from 10° to 150°. The relativistic distorted-wave calculations using multiconfiguration (MCGS) and single-configuration (SCGS) wave functions for the atomic states have been performed at the same energies over the whole range of scattering angles. An energy-loss spectrum of lead at an impact energy of 20 eV and scattering angle of 60° in the energy-loss region up to 8 eV is shown in Fig. 1. All atomic energy levels have been assigned according to Moore [3]. At the overall system energy resolution mentioned above, we could not separate the $6p7s\ ^3P_1$ and $6p7s\ ^3P_0$ levels, but the feature that corresponds to the summed $6p7s\ ^3P_{0,1}$ excitations is clearly resolved from the other ones in the spectrum. The spectrum also contains well resolved features that correspond to the elastic scattering (zero energy loss), $6s^26p^2\ ^3P_1$, $6s^26p^2\ ^3P_2$, $6s^26p^2\ ^1D_2$, and $6s^26p^2\ ^1S_0$ states. The profile of the $6s^26p6d\ ^3D_1$ line is not symmetric due to contribution of the

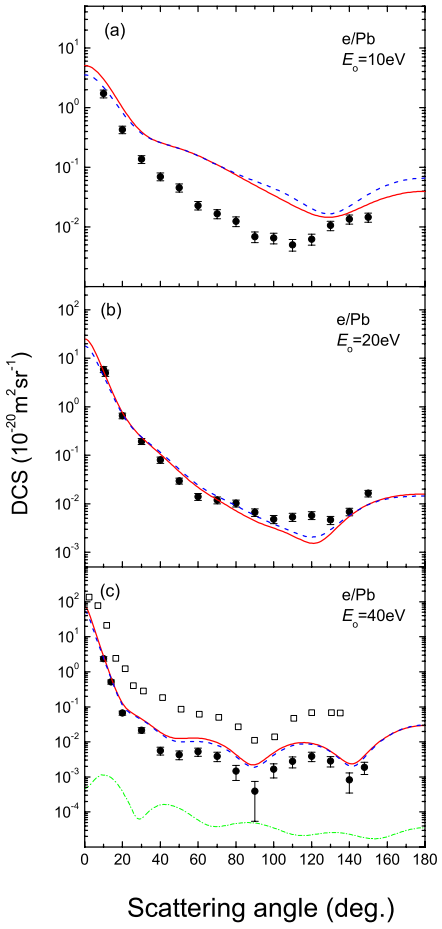

FIG. 2. (Color online) Differential cross sections for the $6p7s\ ^3P_{0,1}$ excitation of lead at (a) 10 eV, (b) 20 eV, and (c) 40 eV electron-impact energies. Filled circles with error bars denote the present experimental results. The solid line shows DCSs calculated by the MCGS approximation and the dashed line shows the results obtained using the SCGS approximation. The open squares represent the results obtained by Williams and Trajmar [6] and the dash-dotted line shows MCGS calculation for the $6p7s\ ^3P_0$ excitation.

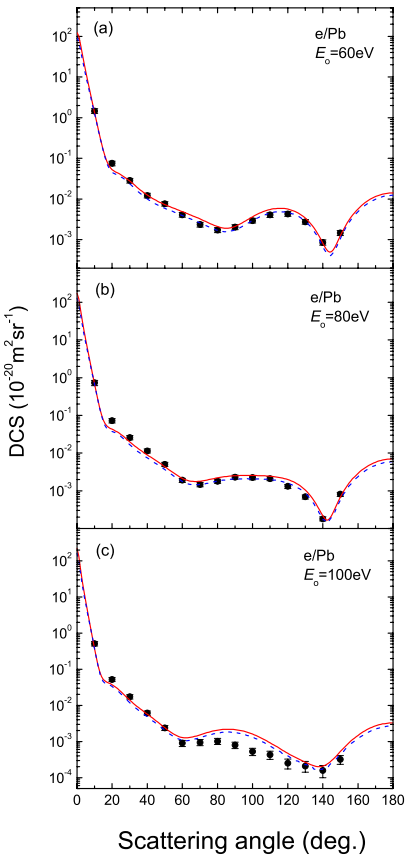

FIG. 3. (Color online) As for Fig. 2 except for (a) 60 eV, (b) 80 eV, and (c) 100 eV electron-impact energies.

$6s^26p6d\ ^3D_2$ state shown as a shoulder at lower energy loss. The features in the energy-loss region from 6 eV to the first ionization potential of 7.4167 eV [4] are not labeled for the sake of clarity.

In Figs. 2 and 3 we present the experimental DCS values together with the results in the RDW approximation using both the SCGS and MCGS wave functions. We note that there is very little difference between the SCGS and MCGS results except at the lowest energy. The experimentally obtained DCSs are also tabulated in Table I. At 10 eV incident electron energy [Fig. 2(a)], the calculated results are higher than the measured ones over the whole angular range. Also, there are slight discrepancies in the DCS shape. While experiment gives one shallow minimum at about 110°, both the MCGS and SCGS calculations predict a minimum at 130°. The reason for the disagreement between obtained experimental and calculated DCSs could be twofold. Firstly, this energy is close to the limit of applicability of the used normalization procedure, which implies that the incident electron energy should be 2.5 times larger than the excitation energy. When applied, this method leads toward lower DCSs, the phenomenon already observed in the case of the excitation of the $3s3p\ ^1P_1$ state of the Mg atom [5]. Secondly, the distorted-wave method is less reliable at impact energies near threshold [1]. In Fig. 2(b) we show our DCS results at 20 eV. Our measured values are in generally good agreement with the present calculations but do not reproduce the minimum at 120° predicted by theory. At 40 eV [Fig. 2(c)], the experimental DCSs are somewhat smaller than the MCGS and SCGS results but their angular dependence is in excellent agreement. Indeed, the calculations completely support our experimental observations of two distinct minima at 90° and

TABLE I. Differential cross sections, in units of 10^{-20} m^2 sr^{-1}, for electron excitation of the $6p7s\ ^3P_{0,1}$ levels of Pb. The numbers in parentheses are absolute errors. The last three lines are integral (Q_I), momentum transfer (Q_M), and viscosity (Q_V) cross sections obtained by integrating our measured DCS in units of 10^{-20} m^2 with absolute errors indicated in parentheses.

Angle (deg)	Electron energy					
	10 eV	20 eV	40 eV	60 eV	80 eV	100 eV
10	1.71(24)	5.91(81)	2.36(32)	1.46(20)	0.73(12)	0.514(65)
11		4.98(72)				
14			0.518(68)			
20	0.425(62)	0.653(90)	0.0669(96)	0.0754(96)	0.0424(92)	0.0525(67)
30	0.136(20)	0.194(27)	0.0215(36)	0.0285(36)	0.0258(33)	0.0174(23)
40	0.069(10)	0.080(11)	0.0056(14)	0.0122(16)	0.0114(14)	0.00615(85)
50	0.0455(70)	0.0298(44)	0.0043(12)	0.00765(98)	0.00504(64)	0.00240(37)
60	0.0229(38)	0.0140(22)	0.0052(14)	0.00412(54)	0.00191(24)	0.00090(17)
70	0.0165(28)	0.0119(19)	0.0039(12)	0.00237(31)	0.00147(19)	0.00095(18)
80	0.0124(22)	0.0102(17)	0.00146(67)	0.00174(24)	0.00180(23)	0.00102(19)
90	0.0068(14)	0.0067(12)	0.00040(34)	0.00205(27)	0.00231(29)	0.00080(16)
100	0.0065(13)	0.00484(93)	0.00166(72)	0.00295(39)	0.00224(28)	0.00053(12)
110	0.0050(11)	0.0054(10)	0.00277(95)	0.00409(53)	0.00211(27)	0.00043(11)
120	0.0062(13)	0.0058(11)	0.0039(11)	0.00433(56)	0.00131(17)	0.000251(77)
130	0.0106(19)	0.00464(89)	0.00286(95)	0.00277(36)	0.000692(88)	0.000211(69)
140	0.0135(24)	0.0069(12)	0.00082(47)	0.00086(12)	0.000181(23)	0.000158(58)
150	0.0145(25)	0.0165(25)	0.00189(72)	0.00147(20)	0.00081(10)	0.000321(86)
Q_I	0.83(25)	2.14(63)	1.42(43)	1.39(42)	1.17(38)	1.00(33)
Q_M	0.34(11)	0.40(12)	0.125(46)	0.103(27)	0.063(18)	0.035(12)
Q_V	0.46(14)	0.61(18)	0.194(66)	0.144(42)	0.095(29)	0.061(20)

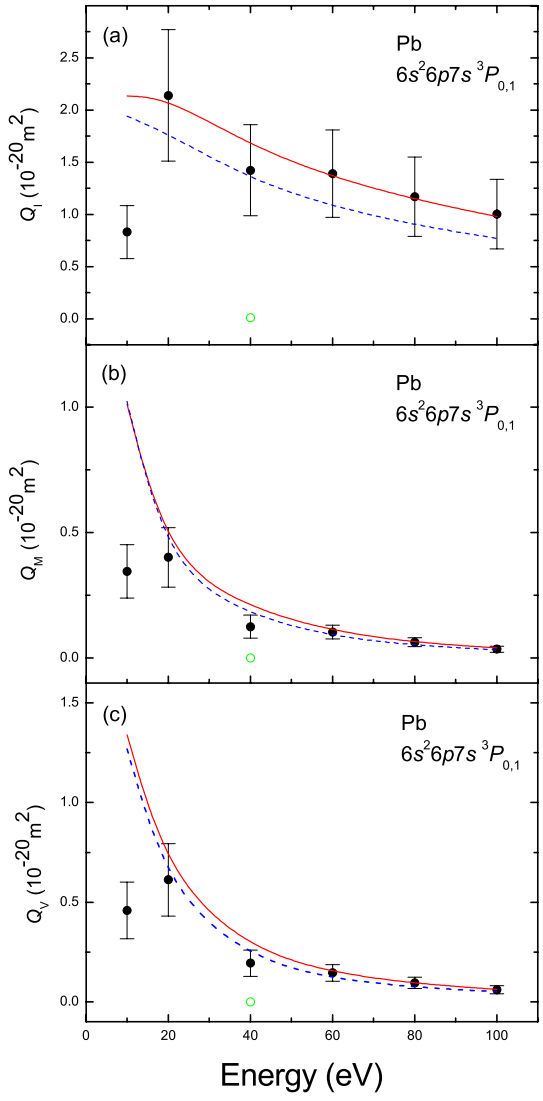

FIG. 4. (Color online) (a) Integral, (b) momentum transfer, and (c) viscosity cross sections for electron-impact excitation of the $6p7s\ ^3P_{0,1}$ states of lead atom. Experiment and theory are as for Fig. 2. Open circles denote MCGS calculations for the $6p7s\ ^3P_0$ excitation.

140° and two inflection points at 20° and 40°. For comparison, we have also included the results for $6p7s\ ^3P_{0,1}$ excitation obtained by Williams and Trajmar [6]. As one can see, their DCSs are significantly higher than our results over the entire range of scattering angle but the shape of their data is very similar to ours. A possible reason for disagreement in absolute values could be the applied normalization procedure. It should be mentioned that previous measurements [6] have been put on an absolute scale using the method based on extrapolating the experimental data, i.e., generalized oscillator strengths (GOSs) down to zero momentum transfer (K^2) and the fact that the value of GOS at $K^2=0$ is equal to the optical oscillator strength (OOS). However, for finite incident energy the zero momentum transfer value is unphysical and the extrapolation is carried out through the unphysical region of scattering angles. Also, this normalization relies entirely on the small scattering angles where it is very difficult to obtain accurate DCS and GOS values. In the present normalization of experimental data values, we have avoided the problem of extrapolation through unphysical region by exploiting the forward scattering function derived by Avdonina *et al.* [7]. Besides these, Williams and Trajmar used the OOS value of 0.25, which is larger than the corresponding OOS value of 0.21 used in our experiment for normalization [1]. We have also carried out MCGS calculations for $6p7s\ ^3P_0$ excitation at 40 eV and the results are included in this figure. It is clear that the contribution of this process to the measured DCSs is much less than the experimental errors. In Fig. 3 we present the DCSs for excitation of the $6p7s\ ^3P_{0,1}$ state at (a) 60 eV, (b) 80 eV, and (c) 100 eV. The comparison between our experimental data and theoretical results shows that there is excellent agreement. The MCGS and SCGS calculations agree very well in shape and magnitude with the measurements across all incident electron energies.

Finally, in Fig. 4 we present results for integrated cross sections. We find good agreement between our theoretical results and experimental Q_I data for $E_0 > 10$ eV [Fig. 4(a)]. Experiment confirms a slow decrease of the Q_I with increasing incident electron energy as is also predicted by theory. But, at the incident electron energy of 10 eV, both the MCGS and SCGS results overestimate the experimentally obtained Q_I. The main reason for this behavior is the fact that, at this energy, the present calculated DCSs are clearly higher than the measured ones over the whole angular range [Fig. 2(a)] but especially at smaller scattering angles, which contribute substantially to the numerical integration. Williams and Trajmar [6] reported Q_I values at 40 eV but this value is not included in Fig. 4 for comparison because it is too large (8.4×10^{-20} m^2) and overestimates both the present experiment and theories. The energy dependences for Q_M and Q_V are very similar [Figs. 4(b) and 4(c)]. Again, our experiment is in agreement with our calculations except at 10 eV. As the impact energy decreases both the MCGS and SCGS cross sections grow rapidly and are significantly higher than our experimental results. We have also presented Q_I, Q_M, and Q_V values for the $6p7s\ ^3P_0$ state at 40 eV obtained using MCGS approximation. It is obvious that these results are significantly smaller, but this behavior is expected since the corresponding DCSs are also smaller.

V. CONCLUSIONS

As an extension of our previous work we have obtained differential and integrated cross sections for the excitation of the combined $6s7p\ ^3P_{0,1}$ levels of lead by electron impact. Measurements have been performed at 10, 20, 40, 60, 80, and 100 eV electron energy and scattering angles from 10° to 150°. Calculations were also carried out for the same energies and all scattering angles. As noted, the agreement between measurement and theory is generally good especially at higher electron-impact energies. It is known that distorted-wave theories are valid primarily at medium and high energies so the disagreement at 10 eV is not surprising since this energy is only slightly more than twice the excitation energy of the measured transition.

In closing, to the best of our knowledge, no previous results have been published for this electron excitation process in Pb atoms. Our data increases the knowledge and understanding of the electronic structure of Pb, and serve as a prelude for further study of this atom, both experimentally and theoretically.

ACKNOWLEDGMENTS

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