

## Electron excitation and autoionisation cross sections for elements of chemically peculiar stars: Study of bismuth

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**Abstract.** Electron impact excitation from the ground state of bismuth atoms has been studied. A beam of electrons was scattered from a beam of atoms and the intensity of scattered electrons was measured for scattering angles up to  $150^\circ$  and incident electron energies of 40 and 60 eV. Obtained intensities were used for the calculation of relative differential cross sections (DCS). In addition, we recorded the energy loss-spectra at different incident electron energies and scattering angles. These spectra were analysed in order to identify the energy levels of bismuth atom below and above (autoionisation) the first ionization limit in electron spectroscopy. The presence of bismuth was confirmed in spectra of the chemically peculiar (CP) magnetic Ap 73 Dra and HR 465 and nonmagnetic Hg-Mn HR 7775 and  $\chi$  Lupi stars. The obtained results for relative DCS and identified autoionised energy levels of bismuth were analysed and compared with previous experimental and theoretical data. The connection between our investigations of bismuth and astrophysical measurements are discussed.

### 1. Introduction

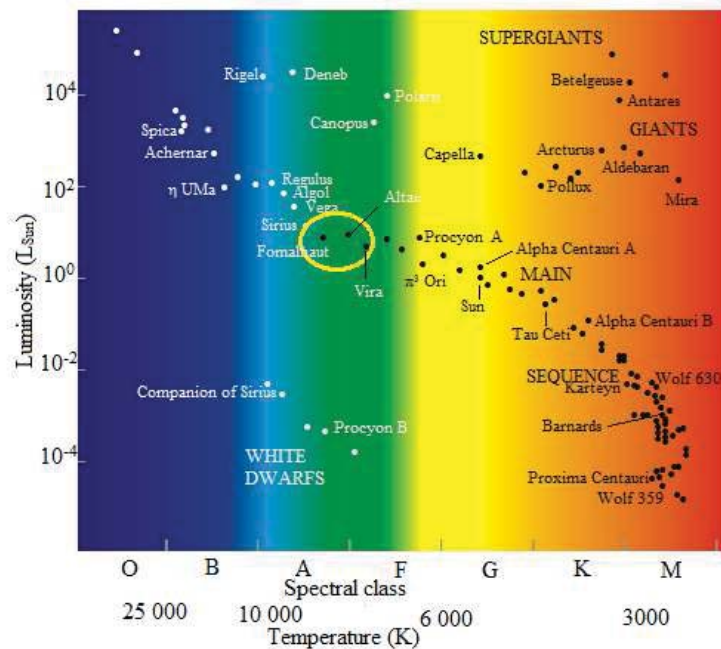
Bismuth is a heavy atom ( $Z=83$ ) that is very interesting subject for investigations in many fields of physics including electron-atom scattering processes and investigation of chemical structure of the stellar atmospheres. The absorption and emission spectra of bismuth, including hyperfine structure, have been the subject of many detailed investigations in both laboratory environment [1-6] and in astronomy observation [7-11].

Only a few papers contain theoretical calculations [12-14] and experimental data [14] of the differential cross sections (DCSs) for elastic and inelastic electron scattering on bismuth atoms. Williams and Trajmar [14] measured DCSs for elastic and inelastic (excitation of the  $6p^3\ ^2D_{3/2}$ ,  $^2D_{5/2}$ ,  $^3P_{1/2}$ , and  $2p^27s\ ^4P_{1/2}$  states) collisions at  $E_0 = 40$  eV and scattering angles from  $0^\circ$  to  $130^\circ$ . The cross sections were normalised to an absolute scale using the optical oscillator strength (OOS) value by Lvov [15] for the  $6p^3\ ^4S_{1/2} \rightarrow 2p^27s\ ^4P_{1/2}$  transition. To our knowledge, no calculations of DCSs exist for the inelastic electron scattering on bismuth atom.

The presence of bismuth features in stellar spectra has been reported in different type of chemically peculiar (CP) stars. The position of CP stars in the Hertzsprung–Russell (HR) diagram is shown in figure 1. Guthrie [7] was the first who has reported and identified the BiI features in magnetic Ap (CP2) star 73 Dra at 472.2 nm. This line corresponds to the  $6p^3\ ^2D_{3/2} \rightarrow 2p^27s\ ^2P_{1/2}$  transition and has



long been known to belong to the emission spectra of bismuth [1]. Two lines of the BiII (139.39 nm, 143.683 nm) were identified from the IUE (International Ultraviolet Explorer) spectrum of the magnetic Ap star HR 465 [9]. Several strong absorption lines due to BiII were observed in nonmagnetic (CP3) Hg-Mn star HR 7775 in high-resolution spectra obtained with the IUE [8]. The HR 7775 is a part of a multiple-star system that includes the bright star HR 7776 (at a distance of 205") and a close companion (the later to lie at a distance of 0.68" from HR 7775). Using high-resolution spectra obtained from the Goddard High Resolution Spectrograph (GHRS) on Hubble Space Telescope (HST) Wahlgren *et al* [10] were able to detect absorption features in spectra of the binary nonmagnetic Ap  $\chi$  Lupi star that contains contributions from AsII and BiII. The strongest transition of BiII in the observed intervals is the  $6p^2\ ^3P_2 \rightarrow 6p7s\ ^3P_1$  transition at 190.23 nm. Its nine hyperfine components were studied by Bouzza and Bauche [16]. Selected lines at 143.683 nm (BiII) and 142.34 nm (BiIII) were studied in the ultraviolet spectrum of the  $\chi$  Lupi [17], with conclusion that the bismuth abundance is only marginally enhanced in this star. Bismuth abundances in HR 7776 and  $\chi$  Lupi stars have been the subject of an extensive study in ultraviolet region of wavelengths by Wahlgren *et al* [18]. In table 1 the summary of the results from this study is given.



**Figure 1.** Approximate position of the chemically peculiar (CP) stars on Hertzsprung–Russell diagram

**Table 1.** Bismuth abundances in HR 7775 and  $\chi$  Lupi,  $\log N_{\text{Bi}}$  includes the Solar system value of 0.7 dex

Wavelength (nm)	Ion	HR 7775	$\chi$ Lupi
143.6	BiII	< 5.5	< 2.3
190.2	BiII	< 6.0	< 2.7
142.3	BiIII	< 6.0	< 1.7

Very good agreement among derived abundances for different lines for HR 7775 star is evident. In contrast, for  $\chi$  Lupi a significant disagreement between abundance of BiII and BiIII was obtained

and an ionisation anomaly is apparent. Dolk *et al* [19] analysed the spectra of HR 7775 recorder by the Nordic Optical Telescope (NOT) in optical region. Fourteen BiII lines were detected in the range from 407.9 to 680.09 nm. The Bismuth abundance was determined using the strongest lines, 514.4 and 520.9 nm. The obtained value of 5.8 is in good agreement with results calculated by Wahlgren *et al* [18].

Line intensities in autoionising spectra of atoms for both "allowed" and "optically forbidden" transitions are of great importance for determination of physical constants in astrophysical plasma. Ionisation processes via autoionisation could be in many cases more important than the direct one. The contribution of core-excited autoionising states to the total ionisation cross section has been in detail examined theoretically by Kim and Stone, in particular for atoms of the IIIA group (boron, aluminium, gallium and indium) [20] and IVA group (silicon, germanium, tin and lead) [21] of the Periodic Table. They found that the core-excited autoionising states contribute significantly to the total ionisation cross sections for all the numbered atoms except for lead.

In this paper we present relative DCS for electron impact excitation of the  $6p^2\ 7s\ ^4P_{1/2}$  state in bismuth at electron impact energies of 40 and 60 eV. In addition, the analysis for the energy loss spectra below and above the first ionisation threshold (autoionisation) is given. The connections between our results and astrophysical measurements are discussed. In section 2, the apparatus is described and the experimental procedure is given. In section 3, results of relative DCS measurements and obtained energy-loss spectra are discussed and presented graphically. Finally, conclusions are formulated in section 4.

## 2. The experiment and procedure

Experimental arrangement used in our measurements is a conventional crossed-beam electron spectrometer described in our previous works [22,23]. The optics of both the monochromator and the analyser are very similar to the one designed by Chutjian [24]. The analyser can be positioned at angles from  $-30^\circ$  up to  $150^\circ$  with respect to the direction of primary electron beam. The electron spectrometer itself can be operated in three different modes: recording of electron energy-loss spectra, scanning incident energy and direct angular distribution measuring of elastically and inelastically scattered electrons. The position of the real zero scattering angle was determined before each angular distribution measurement by checking the symmetry of the scattered electron signal at positive and negative angles, with respect to the un-scattered electron beam. The energy scale was calibrated against the  $3s3p\ ^1P_1$  excitation threshold of Mg at 4.345 eV. Using significantly improved energy resolution (50 meV), we did not find the shift of the energy scale due to contact potential difference between the thoriated tungsten filament (work function of Th 3.4 eV) and magnesium plated (3.66 eV) collision chamber. A channel electron multiplier is used for single-electron counting. The operating condition are summarised in table 2.

**Table 2.** The experimental parameters used in our electron spectrometer

Parameters	Conditions
Impact energy range (eV)	10-100
Energy resolution (meV)	100-150
Uncertainty in energy scale (meV)	300
Angular resolution ( $^\circ$ )	1.5
Uncertainty in angular scale ( $^\circ$ )	0.5
Oven temperature (K)	1000
Metal-vapour pressure (Pa)	10
Oven nozzle aspect ratio ( $\gamma=d/L$ )	0.075
Primary electron current (nA)	10-50
Residual magnetic field in interaction region (double $\mu$ -metal shield) ( $\mu$ T)	< 0.1
Background pressure (mPa)	< 5

The metal-vapour beam source consists of a stainless-steel crucible. The crucible is placed in a stainless-steel cylinder co-axially wrapped with two different resistive bifilar heaters (top and bottom, whose temperatures were monitored with two thermocouples), enabling the top of the source to be at approximately 100 K higher temperature than the bottom. This prevents clogging of the nozzle. An additional outer copper cylinder served as a holder for the helical tube of the water-cooler.

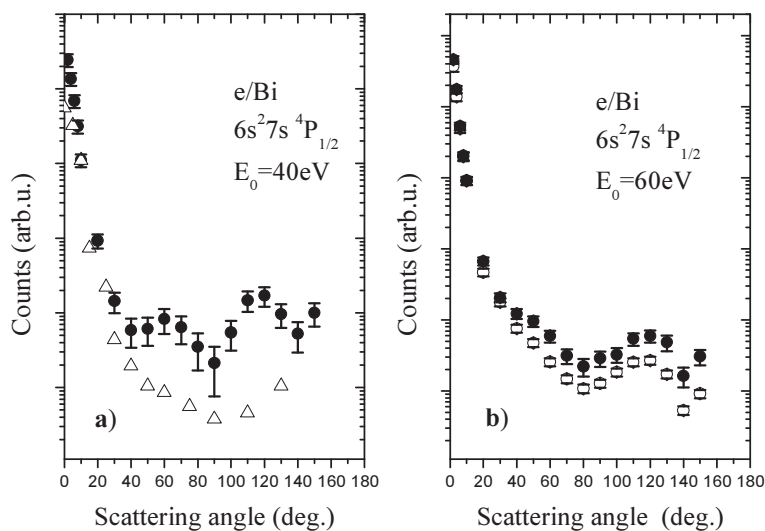
In this work, relative DCSs for electron impact excitation of the  $6p^2 7s \ ^4P_{1/2}$  state from the ground state of bismuth atom are obtained as follows. At a certain incident electron energy and energy-loss ( $\Delta E$ ), the position of the analyser was changed from  $2^\circ$  to  $150^\circ$  and the angular distribution of scattered electron was measured. The scattering intensity was corrected using the effective path-length correction factors according to the approach of Brinkman and Trajmar [25].

The contributions to the total uncertainties of the relative DCSs arise from statistical uncertainties, uncertainty from effective path-length correction factor (0.06), and estimation of the energy (0.01) and angular (0.10) scale.

### 3. Result and discussion

We have measured relative differential cross sections for electron-impact excitation of the  $6p^2 7s \ ^4P_{1/2}$  state of bismuth atom from the ground state at the incident impact energies of 40 and 60 eV and the scattering angle from  $2^\circ$  to  $150^\circ$ . The relative DCSs with total uncertainties are presented graphically in figure 2.

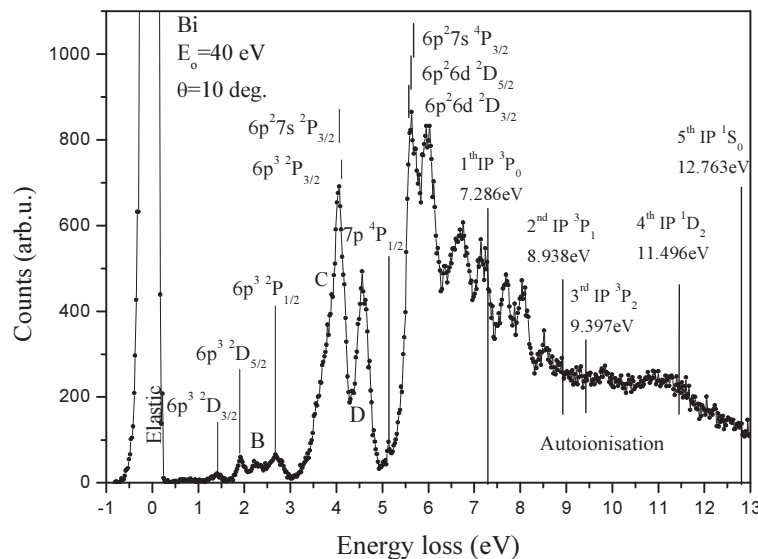
In order to compare in shape the presented DCS at 40 eV electron impact energy with DCS obtained by Williams and Trajmar [14] we normalised their DCS to present DCS at  $10^\circ$ . As one can see in figure 2 the agreement in shape is good up to  $30^\circ$ . At higher scattering angles our DCS have three maxima and two minima; while DCS obtained by Williams et al [14] monotonically decreases up to  $90^\circ$  and after that monotonically increases. For the measured electron impact energy of 60 eV our DCSs show two minima, the first at  $80^\circ$  and the second close to  $140^\circ$ .



**Figure 2.** Relative differential cross sections for electron-impact excitation of the  $6p^2 7s \ ^4P_{1/2}$  state of Bi at **a)** 40 and **b)** 60 eV electron-impact energies. ●, present; △, Williams and Trajmar [14] normalised at present at  $10^\circ$ ; ○, absolute DCS for electron-impact excitation of the  $6p 7s \ ^3P_{0,1}$  state in lead Milisavljević *et al* [26] normalised at present at  $10^\circ$

Generally, present relative DCSs are very similar in shape to DCSs for the excitation of the  $6p7s\ ^3P_{0,1}$  state in lead atom measured by Milisavljević *et al* [26] (see figure 2b). Also, at 60 eV we observe DCSs similar in shape to DCSs for the excitation of the  $6s6p\ ^1P_1$  state of mercury obtained by Panajotović *et al* [27] (not presented here).

We recorded energy-loss spectra at different scattering angles and electron impact energies. Marinković *et al* [22] presented in their study electron energy-loss spectra at 20 and 100 eV while here we present the energy-loss spectrum at the electron impact energy of 40 eV and scattering angle of  $10^\circ$  in the range of energy losses up to 13 eV (see figure 3). Within the literature on BiI the LS system is mostly employed, so we will retain this scheme in our discussion of level structures. Below the  $6p^2\ ^3P_0$  first ionisation limit (7.286 eV) of bismuth, Moore [28] listed 33 levels, which she assigned principally in the series  $6p^2ns\ ^2,4P$  or  $6p^2nd\ ^2D$ , with  $n \leq 10$ . Some of these levels can be recognized in figure 3 and are listed in table 3.



**Figure 3.** Electron energy-loss spectrum of bismuth at 40 eV impact energy and scattering angle of  $10^\circ$ . The ionisation limits (IP) are indicated by vertical lines.

The first detected bismuth lines in spectra of peculiar star 73 Dra at 472.2nm [7] correspond to the transitions between the  $6p^3\ ^2D_{3/2}$  (1.416 eV) and  $6p^27s\ ^4P_{1/2}$  state ( $\Delta E = 2.6247$  eV). Both these states can be seen in figure 3. The search for lines from the BiI spectra of chemically peculiar stars was hampered by line blending and the paucity of strong BiI lines. Wahlgren *et al* [18] tested the presence of two intense lines ( $\lambda = 206.23$  nm and  $\lambda = 227.73$  nm) of BiI in spectra  $\chi$  Lipi star. In order to test the existence of observable BiI lines, synthetic spectra were calculated for the solar abundance and a 5.0 dex enhancement for the  $\lambda = 206.23$  nm line using  $gf = 0.378$  determined by Wiese and Martin [29] was used. A very small difference in blended feature profile resulted from this large enhancement level, indicated that BiI lines in the  $\chi$  Lipi would be noticeable. Nevertheless, none of the strongest BiI lines that were observed in absorption or arc spectra from laboratory measurements were located in the HR 7775 star.

The spectrum shown in figure 3 contains well-resolved features that correspond to low-lying excited  $^2D_{3/2}$ ,  $^2D_{1/2}$  and  $^2P_{3/2}$  states (energy losses of 1.416 eV, 1.914 eV and 2.685 eV respectively) with the  $6s^26p^3$  configuration. Due to the generally lower resolution in electron spectrometry the state  $6s^26p^3\ ^2P_{3/2}$  is not visible. The presence of bismuth dimers could not be avoided. The three features at

2.20 eV, 3.97 eV and 4.52 eV correspond to the optically observed states of Bi<sub>2</sub>. The excited dimer states are labelled as B, C, and D according to Huber and Herzberg [30].

**Table 3.** Electron levels observed in electron energy-loss spectra of bismuth at 40 eV ( $\theta = 10^\circ$ ). Source abbreviation: C, Clearman [3]; A, Assous[4]; M, Mathews *et al* [6]; Moo, Moore [28].

Line No	Energy (eV)	Assignment	Source of data	This experiment (eV)
1	7.348		C	7.34
2	7.537	$6p^2(^3P_1)8s\ J=3/2$	C	7.55
	7.539	$6p^2(^3P_1)8s\ ^4P_{3/2}$	A	
	7.540	$J=3/2$ or $5/2$	M	
	7.540	$6p^2(^3P_1)8s\ J=3/2$	Moo	
3	7.621	$6p^2(^3P_2)6d$	C	7.62
	7.664	$6p^2(^3P_2)6d\ ^4F_{3/2}$	A	
	7.579	-	M	
	7.624	$6p^2(^3P_2)6d\ J=1/2$	Moo	
4	7.776	$6p^2(^3P_2)6d$	C	7.77
	7.777	$6p^2(^3P_2)6d\ ^4D_{3/2}$	A	
	7.779	$6p^2(^3P_2)6d\ J=3/2$	Moo	
5	7.914	$6p^2(^3P_1)8s\ J=5/2$	C	7.89
	7.917	Series B $J=1/2$ or $3/2$	M	
	7.902	$6p^2(^3P_1)8s\ J=1/2$	Moo	
6	7.966	-	C	7.98
	8.051	$6p^2(^3P_1)7d$	A	
	7.969	$J=1/2$ or $3/2$	M	
	7.969	$6p^2(^3P_1)7d\ J=3/2$	Moo	
7	8.135	-	M	8.16
	8.135	$6p^2(^3P_1)9s\ ^2P_{1/2}$	Moo	
8	8.318	$6p^2(^1D_2)7s$	C	8.27
	8.246	$6p^2(^3P_1)9p\ J=1/2$	Mo	
9	8.434	$6p^2(^3P_2)7d$	C	8.43
	8.346	-	M	
	8.410	$6p^2(^3P_1)10s\ ^4P_{3/2}$	Moo	
10	8.634	Series B	M	8.61
	8.570	$6p^2(^3P_1)9s\ ^2P_{3/2}$	Mo	
11	8.875	Series B or D	M	8.88
	8.865	$6p^2(^3P_1)10s\ ^2P_{3/2}$	Moo	
12	9.094	$6p^2(^3P_2)10p$	C	9.09
	9.097	Series X	M	
	9.097	$6p^2(^3P_1)10d\ J=1/2$	Moo	
13	9.264	Series Y	M	9.27
14	-	-	-	9.97
15	-	-	-	11.2

Above the first ionisation limit we identified fifteen autoionising states. These states are listed in table 3. Eleven states are identified between the first and the second ionisation limits, two states between the second and the third and two between the third and the fourth. The assignment of the different series is adopted from [6] and in accordance with the two-limit multichannel quantum defect theory. The two states at 9.97 and 11.2 eV, which have not been observed previously in either photoabsorption or in arc spectra, lie in the energy range between the third and fourth ionisation limits of bismuth atom. The feature at 11.2 eV is very broad (about 0.9 eV half width at full maximum).

#### 4. Conclusion

In this work we have presented relative DCSs for the electron-impact excitation of the  $6p^27s\ ^4P_{1/2}$  state in bismuth. To the best of our knowledge the differential cross sections at 60 eV are reported for the first time. The measured differential cross sections are very similar in shape to the cross sections obtained for the excitation of the  $6p7s\ ^3P_{0,1}$  state in lead. In the autoionising region we have identified



several energy levels up to the fifth ionisation limit. Not many of the BiI lines have been observed in spectra chemically peculiar stars with exception of the 472.2 nm line. In conclusion, our measurements show great similarity between bismuth and lead at least for electron-atom collisions processes which we studied.

## 5. Acknowledgment

This work has been partly supported by the MESTD of the Republic of Serbia under project #OI 171020 and motivated by COST Action CM1301 “Chemistry for Electron-Induced Nanofabrication (CELINA)”.

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