SEARCH FOR RADIATIVE DECAY OF THE 6s6p^2 AUTOIONIZING STATES OF THALLIUM ATOM EXCITED BY ELECTRON IMPACT

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Emission spectra of thallium in the wavelength range of 140–170 nm excited by electron-atom collisions were studied at electron energies from 12 to 100 eV. 13 new lines were revealed in the spectra. Taking into account their intensity behaviour and having analyzed previous data on the 6s6p^2 configuration excitation we have tentatively assigned two of them (at 144.9 and 148.0 nm) to the radiative decay of the autoionizing 6s6p^2 levels. The rest of the lines could probably be attributed to the radiative decay of higher-lying 6s6p*nl* levels.

Introduction

The 6s^{2}6p configuration of thallium atom comprises eight levels. Seven of them lie above the first ionization potential [1]. These levels, excluding two of them with $J={}^5/_2$, are well known from the photoabsorption studies [2]. Four of them were observed in the ejected-electron spectra [3]. A sole experimental observation of radiative transitions from the 6s6p^2 levels was reported earlier in [4]. Four such spectral lines at 130.4, 148.0, 149.0 and 161.0 nm were observed in emission spectrum. They accompanied dielectronic recombination process of thallium ions in collisions with electrons. The present article is devoted to our attempts to reveal radiative decay of the 6s6p^2 autoionizing levels in thallium atom excited by electron impact.

Experiment

The measurements were carried out using an apparatus similar to that described in detail earlier [5]. Briefly, it consisted of a radiation source and a spectral device. The radiation source was based on the method of crossed electronic and atomic beams. As the source of the electron beam, a three-anode electron gun with a ribbon oxide cathode was used in the present experiment. For the output electron energies 10–600 eV the energy spread of the electron beam was about 2 eV and its current density did not exceed the value of 10^{-3} A/cm^2. The atomic beam source was of effusion type with a heater comprising two open molybdenum-wire spirals located close to the crucible. The geometry of the beam was formed by a ”hot” 1.0 mm in diameter and 10-mm long channel made in the crucible cap. The density of the thallium atoms in the interaction region was about 10^{11}-10^{12} at/cm^3. The working pressure of the apparatus was about 5×10^{-7} Torr.

As a spectral device, the vacuum monochromator based on the Seya-Namioka scheme was used. The 1200 lines/mm aluminium-coated toroidal concave grating protected by a MgF_2 layer was mounted in the device. Its meridional and sagittal radii of curvature were 500 and 333 mm, respectively. The computer-controlled stepper motor was employed to rotate the grating of the monochromator by means of a worm gear. The widths of the entrance and exit monochromator slits when recording the spectra were 0.2 mm corresponding to the ~0.32 nm spectral width of the slits. The output photon flux was detected with a solar-blind FEU-142 photomultiplier with CsI photocathode. Its maximal sensitivity wavelength range is shifted to 110–190 nm. The emission spectra were recorded automatically by a computer-controlled data acquisition system with the use of a specially developed software package.

Results and discussion

Thallium spectra in the wavelength range of 140–170 nm at the electron impact energies 12, 14, 16, 23, 26 and 100 eV were obtained. This range was selected to simplify the identification process. Lower and higher wavelength limits were chosen to avoid strong background from the Tl II resonance line 132.2 nm ($6s^2\ ^1S_0 - 6s6p\ ^1P^o_1$) and Tl II intercombination line 190.9 nm ($6s^2\ ^1S_0 - 6s6p\ ^3P^o_1$) which could mask the weaker lines. The wavelength scale was calibrated against the known Tl II line at 149.9 nm ($6p\ ^3P^o_0 - 6d\ ^3D_1$). The determination of spectral line wavelengths was performed with an accuracy of ±0.15 nm.

All the spectra measured are shown in Fig. 1. Dots correspond to the experimental data while solid curves depict the result of 5-point smoothing of the data. Above all, a large number of weak spectral lines which appear in the spectra at the impact electron energies less than 23 eV is evident. They slightly vary in intensity with the incident electron energy increase, but the number of these lines remains the same. With further incident electron energy increase some additional lines appear in the spectra. Taking into account the character of the appearance of the lines in the spectra at different energies and reffering to the data from the spectroscopic tables [6], one can easily identify the lines which dominate at 100 eV. These are Tl II lines at 149.9-nm and 156.2-nm. Their excitation thresholds are about 20.5 eV. In the long wavelength wing of the 156.2-nm line one can see a feature which corresponds to the Tl II line at 156.8 nm. It is not separated because of the poor monochromator resolution. We also clearly observe the Tl III line at 166.0 nm in the 100-eV spectrum.

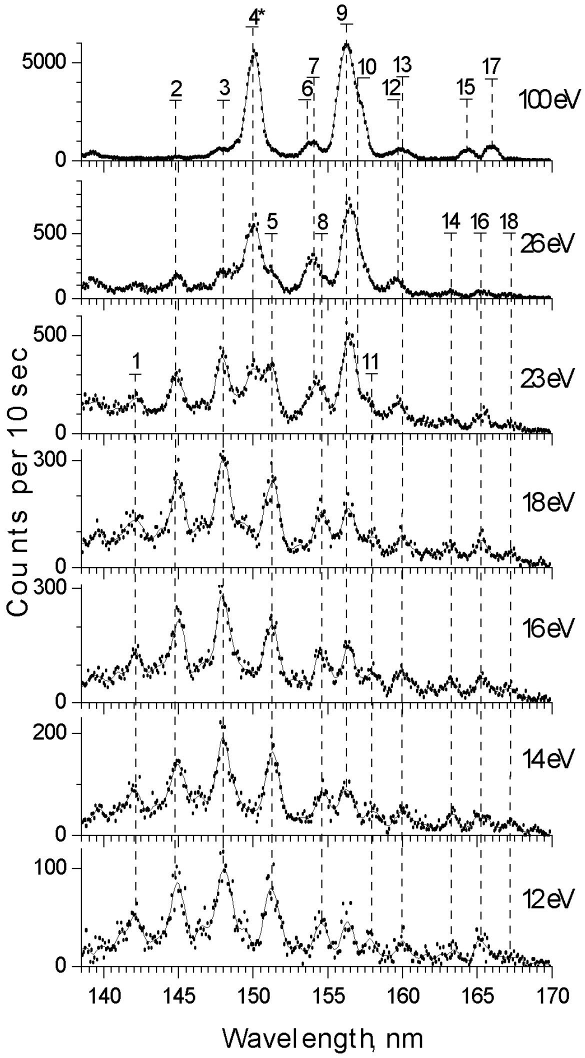

Fig. 1. Thallium photon emission spectra in the wavelength range of 140–170 nm measured at different incident electron energies.

Table 1 presents, where possible, all information on the spectral lines clearly detected, including their wavelengths, impact electron energy values for which the line could be observed, excitation thresholds and assignments. It should be emphasized that we could not identify the unknown lines using the spectroscopic tables, as well as attribute them to the probable impurities such as lead atoms or residual-gas molecules. Most of them could be found in the spectra at 12, 14, 16 and 18 eV. Of the unknown lines the most intense are 144.9, 148.0 and 151.2 nm. We suppose for these lines the excitation thresholds to be less than 12 eV. Thus we relate at least some of these lines to the Tl I level system. One can try to attribute them to radiative transitions from the levels of the lowest autoionizing $6s6p^2$ configuration, all the more so that there is an information on the experimental observation of four emission lines arising from the $6s6p^2$ levels [4].

Table 1.
Wavelengths (λ) and excitation thresholds (E_{exc}) of all lines observed consistently in the emission spectra of thallium in the range 140-170 nm.
Signs "+/-" mark the presence /absence of the lines in spectra.

N	λ, nm	E_{exc}, eV	12	14	16	18	23	26	100	Identification
1	142.0	9.70	+	+	+	+	+	-	-	
2	144.9	9.52	+	+	+	+	+	+	+	Tl I { $6s^26p\ ^2P^o_{3/2} - 6s6p^2\ ^2P_{3/2}$ }
3	148.0	9.36	+	+	+	+	+	+	+	Tl I { $6s^26p\ ^2P_{3/2} - 6s6p^2\ ^2P_{1/2}$ }
4*	149.9	20.51	-	-	-	-	+	+	+	Tl II { $6p\ ^3P^o_0 - 6d\ ^3D_1$ }
5	151.2	11.48	+	+	+	+	+	+	-	
6	153.6	34.48	-	-	-	-	-	-	+	Tl III {$5d^{10}6p\ ^2P^o_{3/2} - 5d^{10}\ (^1S)\ 6p$ }
7	153.9	11.33	-	-	-	-	+	+	+	
8	154.6	8.99	+	+	+	+	+	-	-	
9	156.2	20.54	-	-	-	-	+	+	+	Tl II { $6p\ ^3P^o_1 - 6d\ ^3D_2$ }
10	156.8	20.51	-	-	-	-	+	+	+	Tl II { $6p\ ^3P^o_1 - 6d\ ^3D_1$ }
11	157.8	8.823	+	+	+	+	+	-	-	
12	159.6	11.05	-	-	-	-	-	+	+	
13	160.0	11.03	+	+	+	+	+	+	+	
14	163.2	10.86	+	+	+	+	+	+	-	
15	164.3	10.81	-	-	-	-	-	-	+	
16	165.2	10.79	+	+	+	+	+	+	-	
17	166.0	43.78	-	-	-	-	-	-	+	Tl III { $6s6p7s\ ^2S_{1/2} - 5d^{10}6p\ ^2P^o_{3/2}$}
18	167.2	10.71	+	+	+	+	+	+	-	

* - Calibration point [6]

The difficulties in the identification of the energy levels of the $6s6p^2$ configuration are due to the mixing of the levels which was clarified in [1]. In Table 2, the information about all eight levels of the $6s6p^2$ configuration according to [1] is collected. The last two columns give the wavelengths of the spectral lines (in vacuum) according to their radiative decay to the both ground $6s^26p\ ^2P^o_{1/2,\ 3/2}$ states of thallium.

In the ejected-electron spectra of thallium [3], four lines related to the $6s6p^2$ configuration were found. Three of them are known from the photoabsorption spectra, corresponding to the lines at 161.0, 149.0 and 130.4 nm [1, 2]. The fourth line (the intense line with the ejected-electron energy of 3.23 eV) from the spectra in [3] was identified with the theoretically predicted level [1], but the corresponding line at 132.68 nm (see Table 2) did not appear in the photoabsorption spectra.

Table 2.
Information on the energy levels of the Tl I $6s6p^2$ configuration
and its combinations with the ground levels [1].

LS	Jj	E, cm^{-1}	E, eV	λ_{vac} from $^2P_{1/2}$, nm	λ_{vac} from $^2P_{3/2}$ (7792.7 cm^{-1}), nm
$^4P_{1/2}$	$\left(\frac{1}{2}\frac{1}{2}\frac{1}{2}\right)_{1/2}$	45220	5.607	221.14	267.18
$^4P_{3/2}$	$\left(\frac{3}{2}\frac{1}{2}\frac{1}{2}\right)_{3/2}$	49800	6.174	200.80	238.05
$^4P_{5/2}$	$\left(\frac{3}{2}\frac{1}{2}\frac{1}{2}\right)_{5/2}$	53050	6.577	—	220.96
$^2D_{3/2}$	$\left(\frac{3}{2}\frac{1}{2}\frac{1}{2}\right)_{3/2}$	62112	7.701	161.00	184.10
$^2D_{5/2}$	$\left(\frac{3}{2}\frac{3}{2}\frac{1}{2}\right)_{5/2}$	65063 (theory.)	8.067	—	174.61
$^2P_{1/2}$+$^2S_{1/2}$	$\left(\frac{3}{2}\frac{1}{2}\frac{1}{2}\right)_{1/2}$	67150	8.325	148.92	168.47
$^2S_{1/2}$+$^2P_{1/2}$	$\left(\frac{3}{2}\frac{3}{2}\frac{1}{2}\right)_{1/2}$	75372 (theory)	9.345	132.68	147.97
$^2P_{3/2}$	$\left(\frac{3}{2}\frac{3}{2}\frac{1}{2}\right)_{3/2}$	76805	9.523	130.20	144.90

The width of the lines observed in the photoabsorbtion spectra shows that the main channel of decay of the $6s6p^2$ autoionizing states is electron ejection [2]. That is why the radiative decay of the levels of this configuration could not be intense. At the present time there is no other information on the observation of such lines except [4].

Comparing the experimentally determined wavelengths of the unknown lines from the spectra at different electron impact energies (see Fig. 1) with the calculated wavelength values from Table 2, one can identify two lines at 148.0 and 144.9 nm. Both lines are attributed to the transitions from two higher levels of the $6s6p^2$ configuration to the upper component $^2P_{3/2}$ of the thallium ground state. The line at 148.0 nm was observed as a result of dielectronic recombination in the electron-ion collisions experiment [4] as well as the upper level for the line at 148.0 nm was observed earlier in the ejected-electron spectra [3].

The origin of other unknown lines observed in the spectra could be related to the transitions from highly-excited autoionizing 6s6p7s, 6s6p7p and 6s6p6d configurations to the ordinary $6s^27s$, $6s^27p$ and $6s^26d$ configurations of thallium. According to the calculations of these autoionizing configuration energies, their lower levels should lie in the range of 11–13 eV. Additional information could be obtained after measuring the corresponding excitation thresholds of the above mentioned lines.

Conclusions

Using the electron and atomic crossed beam technique, the emission spectra of thallium were investigated in the wavelength range of 140–170 nm. It was determined that the Tl II and Tl III lines are effectively excited at the incident electron energies above 20.5 eV, and the Tl II lines dominate.

We have found unknown low-intensity lines excited at the energy less than 23 eV. Two of them (148.0 and 144.9 nm) could be related to the radiative decay of the Tl I

$6s6p^2$ configuration. Their initial levels, lying above the ionization potential, decay to the ground $^2P_{3/2}$ -state of thallium. The origin of the other unknown lines could probably be related to the transitions from the highly-excited autoionizing 6s6p7s, 6s6p7p and 6s6p6d configurations to the ordinary $6s^27s$, $6s^27p$ and $6s^26d$ configurations of thallium.

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ПОШУК РАДІАЦІЙНОГО РОЗПАДУ АВТОІОНІЗАЦІЙНИХ СТАНІВ КОНФІГУРАЦІЇ $6s6p^2$ АТОМА ТАЛІЮ ПРИ ЕЛЕКТРОН-АТОМНИХ ЗІТКНЕННЯХ

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Досліджено емісійні спектри талію в діапазоні довжин хвиль 140–170 нм, що збуджуються при електрон-атомних зіткненнях для енергій бомбардуючих електронів від 12 до 100 еВ. У спектрах було виявлено 13 невідомих ліній. Аналізуючи поведінку інтенсивностей цих ліній зі зміною енергії електронів, а також залучаючи наявні дані інших авторів по збудженню $6s6p^2$ конфігурації, ми попередньо приписуємо дві з них (при 144.9 та 148.0 нм) радіаційному розпаду автоіонізаційних рівнів $6s6p^2$-конфігурації. Решту ліній, імовірно, можна віднести до радіаційного розпаду автоіонізаційних рівнів вищих конфігурацій 6s6p*nl*.