



EXCITATION OF ONE-CHARGED TIN ION IN COLLISIONS OF SLOW ELECTRONS WITH TIN ATOMS

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Abstract: Excitation of SnII in *e*-Sn collisions has been studied using the method of extended crossing beams with recording of optical radiation emitted by excited ions. Ninety-one excitation cross sections of SnII spectral lines have been measured at exciting electron energy of 50 eV. Six optical excitation functions have been recorded in the electron energy range of 0 to 250 eV. For eleven SnII spectral series, the excitation cross-section dependence on principal quantum number of upper level is given.

Keywords: cross-section, optical excitation function, extended crossing beams, spectral line, energy level, serial dependence

I. Introduction

Although the melting point of tin being lower than that of copper by $\Delta T = 850^\circ$, saturated vapor pressures of the two metals exhibit only little difference in a wide temperature range. For copper, the stage of laser development boom has seen rather successful empirical attempts at obtaining lasing effect involving several CuI atomic lines as well as multiple CuII single-charged ion transitions (54 CuII lines within the range $\lambda = 248\text{--}2000\text{ nm}$ [1]). Even though tin properties is inferior to copper in a number of aspects, it was similarly possible to produce coherent emission on transitions of singly-charged tin ions. In [1] summarized these knowledge, containing information on nine SnII laser lines within a wavelength range of 558.9 to 1363 nm. Various types of discharges, mostly in pulse mode, have been used to provide excitation for the lasing effect. Besides their use in lasers, various compounds of tin are currently used as phosphors for luminescence. They may be structured as thin films or nanowires produced with the aid of plasma technology. Examples of such compounds include $\text{Ca}_2\text{SnO}_4\text{:Sm}^{3+}$ [2], SnO_2 [3, 4], CsSnI_3 [5], and so on.

As a prerequisite for designing and evaluating lasers based on various active media, as well as diagnosing discharge plasma involving tin compounds, data is needed concerning the properties of elementary processes taking place within the discharge gap or beam plasma. This applies both to emission properties (oscillator forces, transition probabilities) as well as collision properties (cross-sections of various collision types). While the ongoing research into emission constants is presented in numerous publications, studies of collision cross-sections are less representative both in terms of number of works and the amount of data obtained.

A recent paper [6] presents the most exhaustive summary of data on spectrum and electronic structure of a singly-charged tin ion, complementing researchers' own results obtained using a 3 m vacuum spectrograph at Antigonish laboratory (Canada) with a critical review of all preceding experimental and theoretical work. That paper incorporates the most precise and detailed information on wavelengths, level energies, spectral line classifications and transition probabilities for SnII as of mid-2014. A fairly large number of works concerned with determination of SnII transition probabilities are mostly theoretical in nature.

In contrast to studies of A_{ki} , only a single paper [7] has been published so far on experimental study of SnII excitation cross-sections. This paper is based on the extended crossed-beam method whose capabilities and especial features have been discussed in several publications [8–10]. With an incident electron energy of 50 eV, twelve SnII excitation cross-sections have been measured in [7]; three optical excitation functions (OEFs) have been recorded within the electron energy range of 0 to 250 eV. There are no theoretical publications concerned with determination of SnII cross-sections.

In the present work, the recording system has been operated in an optimized mode enabling much more extensive collection of data on SnII excitation cross-sections while maintaining a mode of tin evaporation from the crucible almost identical to that in [7].

II. Main Experimental Conditions

Fundamental bases of the extended crossing-beam method and its technical implementation have been described in sufficient detail in [8–10] sparing us the necessity for repeating this information. We shall only note the basic conditions concerning the tin atom experiment *per se*.

Tin was evaporated from a graphite crucible resting on a heat-insulating lining. An electron beam was used to evaporate the metal, with the power required for evaporation delivered immediately to metal surface. This allowed to keep the crucible at temperatures significantly lower than the temperature in the evaporation zone. This configuration has the dual benefit of extending the operating life of the crucible greatly as well keeping the atomic beam free of contamination with carbides. At an evaporation temperature $T = 1450$ K, tin atom concentration in the intersection zone of atom and electron beams stood at $1.7 \times 10^{10} \text{ cm}^{-3}$. Electron beam current density remained below 1.0 mA/cm^2 throughout the whole working range of electron energies from 0 to 250 eV.

The installation had an effective spectral resolution of about 0.1 nm in the short-wave part of the spectrum, at $\lambda < 600$ nm. It could have been improved down to 0.05 nm for sufficiently intensive lines if necessary. The use of a different monochromator diffraction grating in the longer-wave part of the spectrum, at $\lambda > 600$ nm, has resulted in a deterioration of spectroscopic resolution to 0.2 nm. To ensure proper scaling of absolute cross-section values, the intensity of SnII spectral lines was compared with that of helium atom lines. Helium let into the vacuum chamber in flow-through conditions as a part of a special calibration experiment and also tin atom concentration in the beam was measured. Reference values of excitation cross-sections for helium atom have been sourced from [11].

The ground term of the tin atom $5s^25p^2\ ^3P$ is split into three levels having internal quantum numbers $J = 0, 1, 2$. At temperature indicated above, these levels become populated as a result of thermal excitation. Assuming that a Boltzmann distribution law is correct, the population of ground term levels has been estimated to be distributed as follows (in percentages of total atom concentration in the beam; level energies are indicated in parentheses): $5s^25p^2\ ^3P_0(0) - 58.0$, $5s^25p^2\ ^3P_1(1692) - 32.5$, $5s^25p^2\ ^3P_2(3428) - 9.5$. Presence of this distribution through initial levels must be taken into account when compare the experimental cross-section values with their theoretical counterparts, as partial excitation cross-section values for a concrete upper level there can be a broad divergence under its excitation from lower levels of the same term with different J values. These considerations have been taken into account previously in a number of works by R.K. Peterkop (e.g. for vanadium [12], silicon and germanium [13]).

Relative cross-section values have been measured with an error margin of 5 to 12%, depending on the intensity of lines and their positions within the spectrum. Absolute excitation cross-section values have been determined with a margin of error ranging 20–27%.

III. Results and Discussion

Emission optical spectrum with exciting electron energy of 50 eV has been recorded within a wavelength range of 190 to 850 nm. Spectrograms show spectral lines of tin atom together with those of single-charged tin ion. The latter are located within a spectral range of $\lambda = 204\text{--}790$ nm. Six optical excitation functions (OEFs) have been recorded within an exciting electron energy between excitation threshold and 250 eV.

Measurement results supplemented with necessary spectroscopic data are summarized in Tables 1 and 2. Table

Table I Excitation Cross-Sections of One-Charged Tin Ion (with OEFs recorded)

λ (nm)	Transition	$J_{\text{low}}-J_{\text{up}}$	E_{low} (cm^{-1})	E_{up} (cm^{-1})	Q_{50} (10^{-18} cm^2)	Q_{max} (10^{-18} cm^2)	$E(Q_{\text{max}})$ (eV)	OEF
215.084	$5s^25p\ ^2P^\circ-5s5p^2\ ^4P$	3/2–5/2	4251	50730	} 42.2	43.2	45	6
215.151	$5s^25p\ ^2P^\circ-5s5p^2\ ^4P$	1/2–1/2	0	46464				
226.602	$5s^25p\ ^2P^\circ-5s5p^2\ ^4P$	3/2–3/2	4251	48368	26.6	27.3	46	5
236.823	$5s^25p\ ^2P^\circ-5s5p^2\ ^4P$	3/2–1/2	4251	46464	10.3	10.3	50	4
244.270	$5s5p^2\ ^4P-5s^24f\ ^2F^\circ$	3/2–5/2	48368	89294	0.19	0.19	50	2
259.233	$5s5p^2\ ^4P-5s^24f\ ^2F^\circ$	5/2–5/2	50730	89294	} 0.23	0.24 {	50	2
259.272	$5s5p^2\ ^4P-5s^24f\ ^2F^\circ$	5/2–7/2	50730	89288			35	3
328.314	$5s5p^2\ ^2D-5s^24f\ ^2F^\circ$	3/2–5/2	58844	89294	0.93	0.93	50	2
335.130	$5s5p^2\ ^2D-5s^24f\ ^2F^\circ$	5/2–5/2	59463	89294	0.085	0.085	50	2
335.195	$5s5p^2\ ^2D-5s^24f\ ^2F^\circ$	5/2–7/2	59463	89288	0.91	0.98	35	3
(385.795)	$5s5p^2\ ^4P-5s^26p\ ^2P^\circ$	1/2–3/2	46464	72377	0.036	0.045	32	1
461.824	$5s5p^2\ ^4P-5s^26p\ ^2P^\circ$	5/2–3/2	50730	72377	0.051	0.064	32	1
558.882 ¹	$5s^25d\ ^2D-5s^24f\ ^2F^\circ$	3/2–5/2	71406	89294	0.38	0.38	50	2
579.691	$5s^25d\ ^2D-5s^24f\ ^2F^\circ$	5/2–5/2	72048	89294	0.10	0.10	50	2
579.886	$5s^25d\ ^2D-5s^24f\ ^2F^\circ$	5/2–7/2	72048	89288	0.71	0.77	35	3
645.354 ¹	$5s^26s\ ^2S-5s^26p\ ^2P^\circ$	1/2–3/2	56886	72377	0.93	1.17	32	1
738.717	$5s5p^2\ ^2D-5s^26p\ ^2P^\circ$	3/2–3/2	58844	72377	0.23	0.29	32	1
774.142	$5s5p^2\ ^2D-5s^26p\ ^2P^\circ$	5/2–3/2	59463	72377	0.47	0.6-0	32	1

¹ Laser lines [1]

1 includes lines for which optical excitation functions have been recorded. This table indicates wavelengths λ , transitions, internal quantum numbers for the lower J_{low} and upper J_{up} levels, energies of the lower E_{low} and upper E_{up} levels, excitation cross-sections at exciting electron energy of 50 eV Q_{50} and at OEF maximum Q_{max} , and the position of the maximum $E(Q_{\text{max}})$. Numbers in the OEF column correspond to curve numbers in Fig. 1.

Figure 1 Optical excitation functions of SnII

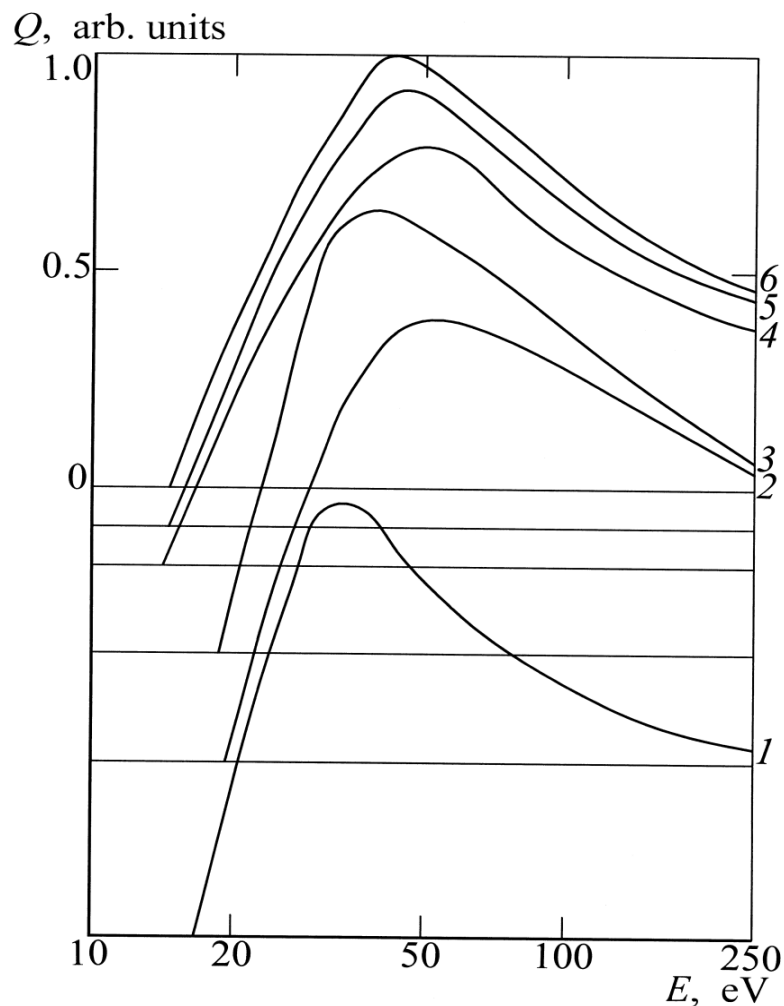


Table II Excitation cross-sections of one-charged tin ion (without OEF's recorded)

λ (nm)	Transitions	$J_{\text{low}}-J_{\text{up}}$	E_{low} (cm ⁻¹)	E_{up} (cm ⁻¹)	Q_{50} (10 ⁻¹⁸ cm ²)
1	2	3	4	5	6
(204.305)	$5s5p^2\ ^4P-5s^25f^2F^\circ$	5/2-7/2	50730	99660)	0.16
(210.345)	$5s5p^2\ ^2D-5s^29p\ ^2P^\circ$	3/2-3/2	58844	106370)	0.10
225.573	$5s^26s\ ^2S-5s^28p\ ^2P^\circ$	1/2-1/2	56886	101204	0.12
229.629	$5s5p^2\ ^4P-5s^27p\ ^2P^\circ$	3/2-1/2	48368	91903	0.11
234.982 ²	$5s5p^2\ ^2D-5s^28p\ ^2P^\circ$	3/2-3/2	58844	101387	0.24
236.000	$5s5p^2\ ^2D-5s^28p\ ^2P^\circ$	3/2-1/2	58844	101204	} 0.10
236.028	$^2D-5s5p(^1P^\circ)5d^2D^\circ$	5/2	90351	132707	
238.456	$5s5p^2\ ^2D-5s^28p\ ^2P^\circ$	5/2-3/2	59463	101387	0.16
243.348 ³	$5s^26p\ ^2P^\circ-5s^211d\ ^2D$	1/2-3/2	71493	112574	0.14
244.891	$5s5p^2\ ^2D-5s^25f^2F^\circ$	3/2-5/2	58844	99666	0.23
(248.561)	$5s^26p\ ^2P^\circ-5s^211d\ ^2D$	3/2-5/2	72377	112596)	} 0.60
248.664	$^2D-5s^25f^2F^\circ$	5/2-5/2	59463	99666	
248.697	$5s5p^2\ ^2D-5s^25f^2F^\circ$	5/2-7/2	59463	99660	
252.269	$5s^26p\ ^2P^\circ-5s^210d\ ^2D$	1/2-3/2	71493	111122	0.12
253.895	$5s^25d\ ^2D-5s5p(^3P^\circ)6s\ ^4P^\circ$	3/2-3/2	71406	110777	0.11
(254.988)	$5s^26p\ ^2P^\circ-5s^211s\ ^2S$	1/2-1/2	71493	110699)	0.086

1	2	3	4	5	6
257.915	$5s^26p\ ^2P^\circ-5s^210d\ ^2D$	3/2-5/2	72377	111143	0.22
260.874	$5s^26p\ ^2P^\circ-5s^211s\ ^2S$	3/2-1/2	72377	110699	0.12
264.356 ⁴	$5s^25d\ ^2D-5s^210p\ ^2P^\circ$	3/2-1/2	71406	109222	0.12
266.499	$5s^26p\ ^2P^\circ-5s^29d\ ^2D$	1/2-3/2	71493	109006	0.20
271.186	$5s^26p\ ^2P^\circ-5s^210s\ ^2S$	1/2-1/2	71493	108357	0.11
272.776	$5s^26p\ ^2P^\circ-5s^29d\ ^2D$	3/2-5/2	72377	109025	0.27
277.849	$5s^26p\ ^2P^\circ-5s^210s\ ^2S$	3/2-1/2	72377	108357	0.15
282.551	$5s^26s\ ^2S-5s^27p\ ^2P^\circ$	1/2-3/2	56886	92268	0.28
(285.487	$5s^26s\ ^2S-5s^27p\ ^2P^\circ$	1/2-1/2	56886	91903)	0.19
286.861	$5s^25d\ ^2D-5s^29p\ ^2P^\circ$	3/2-1/2	71406	106256	0.10
291.282	$5s^25d\ ^2D-5s^29p\ ^2P^\circ$	5/2-3/2	72048	106370	0.16
291.986	$5s^26p\ ^2P^\circ-5s^28d\ ^2D$	1/2-3/2	71493	105731	0.25
294.954	$5s^26d\ ^2D-5s5p(^3P^\circ)5d\ ^4P^\circ$	5/2-3/2	90351	124245	0.18
299.099	$5s5p^2\ ^2D-5s^27p\ ^2P^\circ$	3/2-3/2	58844	92268	0.18
299.446	$5s^26p\ ^2P^\circ-5s^28d\ ^2D$	3/2-5/2	72377	105762	0.32
301.241	$5s^26p\ ^2P^\circ-5s^29s\ ^2S$	1/2-1/2	71493	104678	0.14
302.392	$5s5p^2\ ^2D-5s^27p\ ^2P^\circ$	3/2-1/2	58844	91903	0.16
304.744	$5s5p^2\ ^2D-5s^27p\ ^2P^\circ$	5/2-3/2	59463	92268	0.24
309.468	$5s^26p\ ^2P^\circ-5s^29s\ ^2S$	3/2-1/2	72377	104678	0.20
335.496	$5s^25d\ ^2D-5s^28p\ ^2P^\circ$	3/2-1/2	71406	101204	0.056
340.741	$5s^25d\ ^2D-5s^28p\ ^2P^\circ$	5/2-3/2	72048	101387	0.19
347.233	$5s^26p\ ^2P^\circ-5s^27d\ ^2D$	1/2-3/2	71493	100284	0.30
353.747	$5s^25d\ ^2D-5s^25f\ ^2F^\circ$	3/2-5/2	71406	99666	0.052
357.533	$5s^26p\ ^2P^\circ-5s^27d\ ^2D$	3/2-5/2	72377	100338	0.39
358.235	$5s^26p\ ^2P^\circ-5s^27d\ ^2D$	3/2-3/2	72377	100284	0.063
361.268	$5s^27s\ ^2S-5s5p(^3P^\circ)6s\ ^2P^\circ$	1/2-1/2	86280	113952	0.047
361.996	$5s^25d\ ^2D-5s^25f\ ^2F^\circ$	5/2-5/2	72048	99666	} 0.083
362.049	$\ ^2D-5s^25f\ ^2F^\circ$	5/2-7/2	72048	99660	
370.510	-	-	-	-	0.041
371.515	$5s^26p\ ^2P^\circ-5s^28s\ ^2S$	1/2-1/2	71493	98402	0.13
384.138	$5s^26p\ ^2P^\circ-5s^28s\ ^2S$	3/2-1/2	72377	98402	0.18
(405.534	$5s5p^2\ ^2P-5s^29p\ ^2P^\circ$	3/2-3/2	81718	106370)	0.025
411.03	$5s^24f\ ^2F^\circ-5s^210g\ ^2G$	7/2-7/2,9/2	89288	113610	0.018
411.13	$5s^24f\ ^2F^\circ-5s^210g\ ^2G$	5/2-7/2	89294	113610	0.013
(428.904	$5s^24f\ ^2F^\circ-5s^211d\ ^2D$	7/2-5/2	89288	112596)	0.020
429.327	$5s^24f\ ^2F^\circ-5s^29g\ ^2G$	7/2-7/2,9/2	89288	112574	0.026
429.433	$5s^24f\ ^2F^\circ-5s^29g\ ^2G$	5/2-7/2	89294	112574	0.018
457.37	$5s^24f\ ^2F^\circ-5s^210d\ ^2D$	7/2-5/2	89288	111143	0.031
457.906	$5s^24f\ ^2F^\circ-5s^28g\ ^2G$	7/2-7/2,9/2	89288	111120	0.045
458.022	$5s^24f\ ^2F^\circ-5s^28g\ ^2G$	5/2-7/2	89294	111120	0.034
479.207	$5s^25d\ ^2D-5s^27p\ ^2P^\circ$	3/2-3/2	71406	92268	0.047
487.721	$5s^25d\ ^2D-5s^27p\ ^2P^\circ$	3/2-1/2	71406	91903	0.19
491.71	$5s^27p\ ^2P^\circ-5s^211d\ ^2D$	3/2-5/2	92268	112596	0.11
494.426	$5s^25d\ ^2D-5s^27p\ ^2P^\circ$	5/2-3/2	72048	92268	0.26
(497.624	$5s^27s\ ^2S-5s^29p\ ^2P^\circ$	1/2-3/2	86280	106370)	0.027
507.109	$5s^24f\ ^2F^\circ-5s^27g\ ^2G$	7/2-7/2,9/2	89288	109002	0.078
507.262	$5s^24f\ ^2F^\circ-5s^27g\ ^2G$	5/2-7/2	89294	109002	0.052
(529.649	$5s^27p\ ^2P^\circ-5s^210d\ ^2D$	3/2-5/2	92268	111143)	0.13
533.234	$5s^26p\ ^2P^\circ-5s^26d\ ^2D$	1/2-3/2	71493	90241	0.59
556.191	$5s^26p\ ^2P^\circ-5s^26d\ ^2D$	3/2-5/2	72377	90351	0.77
559.626	$5s^26p\ ^2P^\circ-5s^26d\ ^2D$	3/2-3/2	72377	90241	0.12
596.584	$5s^27p\ ^2P^\circ-5s^29d\ ^2D$	3/2-5/2	92268	109025	0.15
607.763	$5s^24f\ ^2F^\circ-5s^26g\ ^2G$	7/2-7/2,9/2	89288	105737	0.14
607.977	$5s^24f\ ^2F^\circ-5s^26g\ ^2G$	5/2-7/2	89294	105737	0.10
642.84	$5s^28s\ ^2S-5s5p(^3P^\circ)6s\ ^2P^\circ$	1/2-1/2	98402	113952	0.26
(661.759	$5s^27s\ ^2S-5s^28p\ ^2P^\circ$	1/2-3/2	86280	101387)	0.039
(669.882	$5s^27s\ ^2S-5s^28p\ ^2P^\circ$	1/2-1/2	86280	101204)	0.028
676.081	$5s^26p\ ^2P^\circ-5s^27s\ ^2S$	1/2-1/2	71493	86280	0.22
684.419 ¹	$5s^26s\ ^2S-5s^26p\ ^2P^\circ$	1/2-1/2	56886	71493	0.63
719.078 ¹	$5s^26p\ ^2P^\circ-5s^27s\ ^2S$	3/2-1/2	72377	86280	0.39
723.005	$5s^27p\ ^2P^\circ-5s^28d\ ^2D$	1/2-3/2	91903	105731	0.13
740.822	$5s^27p\ ^2P^\circ-5s^28d\ ^2D$	3/2-5/2	92268	105762	0.18
790.353	$5s5p^2\ ^2D-5s^26p\ ^2P^\circ$	3/2-1/2	58844	71493	0.28

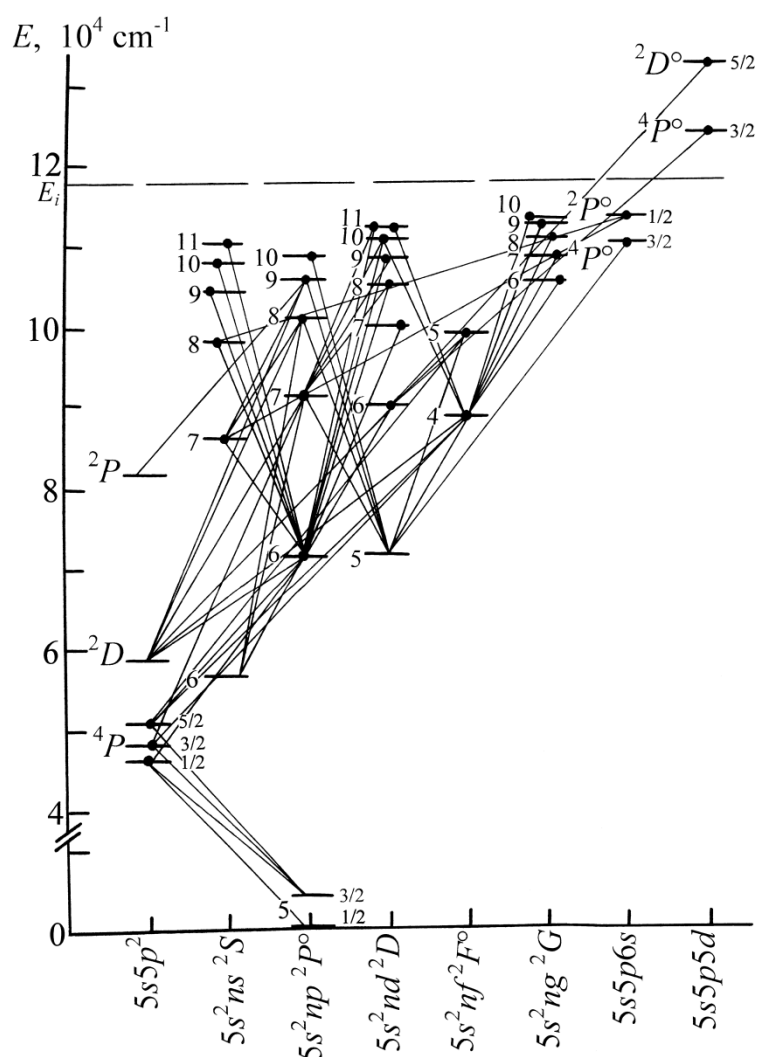
¹ Laser lines [1], ² Possible contribution of SnII line $\lambda = 235.070$ nm, ³ Possible blend of SnI line $\lambda = 243.34769$ nm

Reference values of wavelengths, transitions, J and energy levels have been sourced from [6]. Lines for which reliable OEF recording turned out impossible are listed in Table 2; Table 2 differs from Table 1 by absence of three last columns.

It can be seen in Tables 1 and 2 that, in the case of excitation with simultaneous ionization, in aforesaid spectral range the maximum cross-section values for collisions of electrons with tin atoms take place at levels of displaced quartet term $5s5p^2^4P$. Excitation of this term from initial levels of the tin atom ground term $5s^25p^2^3P$ results from removal of a single equivalent $5s$ electron. Excitation cross-sections of the lowest odd terms, $5s^26p^2P^\circ$ and $5s^24f^2F^\circ$, are smaller then preceding by more than a decimal order of magnitude. In this case, excitation occurs as a result of detaching one of equivalent $5p$ electron while another $5p$ electron becomes excited in $5p \rightarrow 6p$ and $5p \rightarrow 4f$ transitions. Inasmuch as electron shell parity becomes changed in both last cases, such processes are more likely to occur than excitation of even terms of SnII whose energies are quite close to those of $5s^26p^2P^\circ$ and $5s^24f^2F^\circ$. However it should be noted that the excitation of resonant SnII transitions from even levels was not in the scope of our study, as such transitions would lie in the vacuum UV part of the spectrum beyond the operating range of our instruments.

Fig. 2 shows a state diagram for a single-charged tin ion with transitions investigated in this paper. J -splitting is only shown for two lowest-lying terms, $5s^25p^2^2P^\circ$ and $5s5p^2^4P$, where it is large enough ($\Delta E > 1000 \text{ cm}^{-1}$) to be visible without distorting energy scale. The most intensive resonant transitions from single-electron excitation levels $5s^2ns^2S$, $5s^2nd^2D$, as well as transitions from displaced terms $5s5p^2^2S$, $5s5p^2^2P$, $5s5p^2^2D$ are not shown in Fig. 2 as all these levels have energies $E > 55000 \text{ cm}^{-1}$ so that resonant transitions originating there would belong to the vacuum UV part of the spectrum – inaccessible to our instruments.

Figure 2 State diagram of one-charged tin ion with transitions investigated



A dashed horizontal line in the upper part of Fig. 2 represents the first ionization limit $E_i = 118023.7 \text{ cm}^{-1}$ [6]. As far as possible, labels denoting states have been placed below the abscissa axis. This applies first of all to configuration labels. When several terms exist for the same configuration, term symbols are placed within the

plot area. Values of the principal quantum number n for normally excited $5s^2nl\ ^2L$ states are indicated in the plot area to the left of levels. For two low-lying terms mentioned in the previous paragraph, J values are indicated to the right of levels. J values are also indicated for four high-lying levels belonging to displaced terms as each of these terms is represented in Table 2 only by a single level.

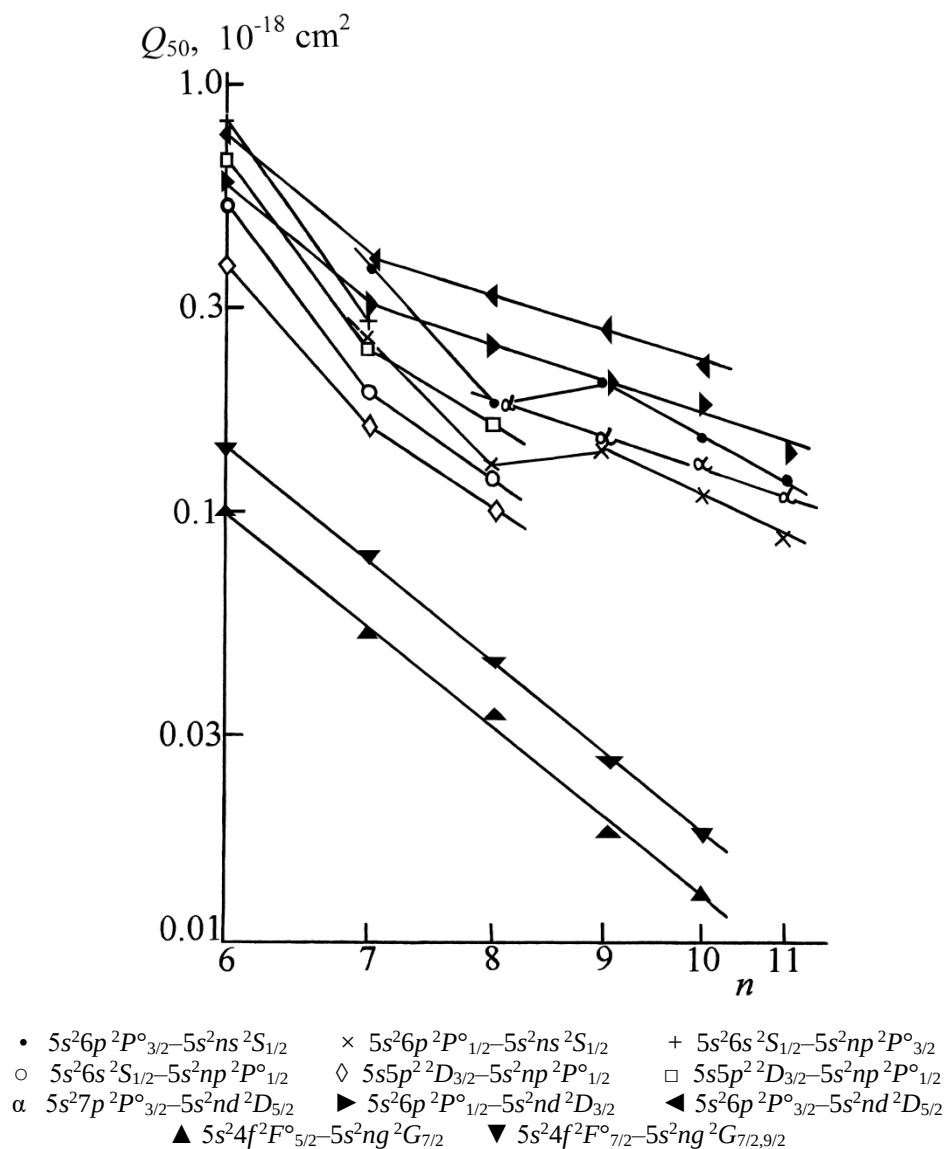
As Fig. 2 shows, a sizeable part of transitions occurs in SnII spectrum as spectral series. A similar phenomenon is observed with indium atom which is isoelectronic with a singly charged tin ion. In many preceding papers (e.g. [9], [14–16]) have so far studied the behavior of excitation cross-sections in spectral series as a function of the principal quantum number of upper levels $Q = f(n)$. For unperturbed series, this was found to be a power function of the form

$$Q = A_i \times n^{-\alpha_i}, \quad (1)$$

where A_i and α_i are constants having characteristic values for individual spectral series. The introduction of perturbation produces the following particular consequences: 1) a deviation of the function $Q = f(n)$ from the formula (1); 2) a different branching behavior; 3) a different OEF form.

Fig. 3 shows the function $Q = f(n)$ for several SnII series. When a logarithmic scale is used for both axes, the relationship (1) will be plotted as a straight line. As Fig. 3 shows, this is entirely true only for G series, as well as $5s^27p\ ^2P^{\circ}_{3/2} - 5s^2nd\ ^2D_{5/2}$ series. These three series occur as a result of excitation of levels lying sufficiently high. For the remaining series inclusive transitions from lower-lying levels with $n = 6$, there is an upward deviation from the power law in the initial section. Cascade population of these levels is viewed as the most likely cause for such a behavior. For that reason, Table 3 listing numerical values of A_i and α_i has been limited to only include those ranges within series where cross-section values still observe the power law in the $\Delta n \geq 2$ area.

Figure 3 Serial dependence of excitation cross-sections on the principal quantum number of upper level:



It can be seen in Table 3 that α_i values – the primary properties of serial dependences – only exhibit minimal differences in each of series with upper levels ^2S , ^2D , ^2G . At the same time, when the behavior of ^2S series is considered in Fig. 3, a significant deviation at $n = 8$ from power law becomes noticeable. Such a deviation may arise owing to the presence of perturbation. However, according to the data from [6], levels $5s^2ns\ ^2S_{1/2}$ with $n = 7, 8, 9$ are not mixed as they are comprised exclusively by 100% main component. Moreover, the only known SnII level with the potential of causing perturbation in $5s^2ns\ ^2S_{1/2}$ levels is the displaced level $5s5p^2\ ^2S_{1/2}$. However, its energy $E = 75954.3\text{ cm}^{-1}$ places it much closer to the $5s^27s\ ^2S_{1/2}$ level than to $5s^28s\ ^2S_{1/2}$. It is likely that this matter can only be clarified by competent theoretical treatment.

Table III A_i and α_i values for spectral series of SnII*

Series	n	α_i	$A_i\text{ (cm}^{-2}\text{)}$
$5s^26p\ ^2P^\circ_{1/2}-5s^2ns\ ^2S_{1/2}$	9–11	2.41	2.80 -17
$5s^26p\ ^2P^\circ_{3/2}-5s^2ns\ ^2S_{1/2}$	9–11	2.54	5.26 -17
$5s^26p\ ^2P^\circ_{1/2}-5s^2nd\ ^2D_{3/2}$	7–11	1.68	7.90 -18
$5s^26p\ ^2P^\circ_{3/2}-5s^2nd\ ^2D_{5/2}$	7–10	1.61	8.92 -18
$5s^27p\ ^2P^\circ_{3/2}-5s^2nd\ ^2D_{5/2}$	8–11	1.55	4.52 -18
$5s^24f^2F^\circ_{5/2}-5s^2ng\ ^2G_{7/2}$	6–10	3.99	1.29 -16
$5s^24f^2F^\circ_{7/2}-5s^2ng\ ^2G_{7/2,9/2}$	6–10	4.01	1.89 -16

* $2.80\text{ -}17 = 2.80 \times 10^{-17}$

Radiative transition probabilities are a matter of great relevance for studies of optical spectra as they determine The relationship between intensities of spectral lines. However, the currently attainable precision of the respective values yield to the precision of wavelength and level energy measurements by several decimal orders of magnitude. This remark applies fully to the determination of radiative constants in the SnII spectrum. Table 4 summarizes properties that define relative SnII spectral line intensities for transitions from three levels: 72377, 89288 and 89294 cm^{-1} . It is worth noting that the intensity ratio is independent of excitation conditions only for those transitions that have a common upper level. At the same time, excitation cross-sections of spectral lines Q , spontaneous transition probabilities A and oscillator forces f are related to each other:

$$Q \sim A \sim gf/\lambda^2, \quad (2)$$

where $g = 2J + 1$ is the statistical weight of the upper level.

It is evident that even for the most intensive lines indicated in Table 4 is absent adequate agreement between A_{ki} values. Not only does this conclusion apply to correlation of experimental and theoretical results, it is also valid within individual sets of experimental or theoretical values. It is likely that A_{ki} values for the majority of SnII spectral lines are most adequately identified in [6] thanks to a thorough survey of the entire corpus of available data on SnII transition probabilities.

Table IV Retrieve data on the A_{ki} and f_{ik} values for one-charged tin ion

Upper level	$E_{up}\text{ (cm}^{-1}\text{)}$	$\lambda\text{ (nm)}$	I		A_{ki}		(10^7 c^{-1})					f_{ik}			
			[1]	[2]	[1]	[2] ¹	[3, 4]	[5]	[6] _{exper}	[6] _{theor}	[7]	[7] _{RHF}	[8] _{ab}	[8] _{fit}	[8] _{fitv}
$5s^25p\ ^2P^\circ_{7/2}$	72377	385.795	-	-	-	-	-	-	-	-	0.00	0.00	2.0 -5	1.8 -5	5.9 -6
		461.824	90	-	0.064	-	-	0.054	0.059	0.045	0.096	2.0 -3	1.5 -3	1.4 -3	1.2 -3
		645.354	2500	70	7.0	12.0	12.1	6.6	5.2	8.0	7.6	9.5 -1	8.9 -1	8.8 -1	8.7 -1
		738.717	480	10	0.23	-	-	-	-	-	0.33	2.7 -2	1.8 -2	1.9 -2	1.8 -2
		774.142	500	13	1.9	-	-	-	-	-	2.6	1.6 -1	1.1 -1	1.1 -1	1.0 -1
$5s^24f^2F^\circ_{5/2}$	89294	244.270	5700	-	0.024	-	-	-	0.13	-	0.55	7.0 -4	3.6 -4	3.2 -4	2.9 -4
		328.314	15000	50	17.0	10.0	10.0	6.8	6.3	17.4	24.9	6.0 -1	4.0 -1	4.1 -1	4.0 -1
		335.130	13000 ²	-	1.2	10.0 ³	-	-	5.7	1.2	1.7	2.9 -2	2.0 -2	2.0 -2	2.0 -2
		558.882	2600	25	7.8	8.5	8.7	11.0	6.7	10.8	5.8	4.1 -1	5.4 -1	5.4 -1	5.4 -1
		579.691	490	1	0.51	2.8	2.8	1.0	0.87	0.75	0.38	1.9 -2	2.5 -2	2.6 -2	2.6 -2
$5s^24f^2F^\circ_{7/2}$	89288	335.195	13000	60	18.2	-	10.0	6.1	6.0	18.3	24.9	5.6 -1	4.0 -1	4.2 -1	4.0 -1
		579.886	2700	15	7.7	8.1	8.1	7.4	8.1	11.2	5.7	3.8 -1	5.0 -1	5.2 -1	5.1 -1

¹ Results cited according to [21]

² There is likely a misprint in [6]: $I = 13000$ has been wrongly taken from an adjacent line

³ There is a misprint in [17]: an A_{ki} value belonging to the line $\lambda = 335.195\text{ nm}$ has been wrongly stated for $\lambda = 335.130\text{ nm}$. Overall, [17] is rife with misprints; particularly, $\pm$ signs are missing from the text and tables in most cases

⁴ f_{ik} values have been rounded by me to two significant digits

IV. Summary

A detailed experimental study of excitation with simultaneous single ionization in collisions of electrons with tin atoms has been carried out using the method of extended crossing beams. Ninety-one excitation cross-sections of SnII spectral lines, all located within a wavelength range of $\lambda = 204\text{--}790\text{ nm}$, have been measured with an exciting electron energy of 50 eV. Six OEFs have been recorded within the exciting electron energy range between the excitation threshold and 250 eV. Unfortunately, the unavailability of a vacuum monochromator prevented the study of the most intensive resonant transitions of SnII that lie within the vacuum UV range.

V. References

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