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BRANCHING RATIO MEASUREMENTS FOR Ge I AND Ge II

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A high resolution Fourier-transform spectrometer was used to measure branching ratios for $5s$–$5p$, $4d$–$6s$, $6s$–$6p$, $5s$–$6p$, $4d$–$6p$, $4d$–$7p$ transitions in neutral germanium and $4d$–$4f$, $4p^2$–$4f$, $4p^2$–$5p$, $5s$–$5p$, $4p^2$–$4p$, $4d$–$6p$, $4p^2$–$6p$, $4d$–$5f$, $4p^2$–$5f$, $4d$–$7p$, $4p^2$–$7p$ of singly ionized germanium. Measurements were performed with a hollow cathode as a light source. Spectral lines intensities were measured in a spectral range from 200 to 3500 nm. Absolute transition probabilities for some Ge II lines were obtained using experimental lifetime values for the $4s^2 4f\,^2F_{5/2}$, $^2F_{7/2}$ and $4s^2 5p\,^2P_{1/2}$, $^2P_{3/2}$ levels. Our results for transitions in neutral germanium show that some infrared lines, so far overlooked in spectral analyses, give a strong contribution to Ge spectrum. Our transition probabilities obtained for Ge II lines are lower than all other experimental and theoretical results, in one case even by an order of magnitude.

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1. Introduction

The germanium spectral lines are observed in spectra of stellar objects and interstellar medium and for this reason transition probabilities of neutral and ionized germanium are of astrophysical interest. Germanium is also an element extensively utilized in electronic industry, where knowledge of physical properties of atoms used in technological processes is important. For these reasons, we have undertaken experimental investigations of the germanium spectra to extend the set of electronic transition probabilities and branching ratios to infrared. Our intention is also to solve existing discrepancies between experimental and theoretical values of electronic transition probabilities. A low accuracy of a single experimental result is its basic feature.

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Our measurements complement previous results of absolute transition probabilities and branching ratios for Ge I and Ge II lines obtained by Biemont et al. [1], Musioł et al. [2], Pokrzywka et al. [3] and Miller & Roig [4].

Biemont et al. have measured branching ratios using inductively coupled plasma emission spectrometry, with intensity calibration performed by means of Ar lines emitted by a hollow cathode. The branching ratios were converted to absolute transition probabilities using lifetimes measured by time resolved laser spectroscopy.

The results of Musioł et al. and Pokrzywka et al. have been obtained by measuring branching ratios with a wall-stabilized arc (plasma in the local thermodynamic equilibrium — in short LTE plasma) and a "ferroelectric" plasma source (non LTE plasma). Calibration of the applied optical system was performed with the tungsten strip lamp and argon mini arc. Absolute values of electronic transition probabilities were obtained using lifetimes values for $4p5s\,^1P_1$, $^3P_0$, $^3P_1$, $^3P_2$ levels measured by Anderson et al. [5].

Finally, Miller and Roig obtained absolute transition probabilities of Ge I and II using an exciting source shock tube. They used argon lines to determine physical parameters of plasma and H_β line to bring relative values to the absolute scale for Ge II.

2. Experimental procedure

The branching ratios were obtained from emission measurements using the high current hollow cathode as the light source (Danzmann et al. [6]) with a copper cathode filled with germanium powder. One of the most important assumptions while measuring branching ratios is that about negligible optical thickness of the light source. This assumption was verified by measuring branching ratios of lines originating from the same upper level as a function of the hollow cathode current and pressure. Self-absorption was found for lines with the lower level being the ground configuration. Therefore these lines were excluded from our analysis. The discharge was operated with neon as the carrier gas and pressures between 130 Pa and 400 Pa. The applied discharge current was in the range between 0.1 A and 1.5 A.

In order to cover the spectral range of wavelengths from 170 nm to 3500 nm two Fourier-transform spectrometers (FTS) were used while studying germanium spectra. The NIST 2 m FTS (Nave et al. [7]) enabled measurements above 400 nm while the FT700 vacuum ultraviolet FTS [8] was specifically designed for a visible and UV part of the spectrum. Nevertheless, spectral lines in the range between 2600 and 2900 nm were not observed as the result of the FTS beam splitter absorption. A resolution of 0.06 cm^{-1} was used for the measurements and it was sufficient to resolve the Doppler broadened lines. Four types of photodetectors were used dependent on wavelength and spectrometer: photomultipliers with the Sb–Cs (190–620 nm) and Cs–Te (170–300 nm) photocathodes, the silica and In–Sb photodiodes for measurements in the infrared region.

Spectral sensitivity of the optical and detection systems was calibrated with the tungsten strip and deuterium lamps (Cathodeon, PTB calibration) with 3% uncertainty. In order to increase the S/N ratio up to 90 FTS scans were co-added.

The T-like setup inserted in a box filled with nitrogen was used to avoid systematic errors in measurements due to absorption of the optical system or oxygen. The branching ratio for wavelengths lower than 193 nm were not measured because of the low response of the optical system. The simultaneous recording of all spectral lines of interest by FTS eliminates uncertainties related to the drifts of the light source.

The NIST data base of energy levels was used to calculate wavelengths of all possible transitions including the intercombination ones [http://physics.nist.gov/cgi-bin/AtData/lines_form].

3. Results

3.1. Branching ratios for Ge I

The Ge I spectra ($4p$–$4s$ and $4p$–$4d$ transitions) have been recently analyzed by Biemont et al. [1]. In our measurements those transitions were affected by the self-absorption. We determined some additional branching ratios for $5s$–$5p$, $4d$–$6s$, $6s$–$6p$, $5s$–$6p$, $4d$–$6p$, $4d$–$7p$ transitions including intercombination lines to complement the results obtained by Biemont et al. These results are shown in Table I. Some of these branching ratios one can bring to an absolute

TABLE I

Branching ratios for Ge I.

Upper level	Lower level	λ [nm]	This work	Uncert. [%]
$4s^24p5p\,^3D_1$	$4s^24p5s\,^1P_1$	1675.979	0.17	9
45985.59 cm^1	$4s^24p5s\,^3P_2$	1455.695	0.003	18
	$4s^24p5s\,^3P_1$	1206.920	1	
	$4s^24p5s\,^3P_0$	1171.476	0.32	5
$4s^24p5p\,^1P_1$	$4s^24p5s\,^1P_1$	1482.238	0.19	10
46765.27 cm^{-1}	$4s^24p5s\,^3P_1$	1103.089	0.045	14
	$4s^24p5s\,^3P_0$	1073.407	1	
$4s^24p5p\,^3D_2$	$4s^24p5s\,^1P_1$	1467.204	0.0034	9
46834.38 cm^{-1}	$4s^24p5s\,^3P_2$	1295.574	0.026	22
	$4s^24p5s\,^3P_1$	1094.742	1	
$4s^24p5p\,^3P_0$	$4s^24p5s\,^1P_1$	1336.164	0.015	16
47502.63 cm^{-1}	$4s^24p5s\,^3P_1$	1020.095	1	
$4s^24p5p\,^3P_1$	$4s^24p5s\,^1P_1$	1239.158	0.88	5
48088.35 cm^{-1}	$4s^24p5s\,^3P_2$	1114.466	0.15	22
	$4s^24p5s\,^3P_1$	962.566	1	
	$4s^24p5s\,^3P_0$	939.887	0.30	11

TABLE I (cont.)

Branching ratios for Ge I.

Upper level	Lower level	λ [nm]	This work	Uncert. [%]
$4s^24p5p\,^3P_2$	$4s^24p5s\,^1P_1$	1148.377	0.025	15
48726.11 cm^{-1}	$4s^24p5s\,^3P_2$	1040.491	1	
	$4s^24p5s\,^3P_1$	906.879	0.077	6
$4s^24p5p\,^3S_1$	$4s^24p5s\,^1P_1$	1104.020	0.022	10
49075.89 cm^{-1}	$4s^24p5s\,^3P_2$	1003.944	1	
	$4s^24p5s\,^3P_1$	878.989	0.030	7
$4s^24p5p\,^1D_2$	$4s^24p5s\,^1P_1$	1038.243	1	
49649.58 cm^{-1}	$4s^24p5s\,^3P_2$	949.256	0.054	4
	$4s^24p5s\,^3P_1$	836.781	0.002	21
$4s^24p6p\,^1P_1$	$4s^24p4d\,^3D_2$	1573.489	1.1	13
55235.834 cm^{-1}	$4s^24p5s\,^3P_1$	570.178	1	
	$4s24p5s\,^3P_0$	562.142	3.0	14
$4s^24p6p\,^3D_2$	$4s^24p6s\,^3P_1$	320.697	1.2	12
55266.09 cm^{-1}	$4s^24p4d\,^3D_3$	1633.09	0.4	33
	$4s^24p5s\,^1P_1$	655.749	0.2	26
	$4s^24p5s\,^3P_1$	569.195	1	
$4s^24p6p\,^3P_0$	$4s^24p4d\,^3D_1$	1528.536	0.6	15
55503.203 cm^{-1}	$4s^24p5s\,^3P_1$	561.614	1	
$4s^24p6p\,^3D_3$	$4s^24p4d\,^3D_3$	1306.991	0.16	19
56793.46 cm^{-1}	$4s^24p4d\,^3D_2$	1263.687	1	
	$4s^24p4d\,^1D_2$	1202.546	0.8	20
	$4s^24p5s\,^3P_2$	565.596	0.4	43
$4s^24p6p\,^3P_2$	$4s^24p6p\,^3P_2$	3292.755	1.5	24
56947.769 cm^{-1}	$4s^24p4d\,^3F_3$	1509.180	0.4	16
	$4s^24p5s\,^1P_1$	590.601	0.07	19
	$4s^24p5s\,^3P_2$	5 60.701	1	
$4s^24p6p\,^3S_1$	$4s^24p6s\,^3P_2$	3152.15	2.1	9
57083.202 cm^{-1}	$4s^24p4d\,^3D_1$	1231.126	0.16	21
	$4s^24p5s\,^3P_2$	556.474	1	
$4s^24p6p\,^1D_2$	$4s^24p6s\,^1P_1$	3250.074	0.76	9
57250.943 cm^{-1}	$4s^24p4d\,^1F_3$	2145.927	0.6	13
	$4s^24p5s\,^1P_1$	580.209	1	
	$4s^24p5s\,^3P_2$	551.326	0.24	19
$4s^24p7p\,^3D_1$	$4s^24p4d\,^3P_1$	1489.998	0.8	31
58414.66 cm^{-1}	$4s^24p4d\,^3P_2$	1432.916	1	

scale using absolute transition probabilities obtained by Miller and Roig [4]. Our results show that some of the infrared transitions are very strong and considerably contribute to the sum of the branching ratios for a given level.

The uncertainty of our branching ratios predominantly results from the uncertainty of the calibration sources. The uncertainty of a single calibration lamp

(3%) was enlarged by additional 1% if the line fell into the spectral range calibrated with two different lamps. If there were more than three measurements for the line its uncertainty was taken as a standard deviation and multiplied by the Student factor. If the line was measured less than four times the uncertainty was estimated from the signal to noise ratio.

3.2. Branching ratios for Ge II

In this work some branching ratios for Ge II transitions $4s^24d$–$4s^24f$, $4s4p^2$–$4s^24f$, $4s^24p$–$4s4p^2$, $4s^25s$–$4s^25p$, $4s4p^2$–$4s^25p$, $4s4p^2$–$4s^26p$, $4s^24d$–$4s^26p$, $4s4p^2$–$4s^25f$, $4s^24d$–$4s^25f$, $4s4p^2$–$4s^27p$, $4s^24d$–$4s^27p$ were measured for the first time. In Table II branching ratios are presented, which we were not able to convert to absolute transition probabilities. In Table III absolute transition probabilities for Ge II are shown. All of them were brought to the absolute scale by using experimental lifetimes measured by Tint et al. [9] and Andersen & Lindegard [5]. The weighted average of measured lifetimes was used as the estimated value of the lifetime. The uncertainty of the branching ratios was calculated in the same way as for Ge I. The uncertainty of the transition probability results from the uncertainty of the branching ratios, described above, and the uncertainty of the measured lifetime which was in the range from 6% to 12%. We did not take into account the uncertainties resulted from overlooking the intensity of the unmeasured lines, because of the low transition probability of intercombination lines or their relatively large wavelengths.

TABLE II

Branching ratios for Ge II.

Upper level (energy)	Lower level	λ [nm]	This work	Uncert. [%]
$4s4p^2\,{}^4P_{1/2}$	$4s^24p\,{}^2P_{3/2}$	200.704	1	
(51575.89 cm^{-1})	$4s^24p\,{}^2P_{1/2}$	193.889	1.3	7
$4s^26p\,{}^2P_{3/2}$	$4s^24d\,{}^2D_{5/2}$	494.127	1	
(101244.64 cm^{-1})	$4s^24d\,{}^2D_{3/2}$	489.873	0.14	20
	$4s4p^2\,{}^2D_{3/2}$	277.235	5.35	5
$4s^25f\,{}^2F_{7/2}$	$4s^24d\,{}^2D_{5/2}$	338.978	1	
(110504.58 cm^{-1})	$4s4p^2\,{}^2D_{5/2}$	220.585	6.3	6
$4s^27p\,{}^2P_{1/2}$	$4s^24d\,{}^2D_{3/2}$	331.255	1	
(111016.3 cm^{-1})	$4s4p^2\,{}^2D_{3/2}$	217.332	1.9	7
$4s^27p\,{}^2P_{3/2}$	$4s4p^2\,{}^2D_{5/2}$	217.765	1	
(111091.55 cm^{-1})	$4s4p^2\,{}^2D_{3/2}$	216.966	0.7	18

Miller & Roig [4], in their emission experiments with homogeneous plasma generated in the shock tube, measured the absolute transition probabilities for many Ge II lines. The precision of transition probabilities determined with this method is limited by the uncertainty of plasma parameters which is usually not better than 25%. Our results are smaller than the results of Miller & Roig by 10 to

40 percent. In the case of the 517.847 nm spectral line, our transition probability is even smaller more than one order of magnitude. It is caused by the fact that Miller & Roig did not resolve this line from the line 517.865 nm.

Fuhr & Wiese [10] calculated branching ratios in the Coulomb approximation and then were able to convert the lifetimes of Andersen et al. [5] to transition probabilities. Biemont et al. [11] and Marcinek [12] have reported relativistic

TABLE III

Transition probabilities for Ge II.

Upper level	Lower level	λ [nm]	A_{ki} [10^7 s^{-1}]					
			This work	[4]	[10]	[11]†	[12]†	[13]‡
$4s^24f\,^2F_{5/2}$	$4s^24d\,^2D_{5/2}$	517.847	0.8(0.2)	8.6A*	1.3	0.85		
100317.98 cm^{-1}	$4s^24d\,^2D_{3/2}$	513.175	7.9(0.6)	13.2B*	19	12.2		
τ = 4.87(33) ns	$4s4p^2\,^2D_{5/2}$	284.547	0.9(0.2)					
	$4s4p\,^2D_{3/2}$	283.184	11.0(0.9)					
$4s^24f\,^2F_{7/2}$	$4s^24d\,^2D_{5/2}$	517.865	8.9(0.9)	8.6A*	20	12.7		
100317.28 cm^{-1}	$4s4p^2\,^2D_{5/2}$	284.553	11.6(1.0)					
τ = 4.87(33) ns								
$4s^25p\,^2P_{3/2}$	$4s4p^2\,^2D_{5/2}$	704.937	1.4(0.2)					
79366.49 cm^{-1}	$4s4p^2\,^2D_{3/2}$	696.633	0.18(0.2)					
τ = 11.8(6) ns	$4s^25s\,^2S_{1/2}$	589.339	6.9(0.4)	8.1A*	9.2	8.7	8.5	9.1
$4s^25p\,^2P_{1/2}$	$4s4p^2\,^2D_{3/2}$	714.539	1.6(0.2)					
79006.89 cm^{-1}	$4s^25s\,^2S_{1/2}$	602.104	7.3(0.6)	10.3A*	8.4	8.2	8.0	8.6

*Estimated error: 23% < A < 28%, 28% < B < 36%;
†HFR-Cl; ‡HFR-SC.

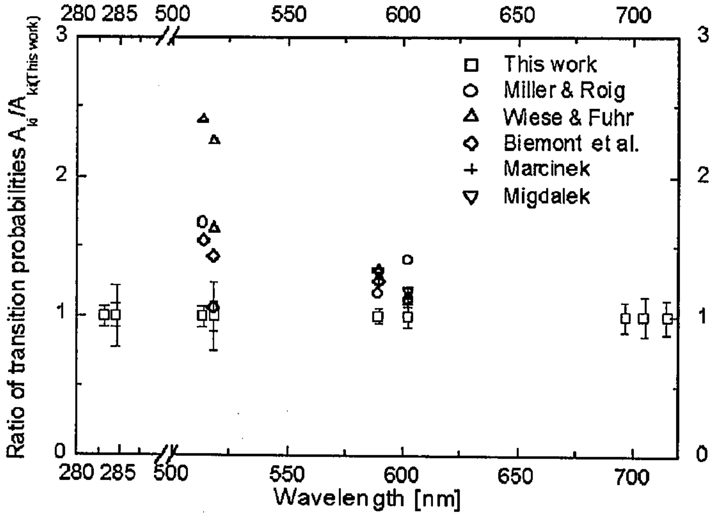

Fig. 1. Ratio of transition probabilities $A_{ki}/A_{ki\ (\text{This work})}$.

Hartree–Fock multiconfigurational calculations (HFR–CI). There is good agreement between their results. The results of Migdałek [13] have been calculated using the monoconfigurational Hartree–Fock (HFR–SC) approach. This approach gives about six percent larger results than the HFR–CI method. As one can see from Table III there are quite large discrepancies between theoretical calculations and experimental results.

Comparison of absolute transition probabilities of different authors is presented in Table III. To show a relative scatter of these data, they are plotted in Fig. 1. As one can see, our transition probabilities are systematically of lower values than the results of other authors. We did not put the results of Miller and Roig for the lines 517.847 nm and 517.865 nm in this figure due to the reason described above.

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