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Investigation of the hyperfine structure of Ta I lines (VI)

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Abstract. We have classified about 200 new lines and have discovered 13 energy levels with even parity and 1 level with odd parity by means of the systematic hyperfine structure investigation of a large number of spectral lines of the neutral tantalum atom. For the new levels we deduced their angular momenta, parity and magnetic hyperfine interaction constants A as well as the electric quadrupole interaction constants B.

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1 Introduction

During several years the hyperfine structure (hfs) of tantalum spectral lines have been investigated. In spite of all those efforts and their results the analysis of the tantalum spectrum is far from being complete. In a successful cooperation, we and groups from Hamburg and Poznan (Poland) [1–3] continued to analyse Ta spectra and to classify lines. Many of the lines investigated in this work are up to now unknown Ta lines, discovered on spectral plates which were exposed to the light of an Ar–Ta hollow cathode lamp using an Ebert monochromator (2 m focal length in fifth order). These spectra are taken by Arcimowicz [4]. Besides all those Ta lines listed in commonly used spectral tables [5–7], we found a large number of additional lines. Some of these lines coincide either with Ce or Tb lines listed in [5]. In order to check if our hollow cathode material contains traces of such elements, we looked for strong lines of Ce or Tb in our spectrum, but without success. Later on we could identify most of these lines as Ta lines. So we have to assume that some errors occurred in the designation of Ce and Tb lines in [5].

In the spectral range 4 171–4 485 Å we excited systematically one transition after the other by laser light; additionally some other lines have been investigated (see Tab. 1). If an excitation could be carried out, we received a characteristic hyperfine pattern, from which we could determine the hyperfine constants of lower and upper level of the transition. These constants were used as a "finger print" for the levels, which allowed us to identify without doubt the involved atomic levels. In some cases the investigations did lead to the discovery of previously unknown fine structure levels.

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2 Experiment

The experimental arrangement was the same as used for our previous investigations [3]. Free tantalum atoms were produced by cathode sputtering in a tantalum hollow cathode lamp by the argon ions of the gas discharge. This source contains Ta atoms not only in the ground state, but also in higher excited states. With chopped radiation of a tunable cw dye laser free atoms could be excited. The laser-induced fluorescence (LIF) light was dispersed by a grating monochromator and detected with a photomultiplier using a lock-in amplifier. Sometimes the optogalvanic signal was also detected. For the accurate determination of the fluorescence wavelengths the fluorescence light was chopped with much higher frequency in front of the entrance slit of the monochromator and the discharge spectrum was recorded by means of a second lock-in amplifier simultaneously with the LIF signal.

3 Results and discussion

All wavelengths mentioned in this paper are given in unit Å in air. All energy levels were corrected with respect to their energetic position due to results of Engleman [8] obtained from Fourier transform spectra. With these corrections the wavelengths evaluated from the spectral plates and from Fourier transform spectra fit better to the values calculated from the pairs of energy levels of the transition.

Table 1 contains all lines for which the corresponding transitions have been excited by laser light, and for which we have observed a laser-induced fluorescence or an optogalvanic signal. The center of gravity wavelengths are determined from wavenumber calibrated Fourier transform spectra provided to us by Pickering [9] and Engleman [8] using the dispersion formula of Reeder and Peck [10] for

Table 1. Investigated lines of Ta I.

	Intensity			Transition		Energy level / cm^{-1}		Remark
λ/Å	this work	[6]	[5]	des. even	des. odd	even	odd	
4 175.806	*nl* 30	-	-	$a^4D_{1/2}$	$m^{\circ}_{3/2}$*	22 236.014	46 176.770	new line
4 176.993	640	15	15	$a^2D_{5/2}$	$z^4G^{\circ}_{7/2}$	12 865.967	36 799.905	[a]
4 183.968	*nl* 70	-	-	$?_{5/2}$	$m^{\circ}_{7/2}$*	47 820.71	23 926.716	new line
4 184.600	*nl* 35	-	-	$?_{7/2}$	$m^{\circ}_{7/2}$*	47 817.167	23 926.716	new line
4 185.939	90	(2)	-	$^2P_{3/2}$**	$m^{\circ}_{5/2}$*	15 903.818	39 786.599	
4 189.017	*nl* 25	-	-	$a^4D_{3/2}$	$^6P^{\circ}_{3/2}$*	21 381.052	45 246.284	new line
4 194.627	*nl* 660	-	-	$a^4P_{3/2}$	$y^6D^{\circ}_{1/2}$	6 068.956	29 902.273	new line
4 196.166	*nl* 1	-	-	$a^4H_{13/2}$	$^2H^{\circ}_{11/2}$*	23 514.923	47 339.489	new line
4 200.302	*nl* 60	-	-	$^4G^{**}_{9/2}$	$m^{\circ}_{11/2}$*	25 376.469	49 177.58	new line
4 204.160	*nl* 100	-	-	$a^6D_{7/2}$	$^6S^{\circ}_{5/2}$*	12 234.772	3 6014.068	new line
4 205.258	*nl* 10	-	-	$^4G_{9/2}$**	$?^{\circ}_{9/2}$	25 376.469	49 149.532	new line
4 205.871	7 800	300	100	$a^4F_{7/2}$	$z^6F^{\circ}_{9/2}$	3 963.922	27 733.511	[b]
4 206.381	800	120	50	$e^6F_{1/2}$	$z^6G^{\circ}_{3/2}$	41 151.381	17 384.689	
4 209.175	*nl* 190	-	-	$^4F_{5/2}$***	$m^{\circ}_{5/2}$*	44 918.665	21 167.596	new line
4 212.571	*nl* 35	-	-	$?_{9/2}$	$^2F^{\circ}_{7/2}$*	50 692.194	26 960.484	new line
4 214.261	*nl* 70	-	-	$?_{5/2}$	$m^{\circ}_{5/2}$*	45 769.81	22 047.454	new line
4 219.680	*nl* 55	-	-	$?_{7/2}$	$z^6F^{\circ}_{5/2}$	48 872.99	25 181.186	new line
4 220.129	*nl* 100	-	-	$?_{5/2}$	$z^2D^{\circ}_{3/2}$	44 461.647	20 772.357	new line
4 224.883	*nl* 10	-	-	$?_{13/2}$	$z^6F^{\circ}_{11/2}$	54 023.88	30 361.262	new line
4 226.758	*nl* 15	-	-	$^4D_{3/2}$*	$m^{\circ}_{5/2}$*	24 275.959	47 928.08	new line
4 228.258	*nl* 25	-	-	$a^4H_{11/2}$	$^2I^{\circ}_{13/2}$*	22 428.650	46 072.280	new line
4 229.392	*nl* 120	-	-	$?_{7/2}$	$m^{\circ}_{5/2}$*	49 857.127	26 219.648	new line
4 231.219	*nl* 55	-	-	$a^2F_{5/2}$	$m^{\circ}_{5/2}$*	17 224.462	40 851.654	new line
4 231.923	*nl* 1	-	-	$a^4G_{5/2}$	$^6P^{\circ}_{3/2}$*	21 623.018	45 246.284	new line
4 232.502	*nl* 45	-	-	$^4G_{7/2}$**	$?^{\circ}_{5/2}$	24 917.996	48 537.973	new line
4 232.923	145	35	-	$^4F_{3/2}$***	$z^4D^{\circ}_{3/2}$	43 275.474	19 657.804	
4 233.699	*nl* 35	-	-	$?_{7/2}$	$m^{\circ}_{9/2}$*	11 884.41	35 497.669	new line
4 235.548	*nl* 35	-	-	$?_{7/2}$	$z^6D^{\circ}_{7/2}$	51 383.695	27 780.652	new line
4 235.889	160	-	5h	$e^6F_{3/2}$	$^4G^{\circ}_{5/2}$*	41 594.852	17 993.726	
4 236.351	*nl* 70	-	-	$a^2F_{7/2}$	$m^{\circ}_{7/2}$*	17 383.173	40 981.768	new line
4 236.998	*nl* 55	-	-	$^4F_{7/2}$*	$z^4F^{\circ}_{5/2}$	46 958.10	23 363.113	new line
4 238.548	*nl* 35	-	-	$^2P_{3/2}$**	$^6F^{\circ}_{1/2}$*	15 903.818	39 490.148	new line
4 238.702	*nl* 250	-	-	$a^6D_{3/2}$	$m^{\circ}_{1/2}$*	9 975.837	33 561.282	new line
4 241.071	*nl* 40	-	-	$^4D_{1/2}$**	$?^{\circ}_{1/2}$	20 144.81	43 717.154	new line
4 242.552	*nl* 65	-	-	$?_{7/2}$	$z^6G^{\circ}_{9/2}$	46 245.64	22 681.695	new line
4 246.887	*nl* 25	-	-	$a^4H_{9/2}$	$^6F^{\circ}_{7/2}$*	21 153.396	44 693.412	new line
4 249.875	*nl* 25	-	-	$^4F_{5/2}$**	$?^{\circ}_{7/2}$	24 546.202	48 069.689	new line
4 250.704	*nl* 70	-	-	$a^4H_{7/2}$	$?^{\circ}_{7/2}$	20 646.702	44 165.583	new line[c]
4 253.908	*nl* 40	-	-	$?_{9/2}$	$^6D^{\circ}_{7/2}$*	51 683.81	28 182.633	new line
4 255.502	*nl* 80	-	-	$a^2G_{7/2}$	$z^6P^{\circ}_{7/2}$	9 705.350	33 197.724	new line
4 256.897	*nl* 100	-	-	$?_{5/2}$	$z^4D^{\circ}_{3/2}$	43 142.50	19 657.804	new line
4 257.807	*nl* 110	-	-	$a^2G_{7/2}$	$m^{\circ}_{5/2}$*	9 705.350	33 185.006	new line
4 259.833	*nl* 15	-	-	$a^2F_{7/2}$	$m^{\circ}_{5/2}$*	17 383.173	40 851.654	new line
4 263.048	*nl* 40	-	-	$a^2P_{1/2}$	$^4P^{\circ}_{3/2}$*	11 792.152	35 242.955	new line
4 263.494	105	(1)	-	$a^6D_{9/2}$	$z^4G^{\circ}_{7/2}$	13 351.546	36 799.905	[d]
4 268.232	*nl* 450	-	-	$e^6F_{7/2}$	$z^6G^{\circ}_{7/2}$	43 982.532	20 560.317	new line
4 270.264	*nl* 15	-	-	$^4H_{7/2}$**	$^6D^{\circ}_{7/2}$*	22 761.279	46 172.492	new line
4 274.266	*nl* 15	-	-	$?_{5/2}$	$^4G^{\circ}_{7/2}$*	45 769.81	22 380.481	new line
4 276.805	*nl* 15	-	-	$^4G_{5/2}$**	$m^{\circ}_{3/2}$*	23 512.447	46 887.789	new line

Table 1. *Continued.*

λ/Å	Intensity this work	[6]	[5]	Transition des. even	des. odd	Energy level / cm^{-1} even	odd	Remark
4 290.753	*nl* 20	-	-	$^4P_{1/2}$*	$^6D^\circ_{3/2}$*	49 889.45	26 590.053	new line
4 291.735	*nl* 40	-	-	$?_{5/2}$	$m^\circ_{5/2}$*	44 461.647	21 167.596	new line
4 291.867	*nl* 55	-	-	$a^2D_{5/2}$	$z^4H^\circ_{7/2}$	12 865.967	36 159.292	new line, blend
4 292.906	*nl* 80	-	-	$^4G_{9/2}$*	$z^4F^\circ_{7/2}$	48 269.57	24 981.880	new line
4 294.386	1 030	55	-	$a^6D_{9/2}$	$m^\circ_{9/2}$*	13 351.546	36 631.213	
4 297.485	*nl* 150	-	-	$a^6D_{7/2}$	$m^\circ_{9/2}$*	12 234.772	35 497.669	new line
4 297.893	*nl* 90	-	-	$^4G_{9/2}$*	$z^6G^\circ_{11/2}$	48 269.57	25 008.899	new line
4 298.882	*nl* 15	-	-	$^4D_{7/2}$**	$?^\circ_{9/2}$	25 894.092	49 149.532	new line
4 310.597	*nl* 40	-	-	$?_{3/2}$	$z^2D^\circ_{3/2}$	43 964.474	20 772.357	new line
4 312.431	*nl* 200	-	-	$?_{11/2}$	$z^6F^\circ_{9/2}$	50 915.638	27 733.511	new line[e]
4 317.377	*nl* 40	-	-	$^2P_{3/2}$**	$m^\circ_{5/2}$*	15 903.818	39 059.531	new line
4 317.535	*nl* 1	-	-	$a4G_{11/2}$	$m^\circ_{11/2}$*	26 022.739	49 177.58	new line
4 319.274	*nl* 270	-	-	$a^4F_{9/2}$	$z^6D^\circ_{9/2}$	5 621.123	28 766.644	new line
4 320.864	*nl* 35	-	-	$a^4D_{3/2}$	$^4P^\circ_{1/2}$*	21 381.052	44 518.050	new line
4 322.681	360	65	5	$a^2F_{7/2}$	$z^4G^\circ_{11/2}$	17 383.173	40 510.392	
4 325.001	*nl* 100	-	-	$a^2F_{5/2}$	$m^\circ_{3/2}$*	17 224.462	40 339.329	new line
4 325.702	*nl* 100	-	-	$a^4H_{11/2}$	$m^\circ_{9/2}$*	22 428.650	45 539.801	new line
4 326.183	*nl* 15	-	-	$a^2F_{5/2}$	$m^\circ_{7/2}$*	17 224.462	40 333.027	new line
4 329.644	*nl* 110	-	-	$e^6F_{3/2}$	$z^4D^\circ_{1/2}$	41 594.852	18 504.755	new line[f]
4 330.857	*nl* 25	-	-	$^4G_{9/2}$*	$^4G^\circ_{9/2}$*	48 269.585	25 185.964	new line
4 331.541	*nl* 10	-	-	$a^2H_{11/2}$	$z^4H^\circ_{11/2}$	15 114.280	38 194.285	new line
4 334.647	*nl* 45	-	-	$^4F_{5/2}$***	$z^4F^\circ_{3/2}$	49 18.665	21 855.124	new line
4 336.998	*nl* 250	-	-	$^6D_{3/2}$**	$m^\circ_{5/2}$*	10 950.262	34 001.203	new line
4 340.681	*nl* 150	-	-	$^4F_{7/2}$*	$m^\circ_{7/2}$*	46 958.10	23 926.716	new line
4 344.301	370	85	20	$a^4H_{9/2}$	$?^\circ_{7/2}$	21 153.396	44 165.583	
4 344.606	*nl* 80	-	-	$a^2D_{5/2}$	$m^\circ_{5/2}$*	12 865.967	35 876.551	new line
4 348.869	*nl* 65	-	-	$a^4H_{9/2}$	$m^\circ_{11/2}$*	21 153.396	44 141.422	new line
4 351.950	*nl* 110	-	-	$a^4F_{5/2}$	$z^4F^\circ_{7/2}$	2 010.134	24 981.880	new line
4 352.427	*nl* 55	-	-	$a^4D_{3/2}$	$m^\circ_{3/2}$*	21 381.052	44 350.284	new line
4 353.893	*nl* 150	-	-	$a^4P_{5/2}$	$m^\circ_{3/2}$*	9 253.453	32 214.941	new line
4 355.090	280	110	80	$e^6F_{9/2}$	$z^6G^\circ_{9/2}$	45 636.874	22 681.695	
4 357.697	*nl* 75	-	-	$^2P_{3/2}$**	$m^\circ_{1/2}$*	15 903.818	38 845.286	new line
4 360.175	*nl* 90	-	-	$?_{3/2}$	$m^\circ_{5/2}$*	44 096.008	21 167.596	new line[g]
4 363.833	*nl* 30	-	-	$?_{9/2}$	$^6F^\circ_{11/2}$*	50 692.194	27 783.084	new line
4 369.033	*nl* 25	-	-	$^4G_{7/2}$**	$^2H^\circ_{9/2}$*	24 917.996	47 799.909	new line
4 371.100	*nl* 90	-	-	$^4F_{5/2}$***	$m^\circ_{5/2}$*	44 918.665	22 047.454	new line[h]
4 398.771	*nl* 60	-	-	$a^4G_{5/2}$	$m^\circ_{3/2}$*	21 623.018	44 350.284	new line
4 401.764	*nl* 1	-	-	$a^2F_{5/2}$	$^4D^\circ_{7/2}$*	17 224.462	39 936.246	new line
4 404.389	*nl* 1	-	-	$^4D_{3/2}$*	$^4S^\circ_{3/2}$*	24 275.959	46 974.209	new line
4 407.745	*nl* 15	-	-	$?_{5/2}$	$m^\circ_{7/2}$*	53 271.95	30 590.985	new line
4 413.121	*nl* 1	-	-	$?_{7/2}$	$m^\circ_{5/2}$*	48 872.99	26 219.648	new line
4 420.203	*nl* 40	-	-	$?_{7/2}$	$z^6D^\circ_{9/2}$	51 383.695	28 766.644	new line
4 427.025	*nl* 45	-	-	$?_{5/2}$	$z^6G^\circ_{7/2}$	43 142.50	20 560.317	new line[i]
4 485.800	150	(1)	-	$a^2P_{1/2}$	$m^\circ_{3/2}$*	11 792.152	34 078.456	
4 513.588	*nl* 35	-	-	$?_{11/2}$	$z^6D^\circ_{9/2}$	50 915.638	28 766.644	new line[b]
5 679.543	*nl* 1	-	-	$^2D_{3/2}$**	$^4D^\circ_{1/2}$*	25 876.05	43 478.215	new line
5 773.179	*nl* 1	-	-	$^4D_{1/2}$**	$m^\circ_{1/2}$*	20 144.81	37 461.485	new line

Table 1. *Continued.*

	Intensity			Transition		Energy level / cm^{-1}		Remark
λ/Å	this work	[6]	[5]	des. even	des. odd	even	odd	
6 047.185	*nl* 1	-	-	$^2H_{9/2}$**	$m^\circ_{7/2}$*	29 116.264	45 648.307	new line
6 547.870	*nl* 15	-	-	$a^2D_{5/2}$	$y^4D^\circ_{5/2}$	12 865.967	28 133.941	new line
6 611.909	800	110	300	$a^6D_{5/2}$	$^6D^\circ_{3/2}$*	11 243.656	26 363.721	
6 653.666	*nl* 1	-	-	$^2H_{9/2}$**	$m^\circ_{11/2}$*	29 116.264	44 141.422	new line
6 776.640	10	-	2	$?_{3/2}$	$m^\circ_{5/2}$*	44 096.008	29 343.501	
6 787.542	1	(1)	-	$e^6F_{3/2}$	$^6D^\circ_{1/2}$*	41 594.852	26 866.045	

If not marked otherwise, designations are taken from reference [13], * designations are taken from reference [14], m mixed configuration, largest eigenvalue component below 25%, ** designation as given in reference [1], *** designation as given in [15], [a] also observed as fluorescence line when exciting the transition belonging to the line $\lambda = 4\,263.53$ Å, [b] this transition appeared also as a negative fluorescence line when exciting $\lambda = 4\,312.44$ Å and as a positive fluorescence line when exciting $\lambda = 6\,450.36$ Å, [c] also observed as fluorescence line when exciting the line $\lambda = 4\,344.301$ Å, [d] also observed as fluorescence line when exciting the line $\lambda = 4\,176.993$ Å, [e] also observed as fluorescence line when exciting the line $\lambda = 4\,513.61$ Å, [f] also observed as fluorescence line when exciting the line $\lambda = 6\,787.59$ Å, [g] also observed as fluorescence line when exciting the line $\lambda = 6\,776.65$ Å, [h] also observed as fluorescence line when exciting the line $\lambda = 4\,209.175$ Å, [i] also observed as fluorescence line when exciting the line $\lambda = 4\,256.89$ Å.
The list contains lines which are already classified if new lines could be found or up to now unassignable lines could be classified when exciting them.

the refraction index of air; the accuracy is better than ±0.005 Å. When a line mentioned is not visible in the Fourier spectra, we give the wavelength calculated from the energy levels, again using the refraction index of air [10].

When the lines in Table 1 were already classified earlier, the excitation did lead to the discovery of at least one ore some new fluorescence lines. For such lines the intensities as given in references [5–7] are listed. For all investigated lines, we give the intensity taken from Fourier transform spectra of Engleman [8]. These intensities are uncorrected concerning instrument and detector sensitivity; the light source for these spectra was a Ta hollow cathode lamp driven with ~300 mA. The noise level is dependent on wavelength and is approximately 5 at 4 300 Å and 1 at 7 000 and 3 000 Å. If a weak line could not be found in the Fourier spectrum but only at the photo plate, we gave it the intensity 1.

When the transitions listed in Table 1 are excited, the upper levels decay to a large manifold of other lower levels and emit thereby fluorescence light which shows the same intensity modulation like the chopped exciting laser light. If the monochromator is tuned to such a fluorescence line, a LIF signal is detected by our lock-in amplifier. When then the laser is tuned over a certain range (up to 0.2 Å), the LIF signal shows the typical hyperfine pattern of the excited transition. Most of the observed fluorescence lines could be assigned to already classified transitions and are therefore not mentioned. Another manifold of fluorescence lines could be classified for the first time. These lines are listed in Table 2. For the wavelengths and intensities of Table 2 the same is valid as for Table 1. For lines, which could not be found in the Fourier spectra, but for which a LIF signal was observed, the calculated wavelength and the intensity 1 is given. In some cases the new classified fluorescence lines coincide with fluorescence lines of nearly the same wavelengths which belong to other transitions. Such blend situations are mentioned in Table 2. Fluorescence lines which are not listed in references [5–7] are indicated as nl (new line). In column 9 of Table 2 the exciting laser wavelengths are listed.

In some cases the investigated new spectral lines could not be assigned to a pair of known levels. That means that at least one up to now unknown level takes part in the transition. A good fit of the recorded hyperfine pattern using programs developed in Hamburg [11,12] gave us the opportunity to determine the J-values and the hyperfine constants A and B of the levels involved. Using a pair of A and B values as a "fingerprint" for a fine structure level, in most cases one of the levels of the involved transition could be identified. The other level could then be calculated using the wavenumber of the line. In other cases the unknown (upper) level could be determined by comparing the wavenumber difference between excitation wavelength and a fluorescence line with wavenumber differences between known levels.

14 previously unknown levels were discovered in such way within the present work. Some of them could be excited on several transitions, confirming in this way their existence. The properties of the new discovered levels are listed in Table 3. Some of these levels were already included in a parametric fine and hyperfine structure analysis and their configuration and designation could be calculated [14]. Taking into account results given in reference [2] and two of the levels mentioned in Table 3, all states of the e^4F of the configuration $5d^36s7s$ are now identified. We will try to identify the levels designated as e^4F in reference [13] in forthcoming papers.

As an example, we discuss a special part of the investigations now in more detail. Figure 1 shows the hyperfine

Table 2. Lines classified *via* laser-induced fluorescence.

	Intensity			Transition		Energy level / cm^{-1}		Excitation	Remark
λ/Å	this work	[6]	[5]	des. even	des. odd	even	odd	λ/Å	
2 242.762	-	4	-	$a^4F_{7/2}$	$?^\circ_{5/2}$	3 963.92	48 537.973	42 32.502	classified
2 254.083	*nl* 1	-	-	$a^4F_{3/2}$	$m^\circ_{3/2}$*	0	44 350.284	4 398.771	
2 286.73	*nl* 25	-	-	$a^4F_{3/2}$	$?^\circ_{1/2}$	0	43 717.154	4 241.071	
2 295.166	15	160	5	$a^4F_{9/2}$	$m^\circ_{11/2}$*	5 621.04	49 177.58	4 200.302	classified
2 299.295	*nl* 1	-	-	$a^4F_{3/2}$	$^4D^\circ_{1/2}$*	0	43 478.215	5 679.543	
2 353.938	*nl* 1	-	-	$a^4P_{3/2}$	$?^\circ_{5/2}$	6 068.956	48 537.973	4 232.502	
2 492.530	*nl* 12	-	-	$a^4P_{3/2}$	$m^\circ_{3/2}$*	6 068.956	46 176.77	4 175.806	
2 592.437	13	12 h	70	$a^6D_{3/2}$	$?^\circ_{5/2}$	9 975.837	48 537.973	4 232.502	classified
2 593.633	*nl* 30	-	-	$a^4F_{9/2}$	$?^\circ_{7/2}$	5 621.04	44 165.58	4 344.301	blend[a]
2 654.009	25	21	15	$a^4P_{1/2}$	$?^\circ_{1/2}$	6 049.42	43 717.154	4 241.071	
2 672.338	25	-	20	$a^4P_{3/2}$	$^4D^\circ_{1/2}$*	6 068.956	43 478.215	5 679.543	
2 753.764	*nl* 1	-	-	$a^6D_{7/2}$	$?^\circ_{5/2}$	12 234.772	48 537.973	4 232.502	
2 790.443	*nl* 1	-	-	$a^6D_{9/2}$	$m^\circ_{11/2}$*	13 351.546	49 177.58	4 200.302	
2 848.428	*nl* 1	-	-	$a^4P_{5/2}$	$m^\circ_{3/2}$*	9 253.453	44 350.284	4 398.771	
2 907.426	*nl* 1	-	-	$a^2P_{1/2}$	$m^\circ_{3/2}$*	11 792.152	46 176.770	4 175.806	
2 934.852	28	70	40	$a^2H_{11/2}$	$m^\circ_{11/2}$*	15 114.280	49 177.58	4 200.302	classified
2 940.090	*nl* 65	-	-	$a^6D_{5/2}$	$^6P^\circ_{3/2}$*	11 243.656	45 246.284	4 189.017	
2 964.811	15	-	3w	$a^6D_{1/2}$	$^4D^\circ_{1/2}$*	9 759.017	43 478.215	5 679.543	
2 983.991	*nl* 1	-	-	$a^6D_{3/2}$	$^4D^\circ_{1/2}$*	9 975.837	43 478.215	5 679.543	
2 988.695	*nl* 25	-	-	$a^6D_{5/2}$	$^6F^\circ_{7/2}$*	11 243.656	44 693.412	4 246.887	
3 050.978	*nl* 10	-	-	$^6D_{3/2}$**	$?^\circ_{1/2}$	10 950.262	43 717.154	4 241.071	
3 131.440	*nl* 20	-	-	$a^2P_{1/2}$	$?^\circ_{1/2}$	11 792.152	43 717.154	4 241.071	
3 155.043	*nl* 20	-	-	$a^2P_{1/2}$	$^4D^\circ_{1/2}$*	11 792.152	43 478.215	5 679.543	
3 175.276	*nl* 1	-	-	$a^2D_{5/2}$	$m^\circ_{3/2}$*	12 865.967	44 350.284	4 398.771	
3 237.483	*nl* 12	-	-	$?_{7/2}$	$^4G^\circ_{5/2}$*	48 872.99	17 993.726	4 219.680	
3 243.355	50	28	-	$?_{7/2}$	$z^6G^\circ_{7/2}$	51 383.695	20 560.317	4 420.203, 4 235.548	classified
3 258.658	*nl* 12	-	-	$?_{7/2}$	$z^6G^\circ_{5/2}$	49 857.127	19 178.426	4 229.392	
3 306.840	*nl* 12	-	-	$^4P_{1/2}$*	$z^4D^\circ_{3/2}$	49 889.45	19 657.804	4 290.753	
3 308.543	15	-	20	$?_{7/2}$	$m^\circ_{5/2}$*	51 383.695	21 167.596	4 235.548	classified
3 351.705	*nl* 1	-	-	$?_{5/2}$	$^4G^\circ_{5/2}$*	47 820.71	17 993.726	4 183.968	
3 366.654	120	45	50	$?_{7/2}$	$z^6G^\circ_{5/2}$	48 872.99	19 178.426	4 219.680	classified
3 412.368	*nl* 20	-	-	$?_{7/2}$	$z^6G^\circ_{7/2}$	49 857.127	20 560.317	4 229.392	
3 445.508	70	-	2h	$?_{13/2}$	$z^6G^\circ_{11/2}$	54 023.88	25 008.899	4 224.859	
3 558.872	*nl* 1	-	-	$?_{5/2}$	$z^6F^\circ_{5/2}$	53 271.95	25 181.186	4 407.745	
3 566.037	1	-	7	$^4P_{1/2}$*	$z^4F^\circ_{3/2}$	49 889.45	21 855.124	4 290.753	
3 567.326	95	-	4	$a^4H_{9/2}$	$m^\circ_{11/2}$*	21 153.33	49 177.58	4 200.302	classified
3 594.383	*nl* 15	-	-	$^2P_{3/2}$**	$?^\circ_{1/2}$	15 903.818	43 717.154	4 241.071	
3 628.493	*nl* 30	-	-	$a^6D_{7/2}$	$m^\circ_{5/2}$*	12 234.772	39 786.599	4 185.939	
3 638.427	*nl* 8	-	-	$?_{7/2}$	$^4G^\circ_{7/2}$*	49 857.127	22 380.481	4 229.392	
3 658.395	*nl* 17	-	-	$a^4P_{5/2}$	$y^4F^\circ_{3/2}$	9 253.453	36 580.06	4 215.714	
3 667.757	*nl* 45	-	-	$?_{7/2}$	$z^6G^\circ_{7/2}$	47 817.167	20 560.317	4 184.600	
3 678.747	*nl* 1	-	-	$?_{7/2}$	$z^6G^\circ_{9/2}$	49 857.127	22 681.695	4 229.392	
3 696.031	*nl* 1	-	-	$?_{5/2}$	$z^2D^\circ_{3/2}$	47 820.71	20 722.357	4 183.968	
3 710.742	*nl* 15	-	-	$a^2F_{5/2}$	$?^\circ_{7/2}$	17 224.462	44 165.583	4 344.301	blend[b]
3 714.346	*nl* 20	-	-	$a^4G_{5/2}$	$?^\circ_{5/2}$	21 623.018	48 537.973	4 232.502	
3 737.430	*nl* 10	-	-	$a^4H_{11/2}$	$m^\circ_{11/2}$*	22 428.650	49 177.58	4 200.302	
3 743.981	*nl* 100	-	-	$?_{9/2}$	$z^4F^\circ_{7/2}$	51 683.79	24 981.880	4 253.908	
3 759.559	*nl* 75	-	-	$?_{5/2}$	$z^6G^\circ_{5/2}$	45 769.81	19 178.426	4 214.271	

Table 2. *Continued.*

λ/Å	Intensity this work	[6]	[5]	Transition des. even	des. odd	Energy level / cm^{-1} even	odd	Excitation λ/Å	Remark
3 765.832	*nl* 13	-	-	$a^4D_{3/2}$	$m^\circ_{5/2}$*	21 381.052	47 928.08	4 226.758	
3 773.375	*nl* 35	-	-	$?_{7/2}$	$z^4F^\circ_{5/2}$	49 857.127	23 363.113	4 229.392	
3 777.086	*nl* 380	-	-	$?_{5/2}$	$^4G^\circ_{5/2}$*	44 461.647	17 993.726	4 220.129	
3 800.470	*nl* 1	-	-	$a^4G_{5/2}$	$m^\circ_{5/2}$*	21 623.018	47 928.08	4 226.758	
3 809.023	*nl* 70	-	-	$?_{13/2}$	$^6G^\circ_{13/2}$*	54 023.88	27 778.093	4 224.883	
3 819.909	*nl* 17	-	-	$a^2G_{7/2}$	$m^\circ_{5/2}$*	9 705.38	35 876.47	4 228.608	
3 829.999	*nl* 65	-	-	$?_{3/2}$	$^4G^\circ_{5/2}$*	44 096.008	17 993.726	4 360.175	
3 850.160	*nl* 1	-	-	$?_{5/2}$	$z^4F^\circ_{3/2}$	47 820.71	21 855.124	4 183.968	
3 858.889	*nl* 1	-	-	$?_{11/2}$	$z^6G^\circ_{11/2}$	50 915.745	25 008.899	4 312.431	
3 885.449	*nl* 40	-	-	$?_{11/2}$	$^4G^\circ_{9/2}$*	50 915.745	25 185.964	4 312.431, 4 513.588	
3 890.678	25	2	-	$^4F_{3/2}$**	$?^\circ_{5/2}$	22 842.851	48 537.973	4 232.502	classified
3 895.609	*nl* 1	-	-	$a^4H_{13/2}$	$m^\circ_{11/2}$*	23 514.923	49 177.58	4 200.302	
3 898.138	*nl* 1	-	-	$^4P_{1/2}$*	$z^6F^\circ_{3/2}$	49 889.45	24 243.447	4 290.753	
3 906.481	*nl* 7	-	-	$?_{3/2}$	$z^4D^\circ_{1/2}$	44 096.008	18 504.755	6 776.640	
3 919.488	100	40	-	$?_{9/2}$	$^4G^\circ_{9/2}$*	50 692.194	25 185.964	4 212.571	classified
3 929.665	*nl* 15	-	-	$?_{5/2}$	$^4G^\circ_{7/2}$*	47 820.71	22 380.481	4 183.968	
3 956.976	*nl* 30	-	-	$^4H_{9/2}$**	$m^\circ_{11/2}$*	23 912.929	49 177.58	4 200.302	
3 957.591	*nl* 25	-	-	$^4F_{5/2}$***	$z^4D^\circ_{3/2}$	44 918.665	19 657.804	4 209.175	
3 965.648	*nl* 20	-	-	$?_{5/2}$	$z^6G^\circ_{7/2}$	45 769.81	20 560.317	4 274.266	
3 972.386	*nl* 15	-	-	$^4H_{7/2}$**	$m^\circ_{5/2}$*	22 761.279	47 928.08	4 225.76	
3 975.211	*nl* 17	-	-	$?_{5/2}$	$^4G^\circ_{5/2}$*	43 142.50	17 993.726	4 256.897	
3 985.284	*nl* 13	-	-	$^4F_{3/2}$**	$m^\circ_{5/2}$*	22 842.851	47 928.08	4 226.758	
3 986.661	*nl* 1	-	-	$e^6F_{9/2}$	$z^6G^\circ_{7/2}$	45 636.874	20 560.317	4 355.090	
3 994.791	*nl* 1	-	-	$^4G_{5/2}$**	$?^\circ_{5/2}$	23 512.447	48 537.973	4 232.502	
4 000.570	*nl* 30	-	-	$?_{11/2}$	$m^\circ_{9/2}$*	50 915.745	25 926.383	4 312.431, 4 513.588	
4 018.936	*nl* 30	-	-	$?_{7/2}$	$z^4F^\circ_{7/2}$	49 857.127	24 981.880	4 229.392	
4 035.881	*nl* 250	-	-	$^4F_{3/2}$***	$z^4D^\circ_{1/2}$	43 275.474	18 504.755	4 232.923	blend[c]
4 051.397	*nl* 90	-	-	$?_{7/2}$	$z^6F^\circ_{5/2}$	49 857.127	25 181.186	4 229.392	
4 052.171	*nl* 1	-	-	$?_{7/2}$	$^4G^\circ_{9/2}$*	49 857.127	25 185.964	4 229.392	
4 069.663	*nl* 75	-	-	$a^6D_{7/2}$	$z^4G^\circ_{7/2}$	12 234.772	36 799.905	4 176.993	
4 088.145	*nl* 10	-	-	$?_{7/2}$	$z^4F^\circ_{5/2}$	47 817.167	23 363.113	4 184.600	
4 094.581	*nl* 5	-	-	$^4G_{5/2}$**	$m^\circ_{5/2}$*	23 512.447	47 928.08	4 226.758	
4 118.064	90	19	5	$^4F_{7/2}$*	$z^6G^\circ_{9/2}$	46 958.10	22 681.695	4 340.681	classified
4 120.491	*nl* 45	-	-	$^4D_{3/2}$*	$?^\circ_{5/2}$	24 275.959	48 537.973	4 232.502	
4 129.329	*nl* 350	-	-	$e^6F_{3/2}$	$z^6G^\circ_{3/2}$	41 594.852	17 384.689	6 787.542, 4 329.644	
4 148.709	*nl* 25	-	-	$^4F_{3/2}$***	$z^6G^\circ_{5/2}$	43 275.474	19 178.426	4 232.923	
4 171.736	*nl* 80	-	-	$?_{5/2}$	$z^6G^\circ_{5/2}$	43 142.50	19 178.426	4 256.897	
4 200.302	*nl* 60	-	-	$^4G_{9/2}$**	$m^\circ_{11/2}$	25 376.469	49 177.58	4 317.535	new line
4 250.704	*nl* 70	-	-	$a^4H_{7/2}$	$?^\circ_{7/2}$	20 646.702	44 165.583	4 344.301	[e]
4 275.613	*nl* 1	-	-	$^4F_{5/2}$**	$m^\circ_{5/2}$*	24 546.202	47 928.08	4 226.758	
4 329.644	*nl* 110	-	-	$e^6F_{3/2}$	$z^4D^\circ_{1/2}$	41 594.852	18 504.755	6 787.542, 4 235.889	[f]
4 331.228	*nl* 1	-	-	$?_{5/2}$	$z^6D^\circ_{3/2}$	47 820.71	24 739.060	4 183.968	
4 334.647	*nl* 45	-	-	$^4F_{5/2}$***	$z^4F^\circ_{3/2}$	44 918.665	21 855.124	4 209.175	[g]
4 334.867	*nl* 20	-	-	$?_{7/2}$	$z^6D^\circ_{5/2}$	49 857.127	26 794.812	4 229.392	

Table 2. *Continued.*

λ/Å	Intensity this work	[6]	[5]	Transition des. even	des. odd	Energy level / cm^{-1} even	odd	Excitation λ/Å	Remark
4 360.175	*nl* 90	-	-	$?_{3/2}$	$m^{\circ}_{5/2}$*	44 096.008	21 167.596	6 776.640	[h]
4 371.100	*nl* 90	-	-	$^4F_{5/2}$***	$m^{\circ}_{5/2}$*	44 918.665	22 047.454	4 209.175	[i]
4 414.427	*nl* 25	-	-	$e^6F_{1/2}$	$z^4D^{\circ}_{1/2}$	41 151.381	18 504.755	4 206.381	
4 427.025	*nl* 45	-	-	$?_{5/2}$	$z^6G^{\circ}_{7/2}$	43 142.50	20 560.317	4 256.897	
4 434.815	*nl* 10	-	-	$a^4G_{5/2}$	$?^{\circ}_{7/2}$	21 623.018	44 165.583	4 344.301	
4 435.639	*nl* 25	-	-	$^4F_{5/2}$***	$^4G^{\circ}_{7/2}$*	44 918.665	22 380.481	4 209.175	
4 474.375	*nl* 140	-	-	$^4G_{9/2}$*	$m^{\circ}_{9/2}$*	48 269.585	25 926.383	4 292.906	
4 475.819	*nl* 50	-	-	$a^4D_{3/2}$	$?^{\circ}_{1/2}$	21 381.052	43 717.154	4 241.071	
4 479.216	*nl* 100	-	-	$?_{7/2}$	$m^{\circ}_{7/2}$*	46 245.64	23 926.716	4 242.552	
4 513.588	*nl* 35	-	-	$?_{11/2}$	$z^6D^{\circ}_{9/2}$	50 915.745	28 766.644	4 312.431	[j]
4 522.003	*nl* 25	-	-	$^4F_{3/2}$***	$m^{\circ}_{5/2}$*	43 275.474	21 167.596	4 232.923	
4 557.221	*nl* 1	-	-	$e^6F_{3/2}$	$z^4D^{\circ}_{3/2}$	41 594.852	19 657.804	4 235.889	blend[k]
4 591.740	*nl* 145	-	-	$^4F_{7/2}$*	$^4G^{\circ}_{9/2}$*	46 958.10	25 185.964	4 236.998	
4 628.100	*nl* 75	-	-	$?_{5/2}$	$m^{\circ}_{5/2}$*	47 820.71	26 219.648	4 183.968	
4 637.897	*nl* 50	-	-	$^4F_{5/2}$***	$z^4F^{\circ}_{5/2}$	44 918.665	23 363.113	4 209.175	
4 651.253	*nl* 20	-	-	$e^6F_{1/2}$	$z^4D^{\circ}_{3/2}$	41 151.381	19 657.804	4 206.381	
4 669.650	*nl* 120	-	-	$a^2H_{9/2}$	$z^4G^{\circ}_{7/2}$	15 391.019	36 799.905	4176.993	
4 670.649	*nl* 1	-	-	$^4H_{7/2}$**	$?^{\circ}_{7/2}$	22 761.279	44 165.583	4 344.301	
4 703.581	*nl* 1	-	-	$e^6F_{3/2}$	$z^2S^{\circ}_{1/2}$	41 594.852	20 340.405	4 235.889	
4 708.853	*nl* 1	-	-	$?_{5/2}$	$^6D^{\circ}_{3/2}$*	47 820.71	26 590.053	4 183.968	
4 755.510	*nl* 35	-	-	$?_{7/2}$	$z^6D^{\circ}_{5/2}$	47 817.167	26 794.812	4 184.600	
4 789.258	155	-	4	$^4F_{3/2}$**	$?^{\circ}_{1/2}$	22 842.851	43 717.154	4 241.071	classified
4 793.287	*nl* 40	-	-	$?_{7/2}$	$^2F^{\circ}_{7/2}$*	47 817.167	26 960.484	4 184.600	
4 803.814	*nl* 1	-	-	$e^6F_{1/2}$	$z^2S^{\circ}_{1/2}$	41 151.381	20 340.405	4 206.381	
4 815.143	*nl* 120	-	-	$?_{5/2}$	$^4G^{\circ}_{7/2}$*	43 142.50	22 380.481	4 256.897	blend[l]
4 835.386	*nl* 90	-	-	$^4F_{5/2}$***	$z^6F^{\circ}_{3/2}$	44 918.665	24 243.447	4 209.175	
4 840.091	*nl* 25	-	-	$e^6F_{9/2}$	$z^4F^{\circ}_{7/2}$	45 636.874	24 981.880	4 355.090	
4 840.522	*nl* 20	-	-	$^4G_{5/2}$**	$?^{\circ}_{7/2}$	23 512.447	44 165.583	4 344.301	
4 905.636	*nl* 60	-	-	$e^6F_{1/2}$	$z^2D^{\circ}_{3/2}$	41 151.381	20 772.32	4 206.381	
4 936.247	*nl* 1	-	-	$^4H_{9/2}$**	$?^{\circ}_{7/2}$	23 912.929	44 165.583	4 344.301	
4 958.110	*nl* 120	-	-	$^4F_{7/2}$*	$z^6D^{\circ}_{5/2}$	46 958.10	26 794.812	4 340.681	blend[m]
4 988.625	*nl* 35	-	-	$?_{5/2}$	$z^6D^{\circ}_{7/2}$	47 820.71	27 780.652	4 183.968	
5 035.731	*nl* 50	-	-	$?_{3/2}$	$z^6F^{\circ}_{3/2}$	44 096.008	24 243.447	6 776.640	
5 054.357	*nl* 80	-	-	$?_{5/2}$	$z^4F^{\circ}_{5/2}$	43 142.50	23 363.113	4 256.897	
5 095.581	*nl* 1	-	-	$^4F_{5/2}$**	$?^{\circ}_{7/2}$	24 546.202	44 165.583	4 344.301	
5 114.349	*nl* 15	-	-	$e^6F_{3/2}$	$m^{\circ}_{5/2}$*	41 594.852	22 047.454	4 235.889	
5 119.037	*nl* 25	-	-	$?_{7/2}$	$m^{\circ}_{5/2}$*	48 872.99	29 343.501	4 219.680	
5 194.006	50	20	-	$^4G_{7/2}$**	$?^{\circ}_{7/2}$	24 917.996	44 165.583	4 344.301	blend[n]
5 208.648	*nl* 1	-	-	$?_{5/2}$	$m^{\circ}_{3/2}$*	53 271.95	34 078.456	4 407.745	
5 213.058	*nl* 1	-	-	$?_{5/2}$	$y^6D^{\circ}_{7/2}$	53 271.95	34 094.692	4 407.745	
5 223.236	*nl* 45	-	-	$a^4H_{7/2}$	$m^{\circ}_{5/2}$*	20 646.702	39 786.599	4 185.939	
5 310.845	*nl* 45	-	-	$^4F_{7/2}$*	$y^4D^{\circ}_{5/2}$	46 958.10	28 133.941	4 340.681	blend[o]
5 320.750	*nl* 10	-	-	$^4G_{9/2}$**	$?^{\circ}_{7/2}$	25 376.469	44 165.583	4 344.301	
5 324.613	*nl* 25	-	-	$^4F_{7/2}$*	$^6D^{\circ}_{7/2}$*	46 958.10	28 182.633	4 236.998	
5 352.862	*nl* 20	-	-	$e^6F_{9/2}$	$^2F^{\circ}_{7/2}$*	45 636.874	26 960.484	4 355.090	
5 454.465	*nl* 35	-	-	$^4F_{5/2}$***	$^6D^{\circ}_{3/2}$*	44 918.665	26 590.053	4 209.175	
5 478.430	*nl* 30	-	-	$^4G_{9/2}$*	$^6D^{\circ}_{9/2}$*	48 269.585	30 021.272	4 330.857, 4 292.906, 4 297.893	

Table 2. *Continued.*

λ/Å	Intensity this work	[6]	[5]	Transition des. even	des. odd	Energy level / cm^{-1} even	odd	Excitation λ/Å	Remark
5 516.090	*nl* 30	-	-	$^4F_{5/2}$***	$z^6D^\circ_{5/2}$	44 918.665	26 794.812	4 209.175	
5 524.023	*nl* 30	-	-	$?_{5/2}$	$m^\circ_{7/2}$*	47 820.71	29 722.985	4 183.968	
5 534.590	*nl* 13	-	-	$?_{7/2}$	$^6D^\circ_{7/2}$*	46 245.64	28 182.633	4 242.552	
5 545.333	*nl* 110	-	-	$a^2G_{7/2}$	$z^6F^\circ_{9/2}$	9705.38	27 733.511	4 205.871	blend[p]
5 565.970	*nl* 15	-	-	$?_{5/2}$	$z^6F^\circ_{5/2}$	43 142.50	25 181.186	4 256.897	
5 566.976	*nl* 22	-	-	$^4F_{5/2}$**	$^2F^\circ_{7/2}$*	44 918.665	26 960.484	4 334.647	
5 637.862	*nl* 12	-	-	$?_{3/2}$	$^6D^\circ_{3/2}$*	44 096.008	26 363.721	6 776.640	
5 881.434	*nl* 1	-	-	$^4G_{5/2}$**	$z^4G^\circ_{11/2}$	23 512.447	40 510.392	4 322.681	
5 958.254	*nl* 5	-	-	$?_{5/2}$	$^6D^\circ_{3/2}$*	43 142.50	26 363.721	4 256.897	
5 997.641	*nl* 1	-	-	$^4G_{9/2}$*	$m^\circ_{7/2}$*	48 269.585	31 600.982	4 292.906	
6 038.241	*nl* 10	-	-	$?_{5/2}$	$z^6F^\circ_{7/2}$	43 142.50	26 585.979	4 256.897	
6 039.730	*nl* 1	-	-	$?_{5/2}$	$^6D^\circ_{3/2}$*	43 142.50	26 590.053	4 256.897	[q]
6 098.619	*nl* 1	-	-	$?_{5/2}$	$m^\circ_{5/2}$*	47 820.71	31 428.092	4 183.968	
6 100.380	*nl* 1	-	-	$a^6D_{3/2}$	$^6D^\circ_{3/2}$*	9 975.837	26 363.721	6 611.909	
6 392.618	*nl* 1	-	-	$e^6F_{1/2}$	$y^4D^\circ_{1/2}$	41 151.381	25 512.63	4 206.381	
6 479.908	*nl* 17	-	-	$^4F_{7/2}$*	$^4H^\circ_{9/2}$*	46 958.10	31 530.050	4 340.681	blend[r]
6 502.182	*nl* 1	-	-	$e^6F_{3/2}$	$m^\circ_{5/2}$*	41 594.852	26 219.648	4 235.889	
6 577.464	*nl* 22	-	-	$^4G_{9/2}$*	$^4H^\circ_{11/2}$*	48 269.57	33 070.364	4 292.906	
6 662.692	*nl* 5	-	-	$e^6F_{3/2}$	$^6D^\circ_{3/2}$*	41 594.852	26 590.053	4 235.889	
6 767.498	*nl* 1	-	-	$^4G_{9/2}$*	$m^\circ_{9/2}$*	48 269.585	33 497.154	4 292.906	
8 026.010	*nl* 95	-	-	$^4G_{9/2}$*	$^4G_{11/2}$*	48 269.585	35 813.517	4 292.906	

If not marked otherwise, designations are taken from reference [13], * designation as given in reference [14], m mixed configuration, largest eigenvalue component below 25%, ** designation as given in reference [1], *** designation as given in reference [15], [a] blend situation with 2 593.660 Å, ionic line 42 959.55 - 4 415.79 cm^{-1} [16], [b] blend situation with 3 710.777 Å, 42 844.673 - 15 903.818 cm^{-1} [17], [c] blend situation with 4 035.893 Å, 35 720.898 - 10 950.22 cm^{-1}, [e], [f], [g], [h], [i], [j] these transitions were also excited, [k] blend situation with 4 557.241 Å, 43 090.337 - 21 153.396 cm^{-1}, [l] blend situation with 4 815.137 Å, 46 981.974 - 26 219.648 cm^{-1}, [m] blend situation with 4 958.110 Å, 46 958.10 - 26 794.812 cm^{-1}, [n] blend situation with 5 193.886 Å, 36 631.213 - 17 383.173 cm^{-1}, [o] blend situation with 5 310.965 Å, 41 585.022 - 22 761.279 cm^{-1}, [p] blend situation with 5 545.153 Å, 30 894.719 - 12 865.967 cm^{-1}, [q] or 6 038.241 was excited or both, [r] blend situation with 6 479.930 Å, 46 981.974 - 31 553.879 cm^{-1}, [s] blend situation with 7 043.457 Å, 32 187.394 - 17 993.726 cm^{-1}. Already known lines are marked as classified.

structure of the new line $\lambda = 4\,200.302$ Å. The line is not listed in the wavelength tables, but we could determine a wavelength of 4 200.32 Å from the photo plate.

Because we are able to set the wavelength of our exciting laser with an accuracy of 0.01 Å, we positioned the laser wavelength in steps of 0.01 Å around this value. At each step we scanned the monochromator until we observed laser-induced fluorescence. With the monochromator fixed at the fluorescence wavelength we scanned the laser around 4 200.32 Å and recorded the hyperfine pattern of the corresponding transition (for obtaining hyperfine constants). Then we set the laser to the strongest hyperfine component and looked for further fluorescence lines. We found 3 fluorescence lines originating from the upper level: 2 295.166 Å, an unclassified line with the relative intensity 5 [5], a new line at 2 790.443 Å, and a further unclassified line at 2 934.852 Å, with the relative intensity 70 [6]. Each of those lines showed the same hyperfine pattern when scanning the laser frequency.

By combining the wavenumbers of the excited transition and the fluorescence lines we found that the excited transition must have 25 376.469 cm^{-1}, 9/2 even as its lower level. By adding the wave number of the exciting laser light we could now calculate the energy of a new upper level to be $49\,177.58 \pm 0.03$ cm^{-1}. The lower levels of the three fluorescence lines had even parity and $J = 9/2$ or $11/2$, so the new one must have odd parity and $J = 11/2$ or $9/2$. Finally a value of $J = 11/2$ followed from the analysis of the hyperfine pattern. Later on four further fluorescence lines could be observed which were calculated as possible decays from the new level: 3 567.326 Å, an unclassified transition with the relative intensity 4 [5], and the new lines 3 737.430 Å, 3 895.609 Å and 3 956.976 Å. In order to determine the hyperfine constants A and B

Table 3. New energy levels.

Configuration	Designation	Energy /cm^{-1}	A / MHz	B / MHz	$\lambda_{\rm exc}$/Å
even parity					
	$?_{5/2}$	43 142.50	254(5)	1 840(100)	4 256.897, 4 171.736, 4 427.025
	$?_{5/2}$	45 769.74	577(8)	260(30)	4 274.266, 4 214.271
	$?_{7/2}$	46 245.79	282.9(52)	298(30)	4 242.552
$5d^36s7s$	$^4F^{***}_{7/2}$	46 958.11	725(4)	−520(60)	4 236.998, 4 340.681
	$?_{5/2}$	47 820.71	1 107(4)	−966(100)	4 183.968
$5d^36s7s$	$^4F^{***}_{9/2}$	48 269.585	982.5(20)	−1 065(20)	4 292.906, 4 297.893, 4 330.857
	$?_{7/2}$	48 872.99	−572(1)	−743(50)	4 413.121, 4 219.680
$5d^36s7s$	$^4P^{*}_{1/2}$	49 889.45	3 375(5)	0	4 290.753
	$?_{11/2}$	50 915.745	813.6(30)	−261(80)	4 312.431, 4 513.588
	$?_{7/2}$	51 383.695	823(5)	377(90)	4 420.203, 4 235.548
	$?_{9/2}$	51 683.81	630(5)	−230(50)	4 253.908
	$?_{5/2}$	53 271.95	1 058(2)	−790(20)	4 407.745
	$?_{13/2}$	54 023.88	1 078(20)	−1 640(100)	4 224.859
odd parity					
$5d^36s7p$	$m^{\circ}_{11/2}{}^{*}$	49 177.58	493(10)	3 020(100)	4 200.302, 4 317.571

If not marked otherwise, designations are taken from reference [13], * Configuration and designation as given in reference [14] (for 49 889.45 cm^{-1} the configuration $5d^36s7s$ is given, since we assume that $5d^5$ does not much contribute to the value of A, as is shown in ref. [1]), m mixed configuration, largest eigenvalue component below 25%, *** Configuration and designation as given in reference [15].

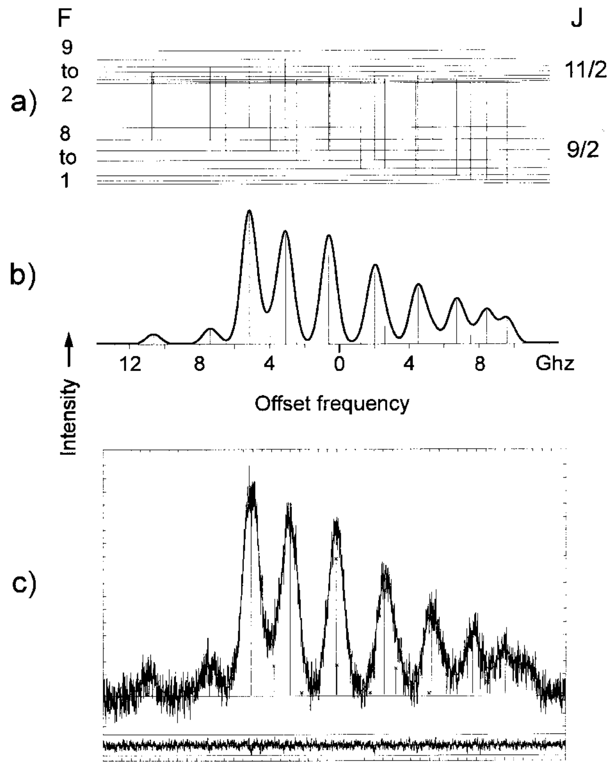

Fig. 1. Hyperfine structure of the Ta I-line $\lambda = 4\,200.302$ Å (transition between the levels 25 376.469 cm^{-1}, $J = 9/2$, even and the new level 49 177.58 cm^{-1}, $J = 11/2$, odd). (a) Level scheme, (b) simulation of the hfs-spectrum using the evaluated A- and B-factors, (c) recorded hyperfine pattern and best fit result. Lower trace: difference between fitted curve and measurement (divided by a factor 3).

of the new level, we used the iterative least squares fitting procedure mentioned before [11,12] and adjusted a calculated spectrum to the measured one. For this procedure we used the already known hyperfine constants of the lower level and considered the theoretical intensity ratio of the hyperfine components. Much later on, when the Fourier spectra were available, we really found the line with a center of gravity wavelength 4 200.302 Å. The new level was included in a fine structure calculation [14], it turned out that no dominant wave function is present, we therefore call it a mixed (m) level. So the new line finally can be classified as

$$m^{\circ}_{11/2}(49\,177.58\ {\rm cm}^{-1}) - {}^4G_{9/2}(25\,376.469\ {\rm cm}^{-1}).$$

The new level could be confirmed by exciting the line 4 317.535 Å, belonging to the transition:

$$m^{\circ}_{11/2}(49\,177.58\ {\rm cm}^{-1}) - a^4G_{11/2}(26\,022.739\ {\rm cm}^{-1}).$$

From the fit of the recorded hyperfine patterns of both lines, 4 200.302 Å and 4 317.535 Å we obtained mean values of the hyperfine constants: $A = 493(10)$ MHz and $B = 3\,020(100)$ MHz.

4 Conclusion

Although many lines have been successfully investigated in recent years, we could clearly classify a large number of additional lines obtained from our spectral plates. In some cases we discovered unknown energy levels, enlarging the knowledge of the fine structure of the Ta I atom using the hyperfine structure of the spectral lines. Further investigations are in progress.

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