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Branching fractions and *A* values in singly ionized tantalum (Ta II)

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ABSTRACT

Aims. We report on the theoretical and experimental lifetimes of Ta II, and calculated branching fractions for selected transitions.
Methods. The theoretical data are obtained by means of a relativistic Hartree-Fock method with detailed attention to correlation effects. The experimental lifetimes are measured with the time-resolved, laser-induced, fluorescence technique.
Results. The calculated results are in good agreement with both previously known and new experimental lifetimes. New transition probabilities have been deduced for a set of Ta II transitions of astrophysical interest.

Key words. atomic processes – line: identification

1. Introduction

There is growing interest in atomic data of heavy ions in different fields of physics including plasma diagnostics in fusion research, absorption spectroscopy in environmental studies, and investigations of the chemical composition of astrophysical objects. As part of an on-going effort to meet this demand, we report on new transition probabilities in singly ionized tantalum (Ta II).

The richness and complexity of the Ta II spectrum impose severe limitations in determining absolute transition probabilities from either lifetime measurements or by absorption and emission methods, because of the need for reliable branching fractions. The experimental determination of these quantities is affected by: fragmentary knowledge of the atomic structure of this ion, even for low-lying configurations; intensity calibration over the wide wavelength range that must be considered and possible "missing" weak branches. As a consequence, the experimental transition probabilities are rather scarse in heavy ions in general, and in Ta II in particular, and must be supplemented by theoretical results.

The singly charged ion Ta^+ has strong $5d^36s$–$5d^36p$ transitions between levels of high J arising within terms of maximum spin. These transitions are suitable for diagnostic purposes when interpreting astrophysical spectra. However, they are strongly influenced by screening effects, configuration interaction, and relativistic contributions. They appear as an interesting challenge for atomic physicists because the theoretical lifetimes and branching fractions are very sensitive to the details of the configuration interaction included in the calculations.

In astrophysics, investigations of the tantalum abundance in the stars have been scarce partly due to the lack of strong transitions observable in accessible spectral ranges. So far, the solar photospheric abundance of tantalum has not yet been determined (see e.g. Asplund et al. 2006). However, Ta II has been investigated in the spectra of chemically peculiar stars including χ Lupi (see e.g. Eriksson et al. 2002).

We present a detailed set of calculated transition probabilities for many transitions in Ta II. The only data available of this nature are those of Corliss & Bozman (1962), which are well known to be affected by large systematic errors. The accuracy of the present results is assessed by comparison between theoretical and experimental lifetimes obtained here and in previous investigations.

The present work extends some results reported in neutral (Fivet et al. 2006) and also in doubly ionized tantalum (Ta III) (Fivet et al. 2008).

2. The theoretical model

According to Moore (1958), the ground state of Ta II is $5d^3(^4F)6s\ ^5F_1$, and the first excited configurations are $5d^26s^2$ and $5d^4$, which are of the same parity (even) as the ground configuration. Extensive contributions to the analysis of the Ta II spectrum are due to Kiess (1962) and, later on, to Wyart (1977) and Wyart & Blaise (1990). The latter investigations led to the elimination of "fortuitous" levels reported in earlier analyses. Our present investigation is based on these three analyses of Ta II.

Configuration interactions appear strong in between the $5d^N6p$, $5d^{N-1}6s6p$, and $5d^{N-2}6s^26p$ odd-parity configurations in the platinum-group elements, the latter configuration being generally unrecognizable. For the even-parity states, the strong interactions between $5d^N$, $5d^{N-1}6s$, and $5d^{N-2}6s^2$ configurations are well known and have been investigated in a systematic way with the parametric method (Wyart 1977).

Atomic-structure calculations in a heavy ion such as Ta II are realistic only if relativistic and correlation effects are considered simultaneously in the physical model. In the past, we performed a large number of atomic-structure calculations (see e.g. Biémont & Quinet 2003; Biémont 2005) using HFR approach (Cowan 1981), which is based on the non-relativistic Schrödinger equation but includes the most significant relativistic effects (Blume-Watson spin-orbit interaction, mass-velocity,

Table 1. Configurations considered for the two models retained for Ta II. For more details, see text.

HFR + CP(A)		HFR + CP(B)	
Even config.	Odd config.	Even config.	Odd config.
5d^{3}6s	5d^{3}6p	5d^{3}6s	5d^{3}6p
5d^{3}7s	5d^{3}7p	5d^{3}7s	5d^{3}7p
5d^{3}6d	5d^{3}5f	5d^{3}6d	5d^{3}5f
5d^4	5d^{3}6f	5d^4	5d^{3}6f
5d^{2}6s^2	5d^{2}6s6p	5d^{2}6s^2	5d^{2}6s6p
5d^{2}6p^2	5d^{2}6s7p	5d^{2}6p^2	5d^{2}6s7p
5d^{2}6d^2	5d^{2}6s5f	5d^{2}6d^2	5d^{2}6s5f
5d^{2}7s^2	5d^{2}6s6f	5d^{2}7s^2	5d^{2}6s6f
5d^{2}6s6d	5d^{2}6p6d	5d^{2}6s6d	5d^{2}6p6d
5d^{2}6s7s	5d6s^{2}6p	5d^{2}6s7s	5d6s^{2}6p
5d6s^{2}6d	5d6s^{2}5f	5d^{2}6p5f	5d^{2}6p7s
5d6s^{2}7s	5d6s^{2}6f	5d^{2}6d7s	
5d6s6p^2	5d6p^3		
6s^{2}6p^2	6s6p^3		
5d^{2}6p5f	5d^{2}6p7s		
6s^{2}6p5f	6s^{2}6p7s		
5d6s6p5f	5d6s6p6d		
5d^{2}6d7s	5d6s6p7s		
5d6s7s^2	6s^{2}6p6d		

and one-body Darwin terms). Configuration interaction can be included in calculations in an extensive way using either an ab initio approach or a semi-empirical one based on a least-squares fitting procedure applied to the calculated eigenvalues to obtain the most appropriate fit with the experimental energy levels. For more detailed and relevant references, we refer the reader to Biémont & Quinet (2003) and Biémont (2005).

In the present calculation, valence-valence type interactions have been considered by including in the configuration-interaction expansions, the configurations presented in Table 1.

Core-valence interactions were taken into account by using a polarization-model potential and a correction to the dipole operator following a well-established procedure (see e.g. Quinet et al. 1999) giving rise to the so-called HFR + CP method. In the present context, two different polarization models were considered. In the first model [HFR + CP(A)], we retained a 5s^{2}5p^{6}4f^{14} Ta^{5+} ionic core surrounded by 4 valence electrons. For the dipole polarizability, we adopted the value α_d = 3.18 a.u. (Fraga et al. 1976). The cut-off radius used was the HFR mean radius of the outermost core orbital and was chosen to equal r_c(5p) = 1.30 a.u. In a second model [HFR + CP(B)], a Ta^{3+} ionic core (5s^{2}5p^{6}4f^{14}5d^2) was considered to be surrounded by 2 valence electrons. The corresponding value of dipole polarisability was α_d = 6.75 a.u., and the cut-off radius r_c(5d) equalled 1.95 a.u. The two sets of configurations adopted in the calculations are reported in Table 1.

In the fitting procedure, we used all the experimentally established levels from Kiess (1962), Wyart (1977), and Wyart & Blaise (1990). All parameters related to the experimentally observed configurations have been adjusted to reproduce the experimental levels in the most accurate way. The standard deviations in the fitting procedures were 60 cm^{-1} and 120 cm^{-1} (model A), and 60 cm^{-1} and 140 cm^{-1} (model B), for the even and odd parities, respectively.

Comparisons between theoretical and experimental energy levels are reported in Tables 2 and 3 for the even and odd parities, respectively, and are limited to the levels $E < 45\,000$ cm^{-1} and $E < 65\,000$ cm^{-1}. In the same tables, we also compare the experimental and calculated Landé g-factors obtained with the two different models. The two sets of g-values agree quite well and are also in excellent agreement with the available experimental results (Wyart 1977; Wyart & Blaise 1990).

The calculated BFs for transitions originating in selected levels of Ta II are reported in Table 4, where contributions above 1% only are quoted. Due to space limitations, the table is restricted to odd-parity levels with energy $E < 44\,000$ cm^{-1}, for which experimental lifetimes are available (see Sect. 3). They should thus contain all the low-excitation transitions of astrophysical interest.

3. The experimental lifetimes

3.1. Previous work

Ta II lifetimes have been the subject of a number of experimental investigations. Six lifetimes were measured by Kwiatkowski et al. (1984) using selective laser excitation and time-resolved observation of the fluorescence light. The ions were produced by a sputtering technique in a low-pressure discharge. Pulsed laser excitation and time-resolved detection were applied by Bergström et al. (1986) in measuring 8 lifetimes using a low-pressure, hollow-cathode discharge as an ion source. Lifetimes of 10 levels in Ta II were obtained by Schade & Helbig (1986) using a similar technique. This work was extended with the same approach to 15 additional levels by Langhans et al. (1995). The latest lifetime measurements in Ta II (6 levels) were performed by Henderson et al. (1999) with the beam-foil spectroscopy technique.

3.2. New measurements

We report on lifetime measurements of three short-lived, odd-parity levels of Ta II obtained using TR-LIF spectroscopy on a laser-produced plasma. The TR-LIF technique has previously provided accurate lifetimes for neutral (Fivet et al. 2006) and doubly ionized tantalum (Fivet et al. 2008). Details of the experimental setup used in the present experiment were described elsewhere (see e.g. Bergström et al. 1986; Xu et al. 2003, 2004; Fivet et al. 2006, 2008) and only a brief description will be provided here.

Tantalum ions, in the ground as well as in excited states, were generated in a laser-produced plasma by focusing a 532 nm Nd:YAG laser pulse (Continuum Surelite) onto a rotating, tantalum target. The density and temperature of the expanding plasma were controlled and adjusted by changing the pulse energy and beam size incident on the target. The different ionization stages, having different velocities, could be separated by selecting an appropriate delay time between the ablation and excitation pulses.

The excitation pulses, obtained from a frequency-doubled Nd:YAG laser pulse (Continuum NY-82) transmitted into a temporal compressor, have a duration of 1−2 ns. To generate the required excitation wavelengths, the compressed pulses were used to pump a dye laser (Continuum Nd-60). Using the DCM dye, excitation wavelengths in the range 191−211 nm were obtained by non-linear processes, such as frequency doubling and tripling using KDP and BBO crystals and stimulated Raman scattering in a hydrogen-gas cell.

The excitation beam interacted with the tantalum ions about 1 cm above the target. The fluorescence, emitted from the excited levels, was collected by a fused-silica lens and focused onto the entrance slit of a 1/8 m monochromator, and then detected by a Hamamatsu 1564U micro-channel-plate photomultiplier tube

Table 2. Experimental and calculated energies (in cm^{-1}) and Landé g-factors for the lowest even-parity levels ($E < 45\,000$ cm^{-1}) of Ta II.

J	E(EXP)^a	g(EXP)^a	E(CALC)^b	g(CALC)^b	ΔE^b	E(CALC)^c	g(CALC)^c	ΔE^c
1	0.00	0.000	–27	0.035	27	–32	0.035	32
2	1031.36	1.008	1023	1.008	8	1021	1.009	10
3	2642.26	1.250	2641	1.247	1	2642	1.247	0
2	3180.04	0.750	3209	0.757	–29	3218	0.755	–38
0	4124.85		4074		51	4062		63
4	4415.79	1.350	4410	1.339	6	4412	1.339	4
1	5330.77	1.550	5303	1.559	28	5296	1.559	35
2	5657.90	1.340	5645	1.329	13	5651	1.332	7
5	6186.81	1.410	6175	1.381	12	6175	1.381	12
3	6831.31	1.098	6858	1.083	–27	6852	1.083	–21
2	9690.47	1.047	9678	1.066	12	9679	1.224	11
4	9746.28	1.225	9688	1.223	58	9698	1.065	48
1	10713.21	2.353	10778	2.361	–65	10781	2.361	–68
3	11767.16	0.908	11740	0.919	27	11733	0.916	34
2	11875.47	1.426	12003	1.399	–128	12010	1.402	–135
3	12435.85	1.594	12406	1.606	30	12410	1.607	26
0	12600.87		12589		12	12591		10
4	12705.33	1.019	12626	1.032	79	12627	1.032	78
4	12966.02	1.040	13073	1.039	–107	13072	1.038	–106
1	13475.38	1.498	13494	1.515	–19	13492	1.514	–17
2	13560.24	1.120	13593	1.135	–33	13609	1.133	–49
5	14158.51	1.150	14261	1.154	–102	14245	1.154	–86
2	14494.87	1.476	14501	1.469	–6	14497	1.006	–2
3	14581.07	0.988	14488	1.004	93	14496	1.469	85
1	14627.64	0.854	14638	0.841	–10	14623	0.842	5
3	15726.15	1.455	15720	1.461	6	15716	1.461	10
4	15851.12	1.140	15747	1.150	104	15752	1.149	99
0	16288.04		16378		–90	16364		–76
2	17168.48	1.204	17143	1.222	25	17138	1.221	30
4	17231.19	1.191	17206	1.151	25	17197	1.152	34
1	17375.00	1.170	17420	1.187	–45	17402	1.187	–27
6	17982.00	1.146	18054	1.167	–72	18038	1.167	–56
5	18186.04	1.100	18162	1.091	24	18149	1.091	37
4	18493.66	1.227	18448	1.246	46	18433	1.439	61
2	18500.62	1.441	18454	1.439	47	18450	1.247	51
3	18553.83	1.355	18514	1.333	40	18504	1.333	50
2	22928.61	0.700	22977	0.705	–48	23011	0.711	–82
4	23082.71	1.026	23038	1.023	45	23048	1.020	35
2	23294.77	1.118	23232	1.106	63	23202	1.099	93
0	23381.28		23304		77	23302		79
1	23406.13		23445	1.163	–39	23477	1.165	–71
3	23620.35	1.076	23658	1.073	–38	23692	1.072	–72
5	24226.20	1.000	24233	1.009	–7	24262	1.009	–36
4	24432.83	0.985	24581	0.998	–148	24573	0.991	–140
3	24869.58	0.995	24875	0.985	–5	24882	0.986	–12
4	25385.49	1.085	25315	1.094	70	25305	1.103	80
5	25414.13	1.060	25457	1.056	–43	25455table	1.056	–41
6	26010.70	1.117	26043	1.136	–32	26038	1.136	–27
1	26234.60	1.332	26298	1.342	–63	26302	1.340	–67
0	26722.38		26654		68	26647		75
3	26829.13	0.850	26820	0.851	9	26827	0.850	2
2	28044.14	1.358	28048	1.367	–4	28053	1.368	–9
4	28165.40	1.094	28171	1.055	–6	28176	1.056	–11
2	29843.58	0.833	29803	0.823	41	29810	0.818	34
1	29963.20	1.004	29987	1.020	–24	29983	1.034	–20
5	30349.83	1.165	30289	1.177	61	30305	1.177	45
2	30405.61	1.051	30395	1.083	11	30405	1.088	1
3	30624.09	1.257	30665	1.247	–41	30676	1.246	–52
6	30954.00	1.020	30963	1.031	–9	30955	1.031	–1
4	31267.10	1.120	31204	1.126	63	31183	1.125	84
3	31531.70	1.130	31516	1.125	16	31533	1.126	–1
0	31924.75		31947		–22	31948		–23
1	31948.68	1.000	31979	0.981	–30	31989	0.966	–40
2	33027.18	1.020	33203	1.072	–176	33204	1.075	–177
2	34879.69	1.400	34973	1.379	–93	34973	1.375	–93
4	35151.35	1.078	35080	1.084	71	35087	1.085	64

Table 2. continued.

J	E(EXP)^a	g(EXP)^a	E(CALC)^b	g(CALC)^b	ΔE^b	E(CALC)^c	g(CALC)^c	ΔE^c
3	36614.88	1.235	36538	1.307	77	36544	1.307	71
2	37274.31	1.105	37192	1.118	82	37203	1.119	71
1			37379	0.508		37415	0.508	
0			37976			37922		
3	40369.15	1.050	40440	1.072	–71	40437	1.072	–68
4	40904.37	1.220	40795	1.224	109	40786	1.224	118
2			41120	0.709		41123	0.709	
2	41513.54	1.460	41571	1.479	–57	41583	1.479	–69
3	43606.36		43574	1.027	32	43579	1.027	27
1			44136	1.493		44159	1.493	

^{a} From Wyart (1977) and Wyart & Blaise (1990); ^{b} this work: model [HFR + CP(A)]; ^{c} this work: model [HFR + CP(B)].

Table 3. Experimental and calculated energies (in cm^{-1}) and Landé g-factors for the lowest odd-parity levels ($E < 65\,000$ cm^{-1}) of Ta II.

J	E(EXP)^a	g(EXP)^a	E(CALC)^b	g(CALC)^b	ΔE^b	E(CALC)^c	g(CALC)^c	ΔE^c
2	29256.87	0.511	29523	0.499	–266	29467	0.506	–210
3	32318.44	0.976	32338	0.975	–20	32310	0.977	8
1	33706.47	0.285	33487	0.231	219	33554	0.233	152
2	33715.27	0.823	33850	0.890	–135	33883	0.866	–168
4	36112.97	1.180	36083	1.168	30	36068	1.168	45
2	36177.10	0.946	35993	0.859	184	36031	0.884	146
3	36763.70	1.169	36874	1.200	–110	36888	1.187	–124
1	36987.71	0.685	37208	0.753	–220	37247	0.761	–259
0			37595			37660		
2	37230.75	0.623	37602	0.704	–371	37553	0.700	–322
2	38515.55	1.006	38544	0.968	–28	38532	0.986	–16
1	38535.21	0.472	38216	0.433	319	38315	0.471	220
3	38962.32	0.976	39197	0.982	–235	39025	1.139	–63
3	39295.81	1.138	39010	1.144	286	39164	0.992	132
4	39743.67	1.223	39799	1.252	–55	39767	1.244	–23
5	39758.81	1.270	39745	1.275	14	39723	1.274	36
0	40023.68		40023		1	40121		–97
2	40233.46	1.165	40263	1.108	–30	40302	1.119	–69
1	40304.78	1.225	40210	1.177	95	40284	1.146	21
2	41144.94	1.152	41025	1.165	120	41222	1.180	–77
1	41355.11	1.885	41508	1.911	–153	41388	1.909	–33
3	41554.42	1.207	41507	1.242	47	41492	1.258	62
5	41709.01	1.244	41759	1.257	–50	41675	1.257	34
4	41775.29	1.249	41815	1.244	–40	41799	1.253	–24
4	42122.91	1.258	42034	1.268	89	42003	1.258	120
2	42153.29	1.212	42086	1.202	67	42174	1.180	–21
3	42959.55	1.120	42926	1.127	34	42973	1.117	–13
2	43064.86	1.041	43022	1.089	43	43174	1.056	–109
0	43068.72		43153		–84	43040		29
3	43544,46	1.059	43603	1.046	–59	43598	1.035	–54
1	43553.67		43547	1.420	7	43421	1.429	133
4	44005.20	1.137	43949	1.208	56	43888	1.241	117
1	44206.24	0.242	44004	0.313	202	44068	0.309	138
2	44259.20	1.256	44140	1.253	119	44113	1.256	146
3	44430.39	0.940	44442	0.954	–12	44405	0.948	25
0	44434.79		44454		–19	44407		28
5	44585.17	1.297	44538	1.271	47	44549	1.274	36
6			44580	1.331		44480	1.331	
4	44626.00	1.265	44660	1.184	–34	44583	1.153	43
3	44835.20	1.242	44747	1.229	88	44873	1.238	–38
1	45233.91	1.458	45229	1.446	5	45223	1.458	11
2	45446.85	1.148	45470	1.098	–23	45510	1.099	–63
1	46174.60	1.367	46121	1.359	54	46136	1.360	39
5	46295.03	1.200	46472	1.202	–177	46391	1.198	–96
2	46387.16	1.323	46509	1.337	–122	46541	1.348	–154
4	46645.70	1.233	46487	1.216	159	46462	1.196	184
3	46831.35	1.214	46714	1.198	117	46817	1.212	14
2	46850.64	1.110	46910	1.016	–59	47073	1.036	–222
3	47168.90	1.096	47128	1.097	41	47128	1.104	41
4	47280.89	1.190	47268	1.223	13	47274	1.227	7

Table 3. continued.

J	*E*(EXP)[a]	*g*(EXP)[a]	*E*(CALC)[b]	*g*(CALC)[b]	Δ*E*[b]	*E*(CALC)[c]	*g*(CALC)[c]	Δ*E*[c]
2	47514.52	1.284	47578	1.341	–63	47609	1.304	–94
1	47595.98	1.520	47687	1.493	–91	47767	1.519	–171
0	47801.03		47853		–52	48003		–202
3	47825.41	1.189	47775	1.190	50	47871	1.216	–46
6	47829.75	1.300	47751	1.299	79	47570	1.300	260
0	48064.57		48161		–96	48234		–169
4	48162.10	1.030	48197	1.157	–35	48183	1.057	–21
2	48223.08	1.446	48329	1.268	–106	48279	1.262	–56
4	48470.41	1.276	48419	1.089	51	48468	1.203	2
2	48666.56	1.131	48605	1.395	62	48598	1.519	69
1	48776.29	0.746	48666	0.772	110	48818	0.830	–42
3	48962.54	1.283	48919	1.303	44	48926	1.342	37
5	49055.18	1.212	48982	1.246	73	48915	1.248	140
2	49080.51	1.320	49076	1.344	5	49083	1.255	–2
3	49536.24	1.317	49359	1.343	177	49363	1.280	173
2	49592.90	1.629	49583	1.588	10	49365	1.613	228
3	49646.62	1.048	49630	1.041	17	49685	1.053	–38
1	49886.97	2.006	49813	1.922	74	49653	2.066	234
4	49937.74	1.207	49961	1.207	–23	49911	1.219	27
3	50314.43	1.281	50262	1.263	52	50201	1.268	113
5	50507.12	1.080	50580	1.102	–73	50604	1.103	–97
1	50531.17	1.370	50224	1.535	307	50134	1.416	397
3	51073.92	1.156	51089	1.209	–15	50907	1.247	167
2	51197.42	1.359	51205	1.350	–8	51187	1.356	10
1	51326.31	1.047	51218	1.124	108	51287	1.444	39
0	51334.37		51285		49	51043		291
4	51479.86	1.095	51454	1.124	26	51537	1.127	–57
2	51534.28	1.299	51693	1.285	–159	51729	1.277	–195
5	51753.70	1.102	51916	1.105	–162	51809	1.107	–55
3	52121.15	1.086	51986	1.128	135	52096	1.159	25
1	52155.76	1.613	51890	1.448	266	51916	1.023	240
4	52492.98	1.101	52595	1.076	–102	52371	1.063	122
1	52824.49	0.907	52935	0.982	–111	52923	0.955	–99
6	52846.28	1.180	52977	1.154	–131	52838	1.158	8
4	52897.80	1.375	52983	1.191	–85	52960	1.285	–62
3			52953	1.371		52949	1.372	
2	53010.95	1.464	53016	1.544	–5	52939	1.609	72
5	53234.65	1.146	53343	1.170	–108	53271	1.170	–36
4	53343.56	1.071	53351	1.318	–7	53447	1.257	–103
3	53465.79	1.216	53285	1.221	181	53380	1.165	86
2	53644.83	1.352	53652	1.301	–7	53678	1.267	–33
1	53746.80	1.234	53802	1.199	–55	53488	1.214	259
5	54048.81	1.260	54062	1.204	–13	54073	1.208	–24
4	54206.69	1.157	54339	1.136	–132	54245	1.102	–38
2	54533.78	1.016	54524	0.939	10	54874	1.077	–340
3	54648.73	0.943	54937	0.940	–288	54999	1.280	–350
3	55128.38	1.260	55091	1.339	37	55216	1.055	–88
0	55295.66		55433		–137	55168		–128
4	55381.25	1.020	55607	1.047	–226	55819	1.337	–438
5	55505.08	1.054	55560	1.070	–55	55623	1.041	–118
1	55528.22	1.464	55312	1.431	216	55451	1.380	77
3	55543.11	1.430	55558	1.340	–15	55557	1.313	–14
2	55551.60	1.031	55532	1.359	20	55651	1.408	–99
2	55859.32	1.343	55878	1.234	–19	55949	1.057	–90
1	55878.70	1.425	55973	1.388	–94	56019	1.393	–140
2	56018.76	1.002	56180	0.852	–161	56293	0.904	–274
4	56142.53	1.270	56057	1.357	86	55923	1.144	220
3	56450.95	1.195	56452	1.238	–1	56492	1.272	–41
5	56521.78	0.980	56612	0.990	–90	56734	1.006	–212
6	56662.76		56529	1.099	134	56684	1.096	–21
4	56753.05	1.197	56639	0.996	114	56481	0.895	272
0			56640			56882		
2			56843	1.366		56588	1.254	
4	56987.88	1.118	56863	1.259	125	56790	1.254	198
3	57060.81	1.390	57158	1.322	–97	57109	1.241	–48
1	57195.81	1.726	57187	1.745	9	57192	1.773	4

Table 3. continued.

J	E(EXP)^a	g(EXP)^a	E(CALC)^b	g(CALC)^b	ΔE^b	E(CALC)^c	g(CALC)^c	ΔE^c
2	57791.58	1.050	57945	1.010	–153	57960	1.189	–168
4	58040.89	1.045	57892	1.054	149	57953	1.065	88
1	58069.18	1.147	57976	1.086	93	57952	1.083	117
3	58108.52	1.145	57809	1.128	300	57957	1.103	152
6	58125.90	1.075	58070	1.087	56	58019	1.090	107
2	58274.85	1.641	58496	1.709	–221	58299	1.521	–24
5	58572.56		58574	1.124	–1	58575	1.107	–2
3			59582	0.949		59616	1.000	
2	59351.96	1.160	59624	1.164	–272	59877	1.202	–525
5	59692.16		59747	1.091	–55	59406	1.105	286
4	59835.92	1.055	59729	1.052	107	59969	1.023	–133
7	59958.59	1.140	59773	1.143	186	59826	1.143	132
3	60241.07	1.176	60054	1.244	187	59844	1.243	397
3	60325.15	1.151	60219	1.134	106	60198	1.104	127
1	60479.60	0.662	60577	0.702	–97	60531	0.679	–51
2	60870.30	1.130	60881	1.100	–11	61277	1.049	–407
4	61105.69	1.007	60999	1.042	107	60911	1.092	195
6	61588.16		61700	1.092	–112	61682	1.113	–94
3	61694.17	0.937	61532	0.924	162	61812	0.925	–118
4	62115.97	1.070	62279	1.054	–163	62346	1.057	–230
5	62204.91		62223	1.066	–18	62362	1.086	–157
1	62296.25	0.600	62095	0.637	201	62237	0.645	59
2	62317.92	0.986	62318	1.055	0	61770	1.032	548
3			62639	1.158		62425	1.179	
1	62854.50	0.908	63048	0.938	–194	63057	0.886	–203
2	63060.46	1.106	63093	0.984	–33	62907	1.094	153
2			63369	0.862		63606	0.831	
3			63550	1.014		63175	1.003	
0			63763			63799		
5	63703.35	0.977	63882	1.127	–179	64009	1.117	–306
4	63820.47	1.010	63807	1.110	13	63554	1.109	266
6	64028.85	1.105	63895	1.132	134	63438	1.105	591
2			64007	0.846		65021	0.796	
3	64121.16	1.180	64279	1.145	–158	64056	1.147	65
1			64341	0.883		64798	1.065	
3	64653.35	1.079	64906	1.063	–253	64898	1.033	–245

[a] From Wyart (1977) and Wyart & Blaise (1990); [b] this work: calculation [HFR + CP(A)]; [c] this work: calculation [HFR + CP(B)].

Table 4. Calculated branching fractions (BF) and normalized transition probabilities (A, in s^{-1}) for transitions originating in selected odd-parity levels of Ta II ($E < 44\,000$ cm^{-1}). Contributions above 1% only are quoted.

$E_{\rm upp}$(cm^{-1})	J	τ(ns)^c	$E_{\rm low}$(cm^{-1})	J	BF^a	$A_{\rm NORM}$(s^{-1})^b
33706.464	1	22.8	0.000	1	0.3296	1.446(7)
			3180.142	2	0.2862	1.255(7)
			4124.880	0	0.1551	6.803(6)
			5330.820	1	0.0600	2.632(6)
			5657.949	2	0.0404	1.772(6)
			9690.489	2	0.0632	2.772(6)
			11875.518	2	0.0140	6.140(5)
			12600.870	0	0.0179	7.851(5)
			13475.400	1	0.0128	5.614(5)
36177.194	2	13.9	0.000	1	0.2051	1.476(7)
			1031.418	2	0.5358	3.855(7)
			5330.820	1	0.0757	5.446(6)
			5657.949	2	0.0796	5.727(6)
			6831.441	3	0.0432	3.108(6)
			9690.489	2	0.0186	1.338(6)
36763.759	3	15.6	1031.418	2	0.6030	3.865(7)
			2642.306	3	0.0112	7.179(5)
			3180.142	2	0.0575	3.686(6)
			5657.949	2	0.1233	7.904(6)
			6831.441	3	0.1118	7.167(6)
			9746.375	4	0.0151	9.679(5)
			14494.873	2	0.0110	7.051(5)

Table 4. continued.

E_{upp}(cm^{-1})	J	τ(ns)[c]	E_{low}(cm^{-1})	J	BF[a]	A_{NORM}(s^{-1})[b]
36987.724	1	12.2	0.000	1	0.1903	1.560(7)
			1031.418	2	0.1017	8.336(6)
			4124.880	0	0.4584	3.757(7)
			5330.820	1	0.0508	4.164(6)
			5657.949	2	0.0238	1.951(6)
			9690.489	2	0.0560	4.590(6)
			11875.518	2	0.0442	3.623(6)
			12600.870	0	0.0291	2.385(6)
			13560.282	2	0.0167	1.369(6)
37230.738	2	5.4	0.000	1	0.6627	1.227(8)
			1031.418	2	0.2367	4.383(7)
			2642.306	3	0.0159	2.945(6)
			5330.820	1	0.0445	8.241(6)
38515.698	2	14.4	0.000	1	0.3452	2.397(7)
			2642.306	3	0.0372	2.583(6)
			3180.142	2	0.0111	7.708(5)
			5330.820	1	0.2906	2.018(7)
			5657.949	2	0.0304	2.111(6)
			6831.441	3	0.1440	1.000(7)
			10713.300	1	0.0177	1.229(6)
			11767.262	3	0.0166	1.153(6)
			13475.400	1	0.0222	1.542(6)
			14581.064	3	0.0403	2.799(6)
38535.375	1	6.9	0.000	1	0.3250	4.710(7)
			1031.418	2	0.2994	4.339(7)
			3180.142	2	0.0748	1.084(6)
			4124.880	0	0.1560	2.261(7)
			5657.949	2	0.0937	1.358(7)
			9690.489	2	0.0231	3.348(6)
38962.375	3	6.2	1031.418	2	0.5868	9.465(7)
			2642.306	3	0.3656	5.897(7)
			9690.489	2	0.0183	2.952(6)
39743.630	4	12.6	2642.306	3	0.6900	5.476(7)
			6831.441	3	0.0833	6.611(6)
			9746.375	4	0.0586	4.651(6)
			11767.262	3	0.0875	6.944(6)
			14581.064	3	0.0258	2.048(6)
			15726.107	3	0.0222	1.762(6)
41145.119	2	4.8	0.000	1	0.1220	2.542(7)
			1031.418	2	0.1386	2.887(7)
			2642.306	3	0.2217	4.619(7)
			5330.820	1	0.1512	3.150(7)
			5657.949	2	0.1406	2.929(7)
			6831.441	3	0.0242	5.042(6)
			9690.489	2	0.0138	2.875(6)
			10713.300	1	0.0375	7.812(6)
			11767.262	3	0.0505	1.052(7)
			13475.400	1	0.0198	4.125(6)
			13560.282	2	0.0192	4.000(6)
			14581.064	3	0.0358	7.458(6)
41775.291	4	6.4	2642.306	3	0.3446	5.384(7)
			4415.764	4	0.5124	8.006(7)
			6831.441	3	0.0445	6.953(6)
			9746.375	4	0.0104	1.625(6)
			11767.262	3	0.0131	2.047(6)
			12435.850	3	0.0301	4.703(6)
			12705.402	4	0.0216	3.375(6)
42959.625	3	6.0	1031.418	2	0.0652	1.087(7)
			2642.306	3	0.0703	1.172(7)
			3180.142	2	0.0145	2.417(6)
			4415.764	4	0.3202	5.337(7)
			5657.949	2	0.3361	5.602(7)
			9690.489	2	0.0262	4.367(6)
			9746.375	4	0.0277	4.617(6)
			11767.262	3	0.0818	1.363(7)
			12966.020	4	0.0197	3.283(6)

Table 4. continued.

$E_{\rm upp}$(cm^{-1})	J	τ(ns)[c]	$E_{\rm low}$(cm^{-1})	J	BF[a]	$A_{\rm NORM}$(s^{-1})[b]
43064.948	2	9.0	1031.418	2	0.1537	1.708(7)
			2642.306	3	0.1766	1.962(7)
			3180.142	2	0.0246	2.733(6)
			5657.949	2	0.2845	3.161(7)
			6831.441	3	0.1446	1.607(7)
			9690.489	2	0.0114	1.267(6)
			10713.300	1	0.0277	3.078(6)
			11875.518	2	0.0198	2.200(6)
			13475.400	1	0.0187	2.078(6)
			13560.282	2	0.0679	7.544(6)
			17375.110	1	0.0144	1.600(6)
			23294.700	2	0.0113	1.444(6)

[a] This work: calculation HFR + CP(A) (see the text); [b] normalized transition probabilities (in s^{-1}). $a(b)$ is written for a 10^b; [c] lifetime value adopted for the normalization. When several experimental results are available, a mean value has been calculated (see the text).

Table 5. Radiative lifetimes for odd-parity levels of Ta II (in ns) ($E < 44\,000$ cm^{-1}).

E(cm^{-1})	J	Exp.	Exp.	HFR + CP(A)	HFR + CP(B)
		Previous	This work	This work	This work
33706.464	1		22.8(1.0)	23.1	29.8
36177.194	2	13.9(9)[c]		10.4	14.0
36763.759	3	15.4(9)[a], 15.8(9)[c]		16.7	21.2
36987.724	1	12.2(8)[c]		7.7	10.1
37230.738	2	5.5(3)[a], 5.2(5)[b], 5.6(3)[c]		5.2	6.2
38515.698	2	13.2(9)[a], 14.7(15)[b], 15.3(8)[c]		13.3	16.5
38535.375	1	6.9(4)[a], 6.6(6)[b], 7.1(3)[c]		7.0	8.7
38962.375	3	6.2(4)[c]		3.6	4.5
39295.954	3	15.4(8)[a], 13.6(14)[b], 15.8(8)[c]		34.8	60.6
39743.630	4	12.6(9)[c]		13.4	15.1
41145.119	2	4.8(4)[a], 4.8(5)[b]		5.1	5.9
41775.291	4	6.6(5)[c], 6.2(6)[e]		4.9	6.7
42959.625	3		6.0(4)	4.3	5.8
43064.948	2		9.0(5)	6.6	8.8

[a] Kwiatkowski et al. (1984); [b] Bergström et al. (1986); [c] Schade & Helbig (1986); [d] Langhans et al. (1995); [e] Henderson et al. (1999).

with a risetime of 0.2 ns and a fall time of 0.6 ns. The signal was recorded by a transient digitizer with a time resolution of 0.5 ns.

In the measurements, the laser pulse and the fluorescence signal were recorded alternatively with the same detection system.

The new experimental lifetime values are reported in Table 5 for the three levels considered at 33 706, 42 960, and 43 065 cm^{-1}. These 3 lifetimes are averages for at least ten recordings. The error bars take into account the statistical uncertainties from the fitting as well as variations between the different recordings. There are no other experimental lifetimes available for comparison.

3.3. Discussion

The calculated lifetimes are given in Table 5 for the low-lying levels ($E < 44\,000$ cm^{-1}) of the odd configurations for which they are compared with the previous experimental results, and also with the 3 new lifetimes obtained in the present work.

It is obvious that the theoretical values for the level at 39 296 cm^{-1}, which disagree with the two experimental values available, are unreliable, the reason being cancellation effects affecting some depopulation channels of this level.

For two levels measured in the present work, the model HFR + CP(B) is in better agreement with the experimental results than the model HFR + CP(A), while the opposite is true for the third level. On the one hand, the model A is in good agreement with the experimental results of both Kwiatkowski et al. (1984) and Bergström et al. (1986). For some levels, on the other hand, the model B agrees quite well with the experimental results of Schade & Helbig (1986). On the basis of this comparison, it is not obvious to decide which model provides the best description of the data. However, the BFs obtained in the two calculations agree quite well (to within a few percent of each other particularly for the strongest transitions).

The transition probabilities (A) for the strongest transitions depopulating the levels of Table 5 are presented in Table 4. They were obtained by combining the experimental lifetimes (either measured in the present work or taken from previous analyses; when several values were available, the mean value was adopted; see Col. 3 of Table 4) with theoretical BFs (which were calculated in the present work with the model A).

Table 4 has been limited to the lines with depopulation channels for which $gA > 10^8$ s^{-1}. Additional results, for the weaker transitions, will be available in the database DESIRE[1].

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[1] This database is available at the URL address: `http://w3.umh.ac.be/~astro/desire.shtml`

4. Conclusions

On the basis of the laser lifetime measurements and HFR calculations performed in the present work, the following conclusions are valid:

1. New BFs and *A*-values have been obtained for a large set of Ta II transitions of astrophysical interest.
2. The accuracy of the results has been assessed by comparing HFR lifetime values with experimental results obtained using the time-resolved, laser-induced, fluorescence technique. The agreement observed between the theoretical results and experimental measurements is good.
3. The new results are expected to be accurate to within a few percent at least for the most intense transitions. Large inaccuracies are possible for the weaker lines, particularly when cancellation effects are present in the calculation of the line strengths. These new results are expected to be useful to astrophysicists investigating some stellar spectra.
4. The present work calls for additional experimental investigations of branching fractions or transition probabilities in this ion.

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References

Asplund, M., Grevesse, N., & Sauval, A. J. 2006, Nucl. Phys. A, 777, 1
Bergström, H., Lundberg, H., Persson, A., Schade, W., & Zhao, Y. Y. 1986, Phys. Scr., 33, 513
Biémont, É. 2005, Phys. Scr. T, 119, 55
Biémont, É., & Quinet, P. 2003, Phys. Scr. T, 105, 38
Corliss, C. H., & Bozman, W. R. 1962, Nat. Bur. Stand. (US), Monogr. 53, Washington D.C.
Cowan, R. D. 1981, The Theory of Atomic Structure and Spectra (Berkeley: University of California Press)
Eriksson, M., Litzén, U., Wahlgren, G. M., & Leckrone, D. S. 2002, Phys. Scr., 65, 480
Fivet, V., Palmeri, P., Quinet, P., et al. 2006, Eur. Phys. J. D, 37, 29
Fivet, V., Biémont, É., Engström, L., et al. 2008, J. Phys. B: At. Mol. Opt. Phys., 41, 015702
Fraga, S., Karwowski, J., & Saxena, K. M. S. 1976, Handbook of Atomic Data (Amsterdam: Elsevier)
Henderson, M., Irving, R. E., Matulioniene, R., et al. 1999, ApJ, 520, 805
Kiess, C. C. 1962, J.R.N.B.S., 66A, 111
Kwiatkowski, M., Naumann, F., Werner, K., & Zimmermann, P. 1984, Phys. Lett. A, 103, 49
Langhans, G., Schade, W., & Helbig, V. 1995, Z. Phys. D, 34, 151
Moore, C. E. 1958, Atomic Energy Levels, Vol. III, NBS Circ., 467
Quinet, P., Palmeri, P., Biémont, É., et al. 1999, MNRAS, 307, 934
Schade, W., & Helbig, V. 1986, Phys. Lett. A, 115, 39
Wyart, J.-F., & Blaise, J. 1990, Phys. Scr., 42, 209
Wyart, J.-F. 1977, Optica Pura y Aplic., 10, 177
Xu, H. L., Jiang, Z. K., Zhang, Z. G., et al. 2003, J. Phys. B: At. Mol. Opt. Phys., 36, 1771
Xu, H. L., Persson, A., Svanberg, S., et al. 2004, Phys. Rev. A, 70, 042508