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Radiative decay rates for W I, W II and W III allowed and forbidden transitions of interest for spectroscopic diagnostics in fusion plasmas

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Abstract

Transition probabilities for allowed and forbidden lines in neutral, singly ionized and doubly ionized tungsten are discussed in the present paper. For the electric dipole transitions, recommended values are proposed from a critical evaluation of the data available in the literature. For the magnetic dipole and electric quadrupole transitions, for which no data have been published so far, a new set of radiative rates has been obtained using a relativistic Hartree–Fock approach including core-polarization effects. The tables summarizing the compiled data are expected to be useful for plasma modelling in fusion reactors.

1. Introduction

Because of its high melting point (3410 °C) and thermal conductivity, and its low tritium retention and erosion rate under plasma loading (see e.g. Federici *et al* 2001, Pospieszczyk 2006), tungsten is a very attractive element to be used as a plasma facing material in tokamak devices. The international thermonuclear experimental reactor ITER will be the next step experimental fusion device which will use tungsten, together with beryllium and carbon-fiber reinforced composite, as plasma facing materials. The main disadvantage of tungsten in these conditions is the large radiative loss due to plasma contamination and its high radiative efficiency.

Several experiments were also carried out at Alcator C-mod (Lipschultz *et al* 2001) and at ASDEX-U (Neu *et al* 2005) to prove the suitability of W as a divertor target material under the conditions of a high-density and low-temperature divertor.

In tokamak devices, tungsten will be sputtered from the plasma wall as a neutral element and the intensity of the well-known W I emission line at 400.8753 nm may be used to estimate tungsten influx (Skinner 2008). Unfortunately, as already mentioned by the latter author, a complication arises from the fact that there exists a coincident W II line at 400.8751 nm. Another difficulty originates from the fact that sputtered high-*Z* metal atoms, such as tungsten, have a low ionization potential (7.864 eV) and a relatively low velocity. They are quickly ionized close to the surface and most ions are promptly redeposited onto the wall near their point of origin (Skinner 2009).

Estimates of the tungsten influx rate to the core plasma will depend on a calculation of transport from the wall surface through the scrape-off layer. Consequently, the identification of emission lines from neutral and lowly ionized tungsten will greatly aid modelling of the plasma edge and scrape-off layer transport and facilitate the analysis of net tungsten influx rates.

However, a very small number of contributions have been devoted, in the past, to the determination of radiative data for the lower charge states of tungsten. The aim of the present paper is to report on the best transition rates for selected electric dipole (E1) transitions and to fill in the gap regarding the transition probabilities for forbidden (E2 and M1) lines in neutral (W I), singly ionized (W II) and doubly ionized (W III) tungsten.

2. Allowed transitions

2.1. W I lines

Wavelengths of all the transitions observed in the W I spectrum, and energy levels derived from these wavelengths, were compiled by Kramida and Shirai (2006) who critically evaluated the data published previously by Laun and Corliss (1968), Shadmi and Caspi (1968), Corliss (1969), Wyart (1978), Martin *et al* (1978) and Campbell-Miller and Simard (1996).

Experimental transition probabilities in W I were first determined by Corliss and Bozman (1962) but their arc measurements later on were recognized to be affected by large systematic errors. These results were supplemented by the relative measurements of Clawson and Miller (1973) and by the absolute measurements of Obbarius and Kock (1982). In the latter case, a stabilized arc, operated in argon, was used for measuring oscillator strengths for 43 W I lines in the wavelength range 240–560 nm.

The first radiative lifetime measurements in W I were performed for 15 levels belonging to the $5d^46s6p$ and $5d^56p$ configurations by Duquette *et al* (1981) who used time-resolved laser-induced fluorescence (TR-LIF) and a hollow cathode effusive atomic beam source. Kwiatkowski *et al* (1982) reported lifetimes for 13 energy levels in the configurations $(5d+6s)^56p$. These measurements were based on the observation of the re-emitted fluorescence with a single-photon-counting technique after a selective excitation of an atomic beam by a pulsed dye laser. Some radiative lifetimes of W I excited states were also published by Plekhotkin and Verolainen (1985).

The lifetimes by Schnabel and Kock (1997), obtained with the TR-LIF method for 47 W I levels in the energy range 27 800–48 200 cm^{-1}, agree within the mutual uncertainties with the results of Den Hartog *et al* (1987) (three lifetimes common to both works). The lifetimes by Kwiatkowski *et al* agree within 7% with those of Den Hartog *et al* (1987) (13 levels in common), the latter work including remeasurements of the values published by Duquette *et al* (1981). It is thus obvious that the three scales of published lifetimes measured with reliable techniques (laser spectroscopy) are in excellent agreement.

The most recent and extensive sets of experimental decay rates in neutral tungsten were reported by Den Hartog *et al* (1987) and Kling and Kock (1999) who measured branching fractions (BF) on high-resolution Fourier transform spectra and were able to deduce absolute transition probabilities for a set of 572 lines covering the wavelength range 225–1035 nm and involving excited energy levels up to 46 932 cm^{-1}. The lifetimes used in these two papers were those of Den Hartog *et al* (1987) and of Schnabel and Kock (1997), respectively. As the work of Kling and Kock (1999) was focused on higher lying levels than that of Den Hartog *et al* (1987), the overlap of the two works is small. In fact, BFs were measured for only 19 lines in common. The agreement is within a few (<7)% for the most intense transitions (BF $>$ 20%), larger discrepancies appearing (as expected) for some weaker lines. In the present work, we have adopted the transition probabilities reported by Den Hartog *et al* (1987) and Kling and Kock (1999). According to these authors, the uncertainties affecting their results are smaller than 10% for the majority of the transitions.

We report in table 1 a list of selected lines of W I covering the UV and visible regions and suitable for plasma diagnostics. This line list has been established by adopting the following criteria. The lines are unblended according to the wavelength compilation of Kramida and Shirai (2006). The list is also limited to the strongest transitions, i.e. the transitions such that the laboratory intensities (Int.) $\geqslant$100. We are conscious however that this choice has its own limitations and is partly dependent upon the physical conditions met in the light source used for establishing the intensity scale. For all the selected transitions, reliable transition probabilities and oscillator strengths are available. They are due to Den Hartog *et al* (1987) and Kling and Kock (1999). It is seen, from the last column of table 1, that these two sets of transition probabilities agree quite well for the six transitions common to both works.

It should be emphasized that the well-known W I emission line at 400.8753 nm, tentatively used for plasma diagnostics as stated in the introduction, has been kept in table 1 despite of the fact that it is blended with a W II line appearing at 400.8751 nm. This line is among the strongest observed in the laboratory and, for that reason, deserves to be considered with a special attention (see the discussion in section 2.2).

2.2. W II lines

76 even levels and 187 odd levels belonging to singly ionized tungsten were reported in the compilation of Kramida and Shirai (2006) which was essentially based on the extensive investigations of the W II spectrum by Ekberg *et al* (2000) and by Cabeza *et al* (1985).

After the pioneering work by Corliss and Bozman (1962), relative and absolute transition probabilities were determined by Clawson and Miller (1973) and Obbarius and Kock (1982), respectively. The latter authors published oscillator strengths for 27 W II transitions between 240 and 560 nm.

Substantial progress in radiative parameter determination in W II resulted from the combination of lifetime measurements with BF determinations. Different sets of lifetimes were reported. Kwiatkowski *et al* (1984) measured three lifetimes using the TR-LIF method, the ions being produced by the sputtering technique in a low-pressure discharge. Using the TR-LIF technique, radiative lifetime measurements were also carried out by Schnabel *et al* (1998) for 19 selected levels with energies between 36 000 and 55 000 cm^{-1} and by Schulz-Johanning *et al* (1999) who used a linear Paul trap for investigating two W II lifetimes. More recently, Henderson *et al* (1999) reported three lifetime values using the beam-foil method. These results were combined with theoretical and experimental BFs deduced from Corliss and Bozman (1962) arc measurements.

The lifetimes by Schnabel *et al* (1998) agree, within the quoted uncertainties, with the results of Kwiatkowski *et al* (1984) for two levels, the measurement reported by these authors for 42 390.27 cm^{-1} being obviously in error

Table 1. UV and visible transitions of neutral tungsten (W I) suitable for plasma diagnostics. For the choice of the lines, see the text.

λ[a] (nm)	E^{b}_{low} (cm^{-1})	J	$E^{b}_{upp.}$ (cm^{-1})	J'	Int.[b]	log gf	gA (s^{-1})
245.1996	0.00	0	40 770.78	1	100	−0.68[c]	2.34(8)[c]
245.6534	3325.53	2	44 021.00	3	150	−0.53[c]	3.30(8)[c]
245.9300	3325.53	2	43 975.22	2	140	−0.41[c]	4.31(8)[c]
246.6848	3325.53	2	43 850.84	3	100	−0.35[c]	4.52(8)[c]
247.4149	6219.33	4	46 625.05	4	140	−0.01[c]	1.07(9)[c]
248.0130	1670.29	1	41 978.62	2	100	−0.67[c]	2.35(8)[c]
248.1440	6219.33	4	46 506.37	5	150	0.18[c]	1.63(9)[c]
249.5264	1670.29	1	41 734.13	2	100	−0.66[c]	2.33(8)[c]
254.7136	3325.53	2	42 573.49	1	100	−0.29[c]	5.25(8)[c]
255.1349	0.00	0	39 183.20	1	200	−0.28[c]	5.34(8)[c]
255.3824	4830.00	3	43 975.22	2	100	−0.68[c]	2.14(8)[c]
256.1968	4830.00	3	43 850.84	3	100	−0.48[c]	3.35(8)[c]
258.0487	1670.29	1	40 411.12	1	125	−0.65[c]	2.25(8)[c]
263.3129	1670.29	1	39 636.62	1	150	−0.69[c]	1.96(8)[c]
265.6540	2951.29	3	40 583.07	4	300	−0.19[c]	6.07(8)[c]
266.2835	3325.53	2	40 868.40	2	200	−0.65[c]	2.11(8)[c]
266.4966	1670.29	1	39 183.20	1	100	−1.25[c]	5.34(7)[c]
267.1472	4830.00	3	42 251.51	3	200	−0.53[c]	2.74(8)[c]
267.7276	3325.53	2	40 665.85	3	100	−0.92[c]	1.11(8)[c]
268.1422	2951.29	3	40 233.97	4	400	−0.15[c]	6.62(8)[c]
269.1094	4830.00	3	41 978.62	2	100	−1.14[c]	6.65(7)[c]
269.567	3325.53	2	40 411.12	1	150	−0.81[c]	1.41(8)[c]
269.9594	6219.33	4	43 251.00	4	150	−0.42[c]	3.42(8)[c]
271.8906	2951.29	3	39 719.96	4	250	−0.33[c]	4.26(8)[c]
272.4352	2951.29	3	39 646.41	3	300	−0.09[c]	7.35(8)[c]
276.2339	0.00	0	36 190.49	1	150	−1.20[c]	5.52(7)[c]
277.0880	2951.29	3	39 030.25	2	200	−0.98[c]	9.15(7)[c]
277.3999	4830.00	3	40 868.40	2	200	−0.64[c]	1.97(8)[c]
277.4476	6219.33	4	42 251.51	3	300	−0.42[c]	3.33(8)[c]
281.8060	6219.33	4	41 694.34	3	250	−0.44[c]	3.02(8)[c]
283.1379	2951.29	3	38 259.40	4	250	−0.27[c]	4.42(8)[c]
283.3630	6219.33	4	41 499.43	3	120	−0.40[c]	3.35(8)[c]
287.9396	0.00	0	34 719.33	1	140	−1.04[c]	7.38(7)[c], 7.3(7)[d]
289.6009	1670.29	1	36 190.49	1	150	−0.98[c]	8.40(7)[c]
291.0997	0.00	0	34 342.44	1	100	−1.56[c]	2.17(7)[c], 2.3(7)[d]
292.3103	4830.00	3	39 030.25	2	150	−1.31[c]	3.83(7)[c]
293.4996	1670.29	1	35 731.96	2	250	−1.03[d]	7.3(7)[d]
294.4398	2951.29	3	36 904.16	2	300	−0.15[c]	5.40(8)[c]
294.6989	2951.29	3	36 874.36	3	300	−0.12[c]	5.76(8)[c]
301.3788	4830.00	3	38 001.12	4	120	−1.10[d]	5.8(7)[d]
301.6466	6219.33	4	39 361.01	5	150	−0.86[d]	1.02(8)[d]
301.7436	2951.29	3	36 082.30	4	200	−0.83[d]	1.09(8)[d]
302.4928	1670.29	1	34 719.33	1	100	−1.19[c]	4.74(7)[c], 4.2(7)[d]
304.6440	1670.29	1	34 485.86	2	120	−1.39[d]	2.9(7)[d]
304.9688	2951.29	3	35 731.96	2	120	−0.92[d]	8.6(7)[d]
309.3500	4830.00	3	37 146.36	4	100	−1.24[d]	4.0(7)[d]
310.7227	3325.53	2	35 499.15	3	100	−1.63[d]	1.63(7)[d]
310.8018	2951.29	3	35 116.78	4	100	−1.69[d]	1.42(7)[d]
317.6601	1670.29	1	33 141.38	2	150	−1.79[d]	1.06(7)[d]
318.4418	3325.53	2	34 719.33	1	120	−1.94[c]	7.59(6)[c], 7.0(6)[d]
319.1572	0.00	0	31 323.48	1	200	−1.83[d]	9.7(6)[d]
319.8840	4830.00	3	36 082.30	4	200	−1.20[d]	4.1(7)[d]
320.725	2951.29	3	34 121.68	4	300	−1.38[d]	2.7(7)[d]
320.828	3325.53	2	34 485.86	2	200	−1.47[d]	2.2(7)[d]
321.5562	6219.33	4	37 309.16	5	200	−0.45[d]	2.3(8)[d]
330.0822	4830.00	3	35 116.78	4	150	−0.92[d]	7.3(7)[d]
331.1388	2951.29	3	33 141.38	2	200	−1.34[d]	2.8(7)[d]
334.5858	13 348.56	3	43 227.66	2	100	−1.11[c]	4.60(7)[c]
353.5539	13 307.10	1	41 583.20	2	100	−1.15[c]	3.78(7)[c]
354.5220	0.00	0	28 198.90	1	200	−1.74[d]	9.6(6)[d]
360.6063	1670.29	1	29 393.40	2	150	−2.03[d]	4.8(6)[d]
361.7515	2951.29	3	30 586.64	3	500	−0.83[d]	7.5(7)[d]
363.1943	1670.29	1	29 195.84	2	200	−1.88[d]	6.6(6)[d]
368.2084	6219.33	4	33 370.04	5	200	−1.35[d]	2.2(7)[d]

Table 1. (Continued.)

λ[a] (nm)	E^b_{low} (cm^{-1})	J	$E^b_{upp.}$ (cm^{-1})	J'	Int.[b]	log gf	gA (s^{-1})
370.7922	2951.29	3	29 912.85	3	300	−1.38[d]	2.0(7)[d]
376.0126	3325.53	2	29 912.85	3	200	−1.53[d]	1.39(7)[d]
376.8447	1670.29	1	28 198.90	1	250	−1.65[d]	1.04(7)[d]
378.0772	2951.29	3	29 393.40	2	200	−1.35[d]	2.1(7)[d]
380.9220	2951.29	3	29 195.84	2	150	−2.01[d]	4.5(6)[d]
381.0790	13 777.71	2	40 011.50	2	120	−1.14[c]	3.30(7)[c]
381.7480	2951.29	3	29 139.12	3	400	−1.32[d]	2.2(7)[d]
383.5058	3325.53	2	29 393.40	2	250	−1.24[d]	2.6(7)[d]
384.6218	1670.29	1	27 662.52	2	300	−1.62[d]	1.07(7)[d]
384.7498	0.00	0	25 983.60	1	150	−2.26[d]	2.5(6)[d]
386.7986	2951.29	3	28 797.24	4	600	−1.04[d]	4.1(7)[d]
388.1405	4830.00	3	30 586.64	3	250	−1.25[d]	2.5(7)[d]
400.8753⋆	2951.29	3	27 889.68	4	1000	−0.44[c]	1.50(8)[c], 1.47(8)[d]
404.5594	2951.29	3	27 662.52	2	100	−1.45[d]	1.44(7)[d]
407.4358	2951.29	3	27 488.11	3	600	−0.74[d]	7.3(7)[d]
410.2702	6219.33	4	30 586.64	3	100	−1.07[d]	3.4(7)[d]
424.1445	15 460.01	3	39 030.25	2	100	−0.84[c]	5.35(7)[c]
424.4364	6219.33	4	29 773.34	5	200	−1.39[d]	1.52(7)[d]
426.9382	2951.29	3	26 367.28	2	200	−1.38[d]	1.52(7)[d]
429.4606	2951.29	3	26 229.77	2	800	−0.77[c]	6.20(7)[c], 6.2(7)[d]
430.2110	2951.29	3	26 189.20	3	200	−1.16[d]	2.5(7)[d]
484.3810	3325.53	2	23 964.67	2	400	−1.47[d]	9.6(6)[d]
488.6899	6219.33	4	26 676.48	5	200	−1.50[d]	8.9(6)[d]
498.2593	0.00	0	20 064.30	1	200	−2.33[d]	1.25(6)[d]
505.3276	1670.29	1	21 453.90	1	400	−1.66[d]	5.7(6)[d]
522.4657	4830.00	3	23 964.67	2	250	−1.60[d]	6.2(6)[d]
524.298	16 431.31	4	35 499.15	3	250	−1.50[d]	7.7(6)[d]
525.4542	15 460.01	3	34 485.86	2	100	−2.10[d]	1.93(6)[d]
525.5396	22 476.68	4	41 499.43	3	120	−1.12[c]	1.83(7)[c]
543.5032	1670.29	1	20 064.30	1	100	−2.92[d]	2.7(5)[d]
551.4676	3325.53	2	21 453.90	1	300	−2.00[d]	2.20(6)[d]
766.488	18 280.48	2	31 323.48	1	200	−2.00[d]	1.14(6)[d]
794.092	13 777.71	2	26 367.28	2	120	−2.63[d]	2.5(5)[d]
801.719	18 116.84	2	30 586.64	3	120	−1.97[d]	1.1(6)[d]
812.382	18 280.48	2	30 586.64	3	150	−2.16[d]	7.0(5)[d]

[a] Observed air wavelengths taken from Kramida and Shirai (2006).
[b] From Kramida and Shirai (2006).
[c] From Kling and Kock (1999).
[d] From Den Hartog *et al* (1987).
⋆ Line blended with a W II transition (see the text).
a(b) is written for a · 10^b.

by more than one order of magnitude. A discrepancy of 40% between the laser measurement of Schnabel *et al* (1998) and the beam-foil measurement of Henderson *et al* (1999) is observed for the level at 54 229.06 cm^{-1}, but according to the quoted uncertainties (10 and 3%, respectively) and the limitations inherent to the techniques involved, the first result is expected to be the most accurate. This is confirmed, in an indirect way, by the nearly perfect agreement observed, for two levels, between the results of Schulz-Johanning *et al* (1999) and of Kwiatkowski *et al* (1984) and, in a more direct way, by the relativistic Hartree–Fock calculations including core-polarization effects (HFR+CPOL) due to Nilsson *et al* (2008). These authors reported in fact TR-LIF lifetime measurements for nine levels and their scale was found in excellent agreement with that of Schnabel *et al* (1998) when relying on the lifetime obtained for the level at 47 179.94 cm^{-1}, the only level common to both works.

BFs for 280 W II lines originating from 19 excited levels in the wavelength range 204–750 nm were obtained by Kling *et al* (2000) from emission measurements on a high-current hollow cathode and a Penning discharge lamp. A much more extensive set of oscillator strengths was reported by Nilsson *et al* (2008) who performed HFR+CPOL calculations (Quinet *et al* 1999) in W II. Only a sample of 290 intense transitions was published in the Nilsson *et al*'s (2008) paper but the whole set of results (6086 transitions in the range 143–990 nm) is listed in the DESIRE database (Fivet *et al* 2007) on the web site http://www.umh.ac.be/~astro/desire.shtml.

As a consequence of the present discussion, it is justified to adopt as the best set of results the lifetimes by Schnabel *et al* (1998) and by Nilsson *et al* (2008) and the transition

Table 2. UV transitions of singly ionized tungsten (W II) suitable for plasma diagnostics. For the choice of the lines, see the text.

λ[a] (nm)	E_{low}[b] (cm^{-1})	J	$E_{\text{upp.}}$[b] (cm^{-1})	J'	Int.[b]	log gf[c]	gA (s^{-1})
178.3042	0.000	1/2	56 084.326	3/2	150	−1.54	6.12(7)[c]
182.8687	3172.473	5/2	57 856.759	5/2	250	−1.08	1.68(8)[c]
184.8106	6147.085	9/2	60 256.547	7/2	250	−0.09	1.60(9)[c]
207.9118	6147.085	9/2	54 229.082	11/2	296	0.50	4.86(9)[c], 4.49(9)[d]
208.8204	3172.473	5/2	51 045.292	7/2	125	−0.02	1.47(9)[c]
209.4751	1518.829	3/2	49 242.042	5/2	142	−0.05	1.34(9)[c], 1.06(9)[d]
215.3558	6147.085	9/2	52 567.276	9/2	103	−0.48	4.73(8)[c]
216.6316	4716.278	7/2	50 863.106	9/2	158	−0.08	1.18(9)[c]
220.4483	6147.085	9/2	51 495.054	11/2	276	0.17	2.02(9)[c]
222.5901	0.000	1/2	44 911.659	3/2	162	−0.46	4.66(8)[c], 3.41(8)[d]
222.9629	1518.829	3/2	46 355.404	5/2	153	−0.41	5.28(8)[c]
224.8275	4716.278	7/2	49 181.034	9/2	128	−0.68	2.78(8)[c]
224.8758	0.000	1/2	44 455.212	1/2	253	−0.32	6.12(8)[c], 6.38(8)[d]
224.9887	19 442.466	13/2	63 875.361	15/2	249	0.73	7.12(9)[c]
226.3519	17 436.932	11/2	61 602.268	13/2	127	0.01	1.33(9)[c]
227.0241	14 857.160	9/2	58 891.742	11/2	110	−0.05	1.15(9)[c]
230.3819	1518.829	3/2	44 911.659	3/2	164	−0.56	3.39(8)[c], 2.86(8)[d]
231.5018	3172.473	5/2	46 355.404	5/2	122	−0.66	2.70(8)[c]
232.6089	6147.085	9/2	49 124.508	7/2	258	−0.49	4.01(8)[c]
234.1368	4716.278	7/2	47 413.270	5/2	117	−0.51	3.76(8)[c]
234.3497	28 187.578	13/2	70 845.790	15/2	109	0.15	1.74(9)[c]
237.0041	20 534.191	11/2	62 714.675	13/2	177	0.10	1.48(9)[c]
239.0370	7420.261	5/2	49 242.042	5/2	110	−0.42	4.38(8)[c], 4.01(8)[d]
239.2928	4716.278	7/2	46 493.356	9/2	231	−0.62	2.81(8)[c], 2.28(8)[d]
239.7079	3172.473	5/2	44 877.209	7/2	294	−0.39	4.76(8)[c], 4.19(8)[d]
239.7107	7420.261	5/2	49 124.508	7/2	421	−0.59	2.97(8)[c]
242.7490	3172.472	5/2	44 354.784	5/2	165	−0.76	1.97(8)[c], 1.54(8)[d]
243.5003	20 534.191	11/2	61 589.457	11/2	109	−0.15	8.02(8)[c]
244.6386	7420.261	5/2	48 284.498	5/2	159	−0.84	1.60(8)[c]
245.1477	1518.829	3/2	42 298.223	3/2	109	−1.04	1.02(8)[c], 7.38(7)[d]
246.6523	1518.829	3/2	42 049.478	5/2	205	−0.78	1.83(8)[c], 1.36(8)[d]
247.7795	6147.085	9/2	46 493.356	9/2	316	−0.45	3.90(8)[c], 2.84(8)[d]
248.8769	7420.261	5/2	47 588.647	3/2	262	−0.34	4.90(8)[c], 5.06(8)[d]
248.9231	4716.278	7/2	44 877.209	7/2	422	−0.19	6.91(8)[c], 5.56(8)[d]
249.6636	4716.278	7/2	44 758.095	9/2	142	−1.00	1.08(8)[c], 9.62(7)[d]
249.7479	6147.085	9/2	46 175.395	7/2	159	−0.76	1.87(8)[c]
249.9683	7420.261	5/2	47 413.270	5/2	136	−0.52	3.27(8)[c]
250.0102	18 000.627	7/2	57 986.939	9/2	127	−0.51	3.30(8)[c]
250.6049	28 187.578	13/2	68 079.006	13/2	100	0.08	1.26(9)[c]
251.0470	19 070.550	9/2	58 891.742	11/2	141	−0.12	7.96(8)[c]
252.2041	4716.278	7/2	44 354.784	5/2	169	−0.76	1.84(8)[c], 1.49(8)[d]
253.4822	20 780.358	9/2	60 219.015	11/2	128	−0.12	7.81(8)[c]
255.4853	0.000	1/2	39 129.460	3/2	156	−1.07	8.83(7)[c], 7.13(7)[d]
255.5095	3172.473	5/2	42 298.223	3/2	224	−0.70	2.05(8)[c], 1.62(8)[d]
256.3156	17 436.932	11/2	56 439.643	13/2	212	−0.05	8.96(8)[c]
257.1444	3172.473	5/2	42 049.478	5/2	364	−0.49	3.30(8)[c], 2.63(8)[d]
257.2229	20 534.191	11/2	59 399.339	9/2	115	−0.26	5.63(8)[c]
257.9252	23 955.349	11/2	62 714.675	13/2	147	0.17	1.48(9)[c]
257.9483	26 929.008	11/2	65 684.866	11/2	113	−0.06	8.74(8)[c]
257.9531	7420.261	5/2	46 175.395	7/2	138	−0.76	1.78(8)[c]
258.9160	6147.085	9/2	44 758.095	9/2	285	−0.59	2.59(8)[c], 1.82(8)[d]
260.3017	16 553.087	9/2	54 958.573	11/2	137	−0.13	7.28(8)[c]
265.3560	4716.278	7/2	42 390.287	7/2	120	−1.50	3.02(7)[c], 3.03(7)[d]
265.8032	1518.829	3/2	39 129.460	3/2	139	−0.77	1.63(8)[c], 1.35(8)[d]
266.4336	17 436.932	11/2	54 958.573	11/2	170	−0.09	7.66(8)[c]
269.7710	1518.829	3/2	38 576.313	1/2	178	−0.87	1.27(8)[c], 9.91(7)[d]
270.2107	19 442.466	13/2	56 439.643	13/2	209	0.07	1.07(9)[c]
270.3456	31 100.286	11/2	68 079.006	13/2	108	0.25	1.60(9)[c]
271.8033	16 589.603	7/2	53 370.011	9/2	108	−0.23	5.38(8)[c]
276.4261	0.000	1/2	36 165.356	1/2	182	−0.89	1.14(8)[c], 9.57(7)[d]
305.1294	13 411.939	7/2	46 175.395	7/2	131	−0.75	1.28(8)[c]
307.7517	23 955.349	11/2	56 439.643	13/2	179	−0.04	6.50(8)[c]
314.5755	16 553.087	9/2	48 332.758	11/2	228	−1.12	5.17(7)[c]
320.1579	8711.274	3/2	39 936.842	5/2	178	−1.68	1.37(7)[c]

Table 2. (Continued.)

λ^a (nm)	E^b_{low} (cm^{-1})	J	$E^b_{upp.}$ (cm^{-1})	J'	Int.[b]	log gf^c	gA (s^{-1})
321.5616	11 301.024	5/2	42 390.287	7/2	108	−1.54	1.90(7)[c]
334.3101	16 589.603	7/2	46 493.356	9/2	102	−1.03	5.52(7)[c], 6.07(7)[d]
340.6833	10 592.485	3/2	39 936.842	5/2	116	−2.12	4.42(6)[c]
341.6625	8711.274	3/2	37 971.528	3/2	296	−1.72	1.10(7)[c]
357.2472	10 592.485	3/2	38 576.313	1/2	114	−1.18	3.51(7)[c], 3.39(7)[d]
361.3790	14 634.336	3/2	42 298.223	3/2	133	−1.07	4.33(7)[c], 4.60(7)[d]
364.1408	8711.274	3/2	36 165.356	1/2	113	−1.33	2.36(7)[c], 1.98(7)[d]
364.5596	14 967.745	5/2	42 390.287	7/2	134	−1.55	1.44(7)[c], 1.17(7)[d]
373.6212	18 000.627	7/2	44 758.095	9/2	141	−1.08	3.96(7)[c], 3.42(7)[d]
434.8113	13 173.337	1/2	36 165.356	1/2	109	−1.40	1.39(7)[c], 1.01(7)[d]

[a] Observed wavelengths taken from Kramida and Shirai (2006). Vacuum wavelengths for λ < 200.0 nm and air wavelengths above that limit.
[b] From Kramida and Shirai (2006).
[c] From Nilsson *et al* (2008).
[d] From Kling *et al* (2000).
a(b) is written for a · 10^b.

probabilities of Kling *et al* (2000) considerably extended and complemented by Nilsson *et al* (2008). From the comparison with the experimental measurements, it is reasonable to consider that the accuracy of the HFR+CPOL results should be better than 15% for the most intense transitions, larger uncertainties being possible for the weaker lines particularly for those susceptible to cancellation effects in the calculation of the line strengths.

We give in table 2 a list of selected UV W II transitions suitable for plasma diagnostics. The list is limited to the strongest transitions, i.e. the lines such that the laboratory intensities (Int.) ⩾100 (Kramida and Shirai 2006). The adopted transition probabilities are those from Kling *et al* (2000) and Nilsson *et al* (2008). The transitions for which the calculated A-values are likely to be affected by cancellation effects (i.e. for which the cancellation factor CF as defined by Cowan (1981) <0.050) have been excluded from the list. Note that the line at 400.8751 nm blended with the W I line at 400.8753 nm is not included in the table because its calculated line strength was found to be affected by strong cancellation effects. However, it is worth mentioning that this W II line, corresponding to the transition between the even level at 30 223.744 cm^{-1} ($J = 3/2$) and the odd level at 55 162.390 cm^{-1} ($J = 5/2$), has an estimated gA-value of 9.7×10^6 s^{-1} (Nilsson *et al* 2008), i.e. more than one order of magnitude smaller than the transition probability obtained by Den Hartog *et al* (1987) and Kling and Kock (1999) for the W I line at 400.8753 nm ($gA = 1.5 \times 10^8$ s^{-1}).

We can see, from the last column of table 2, that the transition probabilities of Kling *et al* (2000) and Nilsson *et al* (2008) are in good agreement, as expected, for the 26 transitions common to both works.

2.3. W III lines

The only term analysis available in W III has been published by Iglesias *et al* (1989) who classified 2636 lines between 60 and 268 nm connecting 235 atomic energy levels.

Very few works have been devoted to radiative rate determinations in doubly ionized tungsten. Schultz-Johanning *et al* (1999) reported lifetime measurements for three levels obtained with the TR-LIF technique and BFs with the Fourier transform spectroscopy for 81 transitions in the 154–334 nm spectral range. These authors also proposed transition probabilities for 37 transitions.

More recently, an extensive set of oscillator strengths for W III electric dipole transitions were calculated by Palmeri *et al* (2008) using the HFR+CPOL method. The accuracy of these new results was assessed through comparisons with the TR-LIF measurements performed by the same authors for two levels belonging to the $5d^3 6p$ configuration and with the few results of Schultz-Johanning *et al* (1999). A very limited sample of transition probabilities is presented in the paper of Palmeri *et al* (2008) but the complete set of results is included in the DESIRE database (4822 transitions in the wavelength range 83–1494 nm).

In the present work, we have adopted the transition probabilities of Palmeri *et al* (2008) and of Schultz-Johanning *et al* (1999). We report in table 3 a list of selected unblended lines (Iglesias *et al* 1989) of W III covering basically the UV region and suitable for plasma diagnostics. The list is limited to the strongest transitions, free of cancellation effects and characterized by laboratory intensities (Int.) ⩾250. It is seen, from the last column of table 3, that the two sets of oscillator strengths agree quite well (for the five lines common to the two papers).

3. New transition probabilities for forbidden lines

To our knowledge, no radiative rates have been published so far for forbidden lines in neutral, singly ionized and doubly ionized tungsten. In the present work, transition probabilities have been obtained for magnetic dipole (M1) and electric quadrupole (E2) transitions using the HFR+CPOL approach mentioned above.

Table 3. UV transitions of doubly ionized tungsten (W III) suitable for plasma diagnostics. For the choice of the lines, see the text.

λ^{a} (nm)	E^{b}_{low} (cm^{-1})	J	$E^{b}_{upp.}$ (cm^{-1})	J'	Int.[b]	$\log gf^{c}$	gA (s^{-1})
128.3711	10 968.54	1	88 867.52	0	300	−0.62	9.76(8)[c]
128.5664	27 252.53	3	10 5033.31	3	300	−0.30	2.03(9)[c]
129.1862	19 632.05	5	97 039.60	6	300	−0.63	9.33(8)[c]
130.1137	12 427.09	2	89 283.42	1	300	−1.16	2.72(8)[c]
131.0199	15 038.04	3	91 362.35	2	300	−0.78	6.42(8)[c]
136.1993	6277.81	3	79 699.75	3	300	−0.91	4.37(8)[c]
137.6777	10 968.54	1	83 601.96	1	300	−0.49	1.12(9)[c]
137.9143	6277.81	3	78 786.47	3	300	−0.94	4.05(8)[c]
138.1104	28 977.44	4	10 1383.26	3	300	−0.40	1.41(9)[c]
138.2742	17 380.40	4	89 700.42	4	300	−0.99	3.62(8)[c]
138.4072	17 380.40	4	89 630.99	5	300	−0.57	9.42(8)[c]
139.9008	6277.81	3	77 757.00	2	500	−0.84	4.92(8)[c]
140.0876	14 899.80	3	86 283.75	3	500	−0.59	8.76(8)[c]
141.1086	16 723.24	5	87 590.69	4	300	−0.20	2.12(9)[c]
141.7358	6277.81	3	76 831.39	2	500	−1.20	2.10(8)[c]
141.8356	18 380.90	6	88 884.95	6	250	−0.29	1.70(9)[c]
142.8590	19 632.05	5	89 630.99	5	250	−0.34	1.52(9)[c]
143.0391	13 700.95	4	83 611.69	3	300	−0.41	1.26(9)[c]
143.3444	6277.81	3	76 039.80	2	300	−0.53	9.53(8)[c]
143.9239	18 380.90	6	87 862.02	5	250	−0.26	1.74(9)[c]
145.9855	16 723.24	5	85 222.97	5	500	0.11	3.96(9)[c]
146.1826	22 955.03	2	91 362.35	2	250	−0.32	1.50(9)[c]
146.5630	19 632.05	5	87 862.02	5	250	−0.59	8.03(8)[c]
146.7436	16 723.24	5	84 869.01	4	350	−0.16	2.13(9)[c]
146.7748	12 427.09	2	80 558.62	3	250	−0.74	5.66(8)[c]
146.8132	7686.68	4	75 800.20	5	400	−0.48	1.03(9)[c]
147.0641	20 432.53	4	88 429.94	3	250	−0.01	2.99(9)[c]
147.1355	4461.19	2	72 425.51	1	400	−0.32	1.47(9)[c]
147.2613	25 963.79	6	93 870.12	6	500	0.27	5.71(9)[c]
147.4593	25 963.79	6	93 778.68	5	500	0.51	9.98(9)[c]
147.9622	18 380.90	6	85 965.60	6	500	0.19	4.71(9)[c]
148.3247	6277.81	3	73 697.35	3	350	−0.48	1.01(9)[c]
148.9018	20 432.53	4	87 590.69	4	250	−0.24	1.72(9)[c]
149.1151	13 992.14	2	81 054.33	1	250	−0.39	1.21(9)[c]
149.2185	19 851.87	3	86 867.50	2	300	−0.14	2.15(9)[c]
149.6061	18 380.90	6	85 222.97	5	350	−0.15	2.11(9)[c]
150.1416	6277.81	3	72 881.50	3	450	−0.55	8.38(8)[c]
150.1897	2256.20	1	68 838.57	0	300	−0.64	6.77(8)[c]
150.3921	18 376.40	4	84 869.01	4	500	0.12	3.84(9)[c]
150.6414	23 317.80	5	89 700.42	4	300	−0.20	1.88(9)[c]
150.8268	4461.19	2	70 762.26	2	500	−0.32	1.40(9)[c]
152.0241	16 723.24	5	82 502.08	4	450	−0.04	2.67(9)[c]
152.3764	12 881.03	1	78 507.70	0	250	−0.38	1.19(9)[c]
152.4941	18 380.90	6	83 957.03	5	500	0.28	5.46(9)[c]
152.8990	20 432.53	4	85 834.94	3	300	−0.09	2.32(9)[c]
153.2907	18 376.40	4	83 611.69	3	300	−0.85	4.04(8)[c]
153.3781	25 963.79	6	91 161.95	5	350	−0.21	1.75(9)[c]
154.1892	2256.20	1	67 111.20	2	250	−0.72	5.32(8)[c]
154.6251	16 621.08	2	81 293.43	2	300	−0.30	1.40(9)[c]
154.9321	23 317.80	5	87 862.02	5	250	−0.13	2.06(9)[c]
155.0009	4461.19	2	68 976.80	1	250	−0.87	3.74(8)[c]
155.0754	6277.81	3	70 762.26	2	350	−0.39	1.14(9)[c]
155.3099	7686.68	4	72 073.75	4	500	−0.06	2.42(9)[c]
155.3608	22 212.08	3	86 578.41	3	250	−0.46	9.77(8)[c]
155.9409	13 700.95	4	77 827.64	4	1000	0.18	4.05(9)[c]
156.3874	6277.81	3	70 221.35	4	500	−0.25	1.53(9)[c]
156.8115	16 723.24	5	80 493.89	5	300	−0.30	1.36(9)[c]
157.8008	13 700.95	4	77 071.73	3	500	−0.10	2.14(9)[c]
158.7424	7686.68	4	70 681.63	3	300	−0.56	7.32(8)[c]
159.0468	16 723.24	5	79 597.73	4	400	−0.26	1.46(9)[c]
159.4222	4461.19	2	67 187.37	3	500	−0.22	1.56(9)[c]
159.6220	23 317.80	5	85 965.60	6	250	−0.23	1.53(9)[c]
159.6611	18 380.90	6	81 013.46	6	500	−0.08	2.18(9)[c]

Table 3. (Continued.)

λ[a] (nm)	E^b_{low} (cm^{-1})	J	$E^b_{upp.}$ (cm^{-1})	J'	Int.[b]	log gf[c]	gA (s^{-1})
159.9109	7686.68	4	70 221.35	4	400	−0.39	1.07(9)[c]
161.9180	17 380.40	4	79 139.81	3	300	−0.93	3.00(8)[c]
162.1131	16 723.24	5	78 408.35	4	300	−0.64	5.86(8)[c]
163.5588	14 899.80	3	76 039.80	2	250	−0.44	9.09(8)[c]
164.3065	19 632.05	5	80 493.89	5	250	−0.38	1.04(9)[c]
165.1104	2256.20	1	62 821.85	2	500	−0.46	8.44(8)[c], 5.25(8)[d]
166.1248	0.00	0	60 195.86	1	500	−0.56	6.58(8)[c], 5.31(8)[d]
166.4965	20 432.53	4	80 493.89	5	250	−0.24	1.38(9)[c]
166.5411	7686.68	4	67 731.94	5	450	−0.47	8.14(8)[c]
166.5782	18 376.40	4	78 408.35	4	250	−0.38	1.01(9)[c]
166.9669	14 899.80	3	74 791.95	2	300	−0.36	1.04(9)[c]
167.1895	13 992.14	2	73 804.59	1	250	−0.42	8.95(8)[c]
167.2420	10 968.54	1	70 762.26	2	250	−0.50	7.67(8)[c]
169.1430	14 899.80	3	74 021.35	4	450	−0.05	2.10(9)[c]
169.7994	23 317.80	5	82 210.83	5	250	−0.26	1.26(9)[c]
169.8099	13 992.14	2	72 881.50	3	350	−0.28	1.22(9)[c]
170.7752	19 851.87	3	78 408.35	4	300	−0.06	1.98(9)[c]
171.1747	17 380.40	4	75 800.20	5	400	−0.15	1.61(9)[c]
171.4230	12 427.09	2	70 762.26	2	400	−0.21	1.42(9)[c]
171.6602	12 427.09	2	70 681.63	3	500	−0.20	1.43(9)[c]
172.3890	10 968.54	1	68 976.80	1	400	−0.26	1.24(9)[c]
172.8799	15 038.04	3	72 881.50	3	450	−0.32	1.06(9)[c]
172.9329	27 252.53	3	85 078.28	4	350	0.08	2.71(9)[c]
173.3229	23 317.80	5	81 013.46	6	300	−0.28	1.18(9)[c]
177.5615	27 252.53	3	83 571.04	4	300	−0.13	1.59(9)[c]
178.0368	19 632.05	5	75 800.20	5	300	−0.23	1.24(9)[c]
178.3636	19 632.05	5	75 697.21	6	1000	0.60	8.34(9)[c]
178.8610	17 380.40	4	73 289.66	5	500	0.22	3.47(9)[c]
179.5149	23 080.82	1	78 786.47	2	300	−0.38	8.70(8)[c]
181.2144	15 038.04	3	70 221.35	4	500	−0.33	9.35(8)[c]
181.5469	35 429.01	6	90 511.29	7	800	0.72	1.06(10)[c]
181.8859	28 977.44	4	83 957.03	5	300	−0.04	1.86(9)[c]
182.1049	18 376.40	4	73 289.66	5	500	−0.15	1.43(9)[c]
182.6357	31 211.76	5	85 965.60	6	300	0.36	4.56(9)[c]
190.6880	19 632.05	5	72 073.75	4	300	−0.25	1.02(9)[c]
197.6701	19 632.05	5	70 221.35	4	800	−0.01	1.67(9)[c]
198.6033	17 380.40	4	67 731.94	5	1000	−0.12	1.29(9)[c], 9.28(8)[d]
199.1777	14 899.80	3	65 106.05	4	800	0.03	1.79(9)[c]
199.7286	15 038.04	3	65 106.05	4	800	−0.96	1.82(8)[c]
200.5799	41 322.55	5	91 161.95	5	300	−0.10	1.32(9)[c]
200.7104	17 380.40	4	67 187.37	3	800	−0.18	1.09(9)[c]
200.7313	31 211.76	5	81 013.46	6	500	−0.18	1.09(9)[c]
204.8067	18 376.40	4	67 187.37	3	500	−0.45	5.59(8)[c]
205.7830	33 631.43	4	82 210.83	5	300	−0.21	9.62(8)[c]
207.8347	19 632.05	5	67 731.94	5	800	0.09	1.89(9)[c], 1.64(9)[d]
209.2755	12 427.09	2	60 195.86	1	800	−0.45	5.34(8)[c], 6.15(8)[d]
214.4516	31 211.76	5	77 827.64	4	300	−0.25	7.97(8)[c]
214.5775	14 899.80	3	61 488.36	3	800	−0.32	6.93(8)[c]
214.586	31 821.76	3	78 408.35	4	500	−0.32	6.98(8)[c]
215.2161	15 038.04	3	61 488.36	3	800	−0.76	2.53(8)[c]
216.0897	10 968.54	1	57 231.04	2	500	−0.10	1.15(9)[c]
218.5424	36 467.29	4	82 210.83	5	500	−0.16	9.76(8)[c]
219.3043	35 429.01	6	81 013.46	6	900	0.20	2.19(9)[c]
223.1251	12 427.09	2	57 231.04	2	500	−0.47	4.56(8)[c]
225.6009	28 977.44	4	73 289.66	5	500	−0.40	5.29(8)[c]
236.8974	31 821.76	3	74 021.35	4	300	−0.46	4.10(8)[c]
257.9570	28 977.44	4	67 731.94	5	800	−0.55	2.86(8)[c]

[a]Observed wavelengths taken from Iglesias *et al* (1989). Vacuum wavelengths for λ < 200.0 nm and air wavelengths above that limit.
[b] From Iglesias *et al* (1989).
[c] From Palmeri *et al* (2008).
[d] From Schultz-Johanning *et al* (2001).
a(b) is written for a · 10^b.

Table 4. Transition probabilities for forbidden lines in W I. Only transitions for which A-values are greater than 0.2 s^{-1} and λ are shorter than 2000 nm are given.

	Lower level		Upper level			
λ (nm)[a]	E (cm^{-1})[b]	J	E (cm^{-1})[b]	J	Type	A_{ki} (s^{-1})
546.880	0.00	0	18 280.48	2	E2	2.15(+0)
552.857	0.00	0	18 082.83	1	M1	2.88(−1)
568.565	1670.29	1	19 253.56	2	E2	8.97(−1)
577.733	1670.29	1	18 974.51	3	E2	1.41(+0)
601.873	1670.29	1	18 280.48	2	M1+E2	2.97(−1)
607.862	1670.29	1	18 116.84	2	M1+E2	2.21(+0)
609.122	1670.29	1	18 082.83	1	M1+E2	6.23(−1)
613.242	2951.29	3	19 253.56	2	M1	1.84(+0)
623.922	2951.29	3	18 974.51	3	M1+E2	5.53(−1)
627.545	3325.53	2	19 256.24	4	E2	1.11(+0)
638.843	3325.53	2	18 974.51	3	M1+E2	3.66(−1)
652.170	2951.29	3	18 280.48	2	M1	1.06(+0)
667.543	0.00	0	14 976.18	2	E2	2.30(−1)
668.490	3325.53	2	18 280.48	2	E2	3.79(−1)
675.886	3325.53	2	18 116.84	2	E2	4.89(−1)
677.444	3325.53	2	18 082.83	1	M1	2.06(+0)
693.119	4830.00	3	19 253.56	2	M1+E2	2.11(+0)
695.429	3325.53	2	17 701.18	3	M1+E2	9.48(−1)
706.793	4830.00	3	18 974.51	3	M1+E2	2.11(−1)
743.263	4830.00	3	18 280.48	2	M1	3.67(−1)
751.340	1670.29	1	14 976.18	2	M1+E2	2.98(−1)
752.417	4830.00	3	18 116.84	2	M1+E2	6.04(−1)
776.716	4830.00	3	17 701.18	3	M1	1.53(+0)
783.780	6219.33	4	18 974.51	3	M1	3.26(−1)
799.222	2951.29	3	15 460.01	3	M1	9.07(−1)
818.307	4830.00	3	17 107.01	4	M1	8.98(−1)
825.713	1670.29	1	13 777.71	2	M1+E2	1.60(+0)
858.085	3325.53	2	14 976.18	2	M1+E2	6.14(−1)
918.217	6219.33	4	17 107.01	4	M1	1.55(+0)
956.476	3325.53	2	13 777.71	2	M1	1.15(+0)
997.429	3325.53	2	13 348.56	3	M1	8.95(−1)
1001.572	3325.53	2	13 307.10	1	M1	5.36(+0)
1081.875	6219.33	4	15 460.01	3	M1	9.81(−1)
1129.558	6219.33	4	15 069.93	5	M1+E2	2.09(−1)
1173.586	4830.00	3	13 348.56	3	M1	1.47(+0)
1168.619	9528.06	0	18 082.83	1	M1	2.30(+0)
1272.278	1670.29	1	9528.06	0	M1	8.89(+0)
1363.519	4830.00	3	12 161.96	4	M1	3.56(−1)
1681.214	13 307.10	1	19 253.56	2	M1	2.37(−1)
1682.297	6219.33	4	12 161.96	4	M1	1.27(+0)

[a] Air wavelengths deduced from the experimental levels.
[b] From Kramida and Shirai (2006).
a(b) is written for $a \cdot 10^b$.

For W I, the most important forbidden transitions connect the lowest states belonging to the $5d^46s^2$ and $5d^56s$ even-parity configurations. In our calculations, intra-valence-type interactions were considered by including, in the configuration interaction expansions, the configurations $5d^46s^2$, $5d^56s$, $5d^57s$, $5d^6$, $5d^46s7s$, $5d^46s6d$, $5d^56d$, $5d^46p^2$, $5d^46d^2$, $5d^36s6p^2$ and $5d^26s^26p^2$. Core–valence interactions were taken into account using a core-polarization potential with $\alpha_d = 4.59\ a_0^3$ as the dipole polarizability of the W^{4+} ionic core (Fraga *et al* 1976) and $r_c = 1.99\ a_0$ as the cut-off radius, this latter parameter corresponding to the HFR mean value $\langle r \rangle$ of the outermost 5d core orbital. The HFR+CPOL method was then combined with a least-squares optimization routine using the energy levels compiled by Kramida and Shirai (2006) for $5d^46s^2$ and $5d^56s$ configurations. The standard deviation of the fit was found to be equal to 73 cm^{-1}.

In W II, the HFR+CPOL approach was also used for calculating the transition rates for forbidden lines involving the energy levels of $5d^5$, $5d^46s$ and $5d^36s^2$ even-parity configurations. The same set of interacting configurations as the one considered by Nilsson *et al* (2008) was included in the model, i.e. $5d^5$, $5d^46s$, $5d^47s$, $5d^48s$, $5d^36s^2$, $5d^36s7s$, $5d^36s8s$, $5d^46d$, $5d^36s6d$, $5d^26s^26d$ and $5d^36p^2$. The core-polarization potential was chosen by assuming a $4f^{14}5d^2$ Yb-like W^{4+} ionic core surrounded by three valence electrons. The dipole polarizability tabulated by Fraga *et al* (1976) for W V was adopted, i.e. $\alpha_d = 4.59\ a_0^3$. The cut-off radius used was the HFR mean radius of the 5d orbital in W II, i.e. $r_c =$

Table 5. Transition probabilities for forbidden lines in W II. Only transitions for which *A*-values are greater than 0.2 s^{-1} and λ are shorter than 2000 nm are given.

	Lower level		Upper level			
λ (nm)[a]	E (cm^{-1})[b]	J	E (cm^{-1})[b]	J	Type	A_{ki} (s^{-1})
515.214	0.000	1/2	19 403.991	1/2	M1	1.67(+0)
526.421	0.000	1/2	18 990.929	3/2	M1	2.42(−1)
551.769	1518.829	3/2	19 637.309	5/2	M1	2.82(−1)
558.967	1518.829	3/2	19 403.991	1/2	M1+E2	3.86(−1)
562.983	1518.829	3/2	19 276.431	5/2	M1	3.90(−1)
572.182	1518.829	3/2	18 990.929	3/2	M1	7.62(−1)
607.187	3172.473	5/2	19 637.309	5/2	M1	2.93(−1)
620.794	3172.473	5/2	19 276.431	5/2	M1	2.02(−1)
631.998	3172.473	5/2	18 990.929	3/2	M1	9.32(−1)
670.010	4716.278	7/2	19 637.309	5/2	M1	4.37(−1)
686.617	4716.278	7/2	19 276.431	5/2	M1	2.05(−1)
758.900	0.000	1/2	13 173.337	1/2	M1	3.92(−1)
857.801	1518.829	3/2	13 173.337	1/2	M1	7.65(−1)
914.994	8711.274	3/2	19 637.309	5/2	M1	9.12(−1)
934.959	8711.274	3/2	19 403.991	1/2	M1+E2	5.35(−1)
972.529	8711.274	3/2	18 990.929	3/2	M1	8.82(−1)
976.346	3172.473	5/2	13 411.939	7/2	M1	4.94(−1)
985.837	4716.278	7/2	14 857.160	9/2	M1	4.76(−1)
1021.985	1518.829	3/2	11 301.024	5/2	M1+E2	3.27(−1)
1131.843	0.000	1/2	8832.728	1/2	M1	1.39(+0)
1134.569	10 592.485	3/2	19 403.991	1/2	M1	2.73(+0)
1146.765	4716.278	7/2	13 434.070	5/2	M1+E2	2.62(−1)
1147.782	6147.085	9/2	14 857.160	9/2	M1	2.23(+0)
1149.684	4716.278	7/2	13 411.939	7/2	M1	1.11(+0)
1151.235	10 592.485	3/2	19 276.431	5/2	M1	2.07(−1)
1190.371	10 592.485	3/2	18 990.929	3/2	M1	1.61(+0)
1229.895	3172.473	5/2	11 301.024	5/2	M1	3.05(−1)
1300.051	11 301.024	5/2	18 990.929	3/2	M1	1.36(+0)
1347.338	3172.473	5/2	10 592.485	3/2	M1	1.19(+0)
1366.886	1518.829	3/2	8832.728	1/2	M1	2.83(+0)
1604.530	13 173.337	1/2	19 403.991	1/2	M1	4.76(−1)
1611.621	13 434.070	5/2	19 637.309	5/2	M1	4.92(−1)
1662.385	7420.261	5/2	13 434.070	5/2	M1	8.92(−1)
1704.712	13 411.939	7/2	19 276.431	5/2	M1	2.12(−1)
1718.455	13 173.337	1/2	18 990.929	3/2	M1	9.93(−1)
1998.266	14 634.336	3/2	19 637.309	5/2	M1	3.73(−1)

[a] Air wavelengths deduced from the experimental levels.
[b] From Kramida and Shirai (2006).
a(b) is written for $a \cdot 10^b$.

1.77 a_0. The HFR+CPOL method was then combined with the least-squares optimization routine using experimental energy levels published in the recent compilation of Kramida and Shirai (2006) for $5d^5$, $5d^46s$ and $5d^36s^2$ configurations. The standard deviation of the fit was found to be equal to 99 cm^{-1}.

The HFR+CPOL method was also considered for computing the transition probabilities for M1 and E2 transitions within the $5d^4$, $5d^36s$ and $5d^26s^2$ lowest configurations of W III. In this case, the valence–valence interactions were taken into account by including, in the theoretical model, the same configurations as those included by Palmeri *et al* (2008), i.e. $5d^4$, $5d^36s$, $5d^37s$, $5d^38s$, $5d^26s^2$, $5d^26s7s$, $5d^26s8s$, $5d^36d$, $5d^26s6d$, $5d6s^26d$ and $5d^26p^2$. The core-polarization potential used a $4f^{14}5d$ Tm-like W^{5+} ionic core surrounded by three valence electrons. As no dipole polarizability was tabulated by Fraga *et al* (1976) for W VI, a value of 4.00 a_0^3 was extrapolated along the Tm isoelectronic sequence. The cut-off radius used was the HFR mean radius of the 5d orbital in W III, i.e. 1.66 a_0. Then a least-squares fitting procedure was applied using the energy levels published by Iglesias *et al* (1989) for the $5d^4$, $5d^36s$ and $5d^26s^2$ configurations. The standard deviation of the fit was found to be equal to 122 cm^{-1}.

The computed transition probabilities, A_{ki}, for M1 and E2 lines connecting the metastable levels in W I, W II and W III are listed in tables 4, 5 and 6, respectively. If the two types of radiation contribute significantly to the total intensity of a line, the sum of both components is given. The exclusion criterion of one particular type of radiation for a given transition is that the corresponding *A*-value should be less than 1% of the sum of M1 and E2 contributions. Owing to the extensive nature of the results, only transitions for which A_{ki} is greater than 0.2 s^{-1} and λ shorter than 2000 nm are reported in the tables.

Table 6. Transition probabilities for forbidden lines in W III. Only transitions for which A-values are greater than 0.2 s^{-1} and λ are shorter than 2000 nm are given.

	Lower level		Upper level			
λ (nm)[a]	E (cm^{-1})[b]	J	E (cm^{-1})[b]	J	Type	A_{ki} (s^{-1})
695.950	2256.20	1	16 621.08	2	M1+E2	5.44(−1)
736.496	6277.81	3	19 851.87	3	M1+E2	4.29(−1)
821.792	7686.68	4	19 851.87	3	M1+E2	6.47(−1)
822.150	4461.19	2	16 621.08	2	M1+E2	2.06(−1)
826.315	6277.81	3	18 376.40	4	M1	7.69(−1)
851.849	2256.20	1	13 992.14	2	M1	1.76(+0)
935.222	7686.68	4	18 376.40	4	M1+E2	1.82(+0)
945.202	4461.19	2	15 038.04	3	M1	8.16(−1)
957.719	4461.19	2	14 899.80	3	M1+E2	5.40(−1)
966.547	6277.81	3	16 621.08	2	M1	2.00(+0)
1048.926	4461.19	2	13 992.14	2	M1	1.48(+0)
1106.313	7686.68	4	16 723.24	5	M1	3.22(−1)
1141.210	6277.81	3	15 038.04	3	M1	1.60(+0)
1159.508	6277.81	3	14 899.80	3	M1+E2	8.27(−1)
1187.346	4461.19	2	12 881.03	1	M1	4.73(+0)
1307.157	2256.20	1	9904.30	0	M1	9.62(+0)
1346.771	6277.81	3	13 700.95	4	M1	4.76(−1)
1536.304	4461.19	2	10 968.54	1	M1+E2	2.16(−1)
1662.258	7686.68	4	13 700.95	4	M1	1.68(+0)
1706.097	13 992.14	2	19 851.87	3	M1	1.91(+0)

[a] Air wavelengths deduced from the experimental levels.
[b] From Iglesias *et al* (1989).
a(b) is written for a · 10^{b}.

4. Conclusion

Critically evaluated transition rates available in the literature for allowed electric dipole transitions together with a new set of computed A-values for forbidden lines are reported in the present work for W I, W II and W III. These results are intended to provide plasma physicists with some of the data they need for spectroscopic diagnostics and modelling of fusion plasmas magnetically confined in reactors where tungsten is expected to be used as a facing material.

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