

Article

Detailed Analysis of Configuration Interaction and Calculation of Radiative Transition Rates in Seven Times Ionized Tungsten (W VIII)

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Abstract: A new set of oscillator strengths and transition probabilities for EUV spectral lines of seven times ionized tungsten (W VIII) is reported in the present paper. These results have been obtained using the pseudo-relativistic Hartree-Fock (HFR) method combined with a semi-empirical optimization of the radial parameters minimizing the discrepancies between computed energy levels and available experimental data. The final physical model considered in the calculations has been chosen further to a detailed investigation of the configuration interaction in this atomic system characterized by complex configurations of the type $4f^{14}5s^25p^5$, $4f^{14}5s^25p^4nl$, $4f^{14}5s5p^6$, $4f^{13}5s^25p^6$, $4f^{13}5s^25p^5nl$ and $4f^{12}5s^25p^6nl$ ($nl = 5d, 6s$).

Keywords: atomic structure; oscillator strengths; transition probabilities; W VIII spectrum

1. Introduction

It is now well established that tungsten plays an important role in the development of fusion reactors (see e.g., [1–5]). Indeed, this element has been chosen to be the main component of the divertor of the International Thermonuclear Experimental Reactor (ITER) so that spectral lines of W ions sputtered from the wall to the core plasma provide a key information for plasma emission analysis

and diagnostic purposes. As a consequence, a detailed knowledge of the atomic structure and radiative properties of almost each ionization stage of tungsten is required. Over the past few years, several of our works were focused on the determination of spectroscopic data for neutral to moderately ionized tungsten. More precisely, oscillator strengths and transition probabilities were calculated for a large number of lines in W I [6], W II [7], W III [8], W IV [9], W V [10] and W VI [11]. In all these studies, the pseudo-relativistic Hartree-Fock (HFR) method including a large amount of intravalence and core-valence electronic correlation effects was combined with a semi-empirical process minimizing the discrepancies between calculated and available experimental energy levels. For W I, W II and W III, the accuracy of this approach was assessed through detailed comparisons with experimental radiative lifetimes measured with the time-resolved laser-induced fluorescence (TR-LIF) technique while, for W IV, W V and W VI, our new HFR results were supported by a detailed comparison with transition probabilities obtained using different theoretical methods. In all cases, it was shown that the methodology used for modeling the atomic structure and computing the radiative parameters of lowly ionized tungsten was able to provide reliable spectroscopic data of great interest in fusion research. Let us also mention here that one of our recent papers [12] was dedicated to a critical evaluation of the transition rates available in the literature for electric dipole lines in W I, W II and W III.

The main goal of the present work is to extend all our previous studies related to tungsten ions to the seven times ionized species (W VIII) for which 187 spectral lines were very recently observed leading to the first experimental identification of energy levels in this ion [13]. As we did for the first W ions, we also used here the pseudo-relativistic Hartree-Fock method putting the emphasis on the sensitivity of the radiative rates to electronic correlation effects in this particularly complex atomic system characterized by interacting configurations of the type $4f^{14}5s^25p^5$, $4f^{14}5s^25p^4nl$, $4f^{14}5s5p^6$, $4f^{13}5s^25p^6$, $4f^{13}5s^25p^5nl$ and $4f^{12}5s^25p^6nl$ ($nl = 5d, 6s$). The final theoretical model was then optimized through a semi-empirical adjustment of the radial energy parameters to compute the oscillator strengths and transition probabilities for a set of 227 lines involving experimentally known levels with gf -values larger than 0.0001 in the extreme ultraviolet (EUV) wavelength region from 160.9 to 347.0 Å of the W VIII spectrum.

2. Available Atomic Data in W VIII

Up until very recently, nearly nothing was known about the atomic structure of seven times ionized tungsten. This lack of knowledge was underlined by Kramida and Shirai [14] who compiled all the classified energy levels and spectral lines of multiply ionized tungsten atoms from W^{2+} to W^{73+} . In this compilation, it was reminded that it was by the way uncertain whether the ground state of W VIII was $4f^{13}5s^25p^6 \ ^2F^{\circ}_{7/2}$ or $4f^{14}5s^25p^5 \ ^2P^{\circ}_{3/2}$, making this ion the only known case of p and f orbitals competing for the ground state, as previously noted by Sugar and Kaufman [15]. An isoelectronic study was not even of great help to solve the problem since it was found that the ground configuration was $4f^{11}5s^25p^66s^2$ for the first members of the sequence, Ho I and Er II, $4f^{13}5s^25p^6$ for Hf VI and Ta VII, and $4f^{14}5s^25p^5$ for Re IX and the rest of the sequence. By analyzing the $4f^{13}(^2F^{\circ}_{7/2})5s^25p^6ns$ and $4f^{14}5s^25p^5(^2P^{\circ}_{3/2})ns$ series of W VII, Sugar and Kaufman [15] asserted that the ground state of W VIII was probably $4f^{13}5s^25p^6 \ ^2F^{\circ}_{7/2}$, the $4f^{14}5s^25p^5 \ ^2P^{\circ}_{3/2}$ level being predicted $800 \pm 700 \text{ cm}^{-1}$ above it. This assumption was in agreement with the calculations performed earlier by Carlson *et al.* [16] who

showed that 4f was the least-bound orbital of W VII. Later on, an experimental observation of W VIII spectrum was performed by Veres *et al.* [17] in emission of tokamak plasma but the low spectral resolution did not allow them to identify the observed broad peaks. However, using the weighted average energies of sub-configurations based on the $4f^{13}5s^25p^6\ ^2F^{\circ}_{7/2,5/2}$ and $4f^{14}5s^25p^5\ ^2P^{\circ}_{3/2,1/2}$ in W VII, taken from [15], Kramida and Shirai [14] predicted the position of the four corresponding energy levels in W VIII at 0 cm^{-1} , $17,440 \pm 60\text{ cm}^{-1}$, $800 \pm 700\text{ cm}^{-1}$ and $87,900 \pm 300\text{ cm}^{-1}$, respectively.

Two years ago, the first extensive analysis of the W VIII spectrum was reported by Ryabtsev *et al.* [13] who used two experimental setups installed at the Institute of Spectroscopy in Troitsk (Russia) and at the Observatory of Paris-Meudon (France) for obtaining tungsten ion spectra. In their work, a total of 187 W VIII lines in the region 160–271 Å were identified as transitions from the interacting excited even $4f^{12}5s^25p^65d + 4f^{13}5s^25p^5(5d + 6s) + 4f^{14}5s^25p^4(5d + 6s) + 4f^{14}5s5p^6$ configurations to the low-lying odd configurations $4f^{13}5s^25p^6$ and $4f^{14}5s^25p^5$. This gave rise to the establishment of the energy values of 4 odd- and 98 excited even-parity levels up to $622,123\text{ cm}^{-1}$ with estimated uncertainties ranging from 5 to 18 cm^{-1} . It was also firmly established that the ground state of W VIII was $4f^{13}5s^25p^6\ ^2F^{\circ}_{7/2}$ and the first excited $4f^{14}5s^25p^5\ ^2P^{\circ}_{3/2}$ level was located $1233 \pm 3\text{ cm}^{-1}$ above it, in agreement with the value $800 \pm 700\text{ cm}^{-1}$ predicted by Kramida and Shirai [14]. The level identifications reported in [13] were supported by calculations performed using the pseudo-relativistic Hartree-Fock (HFR) method of Cowan [18] combined with a semi-empirical adjustment of the energy parameters. In the HFR model considered by these latter authors, also used for providing transition probabilities corresponding to the experimentally observed spectral lines, the $4f^{13}5s^25p^6$ and $4f^{14}5s^25p^5$ odd-parity configurations and the $4f^{12}5s^25p^6(5d + 6s + 6d)$, $4f^{13}5s^25p^5(5d + 6s + 6d + 7s)$, $4f^{14}5s^25p^4(5d + 6s + 6d + 7s)$, $4f^{14}5s5p^6$ and $4f^{14}5s5p^55f$ even-parity configurations were included. Furthermore, these calculations revealed a very strong mixing in the eigenvector compositions for many excited even-parity states, neither the *LS*-coupling nor the *jj*-coupling appearing to give a good overall description of the energy levels.

3. Configuration Interaction Analysis

As mentioned in the previous section, the only available radiative rates in W VIII were reported by Ryabtsev *et al.* [13] who used the HFR method with a rather unbalanced physical model since it included only 2 odd-parity configurations ($4f^{13}5s^25p^6$ and $4f^{14}5s^25p^5$) for 13 configurations ($4f^{12}5s^25p^6(5d + 6s + 6d)$, $4f^{13}5s^25p^5(5d + 6s + 6d + 7s)$, $4f^{14}5s^25p^4(5d + 6s + 6d + 7s)$, $4f^{14}5s5p^6$ and $4f^{14}5s5p^55f$) in the even parity. In order to estimate the effects of configuration interaction on the radiative parameters of W VIII, different physical models based on the pseudo-relativistic Hartree-Fock method were considered in the present work. In all of them, the electrostatic interaction Slater integrals, F^k , G^k and R^k were scaled down by a factor 0.85, as suggested by Cowan [18] while the spin-orbit parameters were kept to their *ab initio* values. The first model used, HFR(A), was the same as the one considered in [13] for computing their transition probabilities. The second model, HFR(B), was built to rebalance configuration interaction within both parities by adding to the HFR(A) model the $4f^{12}5s^25p^6(5f + 6p) + 4f^{13}5s^25p^5(5f + 6p) + 4f^{14}5s^25p^4(5f + 6p) + 4f^{14}5s5p^5(5d + 6s + 6d + 7s)$ odd-parity configurations, leading to 12 and 13 configurations in each parity, respectively. In the third model, HFR(C), we proceeded in a more systematic way since all the configurations of the type $(4f + 5s + 5p)^k nl$ ($k = 20$ or 21 , $nl = 5d, 5f, 6s, 6p, 6d, 7s$) with one or two holes in the 4f, 5s and 5p subshells were included in the multiconfiguration

expansions. This gave rise to the 18 odd-parity configurations $4f^{13}5s^25p^6$, $4f^{14}5s^25p^5$, $4f^{14}5s^25p^4(5f + 6p)$, $4f^{14}5s5p^5(5d + 6s + 6d + 7s)$, $4f^{13}5s^25p^5(5f + 6p)$, $4f^{13}5s5p^6(5d + 6s + 6d + 7s)$, $4f^{14}5p^6(5f + 6p)$, $4f^{12}5s^25p^6(5f + 6p)$ and the 21 even-parity configurations $4f^{14}5s5p^6$, $4f^{14}5s^25p^4(5d + 6s + 6d + 7s)$, $4f^{14}5s5p^5(5f + 6p)$, $4f^{13}5s^25p^5(5d + 6s + 6d + 7s)$, $4f^{13}5s5p^6(5f + 6p)$, $4f^{14}5p^6(5d + 6s + 6d + 7s)$, $4f^{12}5s^25p^6(5d + 6s + 6d + 7s)$. Finally, a fourth model, HFR(D), was tested. In this one, the same set of interacting configurations as the one considered in model HFR(C) was included with the additional permission that one electron could be excited on the 6f or the 7p subshell, giving rise to a total of 26 odd-parity and 25 even-parity configurations. Using the four HFR models presented hereabove, we computed and compared the radiative lifetimes for the 250 lowest even-parity energy levels with τ -values smaller than 100 ns. These comparisons are summarized in Figure 1 showing the ratios $\tau(B)/\tau(A)$, $\tau(C)/\tau(B)$ and $\tau(D)/\tau(C)$, respectively. When looking at Figure 1a, it is clear that the numerous missing odd-parity configurations in the HFR(A) model, similar to the one used by Ryabtsev *et al.* [13], make without doubt this latter model insufficient to provide a reliable set of transition probabilities, the mean deviation between the HFR(B) and HFR(A) lifetimes being found to be within about 30%, with notable discrepancies reaching a factor of 2–3 in some cases. Moreover, Figure 1b shows that the HFR(B) model does not either include enough configuration interaction to give a reasonable accuracy of the radiative lifetime calculations, the differences between the data computed with models HFR(C) and HFR(B) still reaching a factor of 1.5–2 in many cases. However, as shown in Figure 1c, the excitations of one electron to the 6f or 7p subshell included in model HFR(D) do not really change the results obtained in model HFR(C), the mean deviation between both sets of lifetimes not exceeding 2%. We can therefore conclude that the one single excitation from 4f, 5s and 5p to nl orbitals with $nl = 5d, 5f, 6s, 6p, 6d$ and $7s$, as considered in the configuration interaction expansions of model HFR(C), should form a good basis for computing the spectroscopic data in W VIII.

Furthermore, it is also interesting to estimate the influence of the double excitations on the radiative parameters. Indeed, for transitions of the type $4f^{14}5s^25p^5 - 4f^{14}5s^25p^45d$ and $4f^{13}5s^25p^6 - 4f^{13}5s^25p^55d$, the $5p^2 \rightarrow 5d^2$ double excitation in the lower odd-parity state leads to an allowed transition to the upper even-parity state with an electric dipole matrix element which is equal in magnitude to that for the primary transition. In order to evaluate this effect on the decay rates, we extended the multiconfiguration expansion of model HFR(C) with the two additional odd-parity configurations $4f^{14}5s^25p^35d^2$ and $4f^{13}5s^25p^45d^2$, giving rise to model HFR(E). Finally, as similar speculations can be made for the double excitation $4f^2 \rightarrow 5d^2$ in the case of the $4f^{14}5s^25p^5 - 4f^{13}5s^25p^55d$ and $4f^{13}5s^25p^6 - 4f^{12}5s^25p^65d$ transitions and for the double excitation $5p^2 \rightarrow 6s^2$ in the case of the $4f^{14}5s^25p^5 - 4f^{14}5s^25p^46s$ and $4f^{13}5s^25p^6 - 4f^{13}5s^25p^56s$ transitions, the odd-parity configurations $4f^{12}5s^25p^55d^2$ and $4f^{11}5s^25p^65d^2$ were added to model HFR(E) to give model HFR(F), while $4f^{14}5s^25p^36s^2$ and $4f^{13}5s^25p^46s^2$ were added to model HFR(F) to give model HFR(G). The radiative lifetimes calculated with these latter models are compared to those obtained with HFR(C) in Figure 2. As observed in this figure, if the $5p^2 \rightarrow 6s^2$, considered in model HFR(G) do not change the final results (see Figure 2c), it is not the same for the $5p^2 \rightarrow 5d^2$ and $4f^2 \rightarrow 5d^2$ excitations, respectively included in models HFR(E) and HFR(F), which both lead to non negligible changes in the computed radiative lifetimes by about 20% (see Figures 2a,2b). This is nevertheless not very surprising since this kind of effect was already highlighted by Quinet and Hansen [19] who

pointed out the influence of $3p^2 \rightarrow 3d^2$ core excitation on the $3p^6 3d^N - 3p^5 3d^{N+1}$ transition rates in iron group elements.

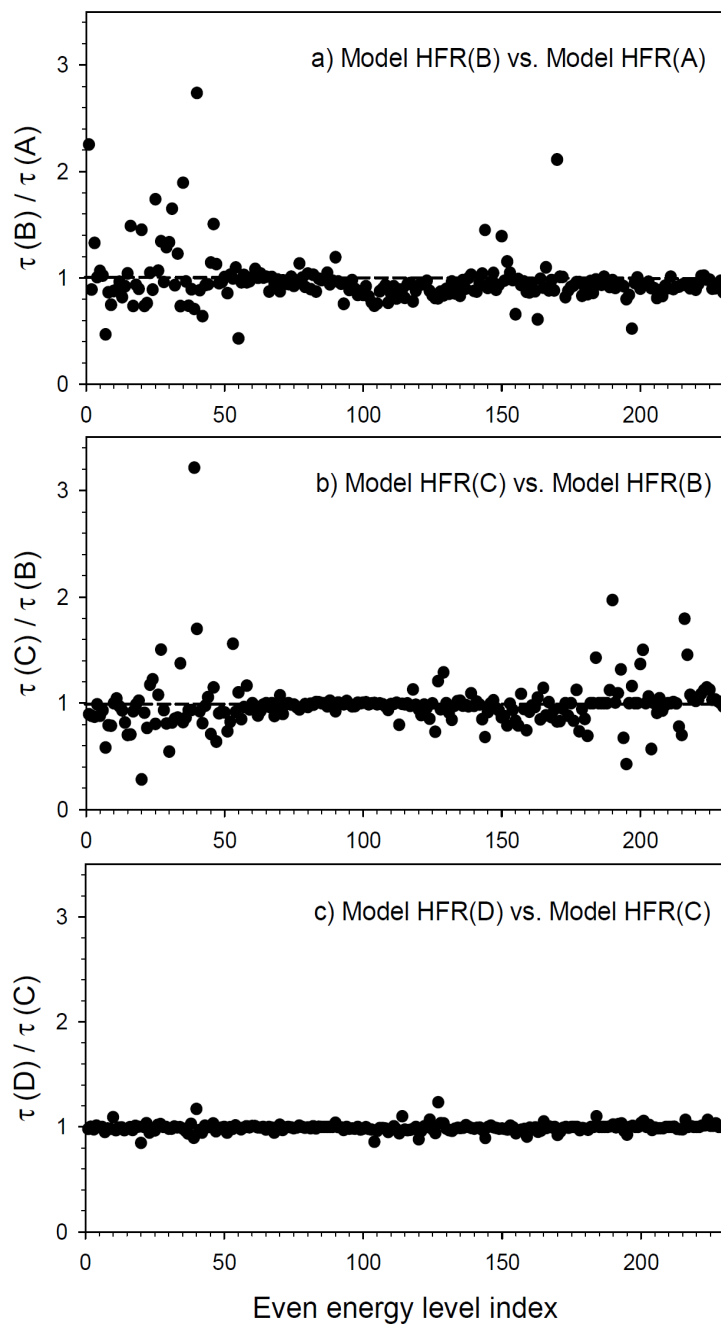


Figure 1. Comparison between radiative lifetimes obtained in the present work using different HFR models for short-lived even-parity energy levels ($\tau < 100$ ns) in W VIII. In each panel, the y-axis gives the ratio of τ -values computed with two successive models including only single excitations (see text) while the x-axis corresponds to the level indexes, assigned according to the order of increasing energies.

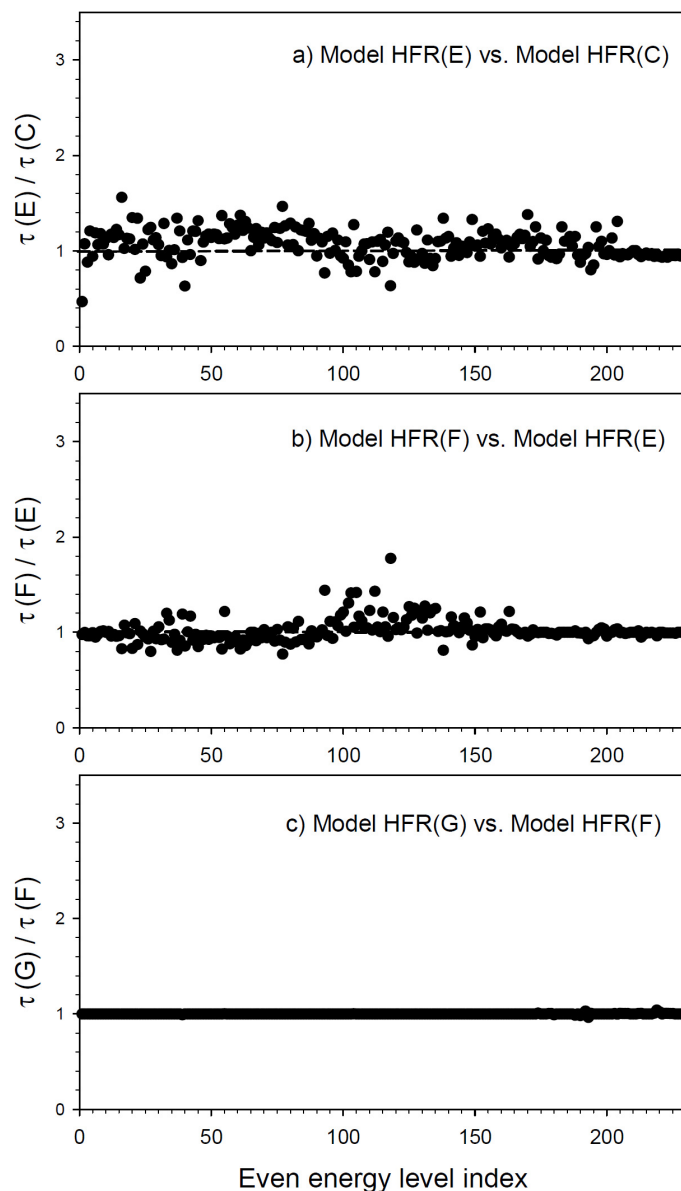


Figure 2. Comparison between radiative lifetimes obtained in the present work using different HFR models for short-lived even-parity energy levels ($\tau < 100$ ns) in W VIII. In each panel, the y-axis gives the ratio of τ -values computed with two successive models including both single and double excitations (see text) while the x-axis corresponds to the level indexes, assigned according to the order of increasing energies.

4. Radiative Parameter Calculations

Further to the detailed discussion presented in the previous section, HFR(F) was chosen as the final model to compute the radiative parameters in W VIII. To summarize, the following configurations were explicitly included in the calculations: $4f^{13}5s^25p^6 + 4f^{14}5s^25p^5 + 4f^{14}5s^25p^4(5f + 6p) + 4f^{14}5s5p^5(5d + 6s + 6d + 7s) + 4f^{13}5s^25p^5(5f + 6p) + 4f^{13}5s5p^6(5d + 6s + 6d + 7s) + 4f^{14}5p^6(5f + 6p) + 4f^{12}5s^25p^6(5f + 6p) + 4f^{14}5s^25p^35d^2 + 4f^{13}5s^25p^45d^2 + 4f^{12}5s^25p^55d^2 + 4f^{11}5s^25p^65d^2$ (odd parity) and $4f^{14}5s5p^6 + 4f^{14}5s^25p^4(5d + 6s + 6d + 7s) + 4f^{14}5s5p^5(5f + 6p) + 4f^{13}5s^25p^5(5d + 6s + 6d + 7s) + 4f^{13}5s5p^6(5f + 6p) + 4f^{14}5p^6(5d + 6s + 6d + 7s) + 4f^{12}5s^25p^6(5d + 6s + 6d + 7s)$ (even parity). This

model was then combined with a semi-empirical adjustment of the radial energy parameters in order to minimize the discrepancies between calculated and available experimental energy levels. The strategy followed in the fitting process was exactly the same as the one developed by Ryabtsev *et al.* [13] to the extent that, starting with the numerical values given in their paper, the same parameters were adjusted with the same constraints as those used by these latter authors. This allowed us simply to adapt and optimize the final radial parameters to our physical model including a much larger number of interacting configurations than the model used in [13].

The numerical values of the radial parameters adopted in our work are reported in Table 1 while the calculated energy levels are compared to the experimental data in Table 2. For the 98 even-parity levels, the standard deviation of the fit was found to be equal to 438 cm^{-1} which is comparable to the value of 443 cm^{-1} obtained by Ryabtsev *et al.* [13]. When looking at the table, it appears that the ordering of experimental and calculated energy levels can be different in a few cases. This is simply due to the fact that some experimental level values are close to each other, with a difference of the same order of magnitude as the standard deviation mentioned above. However, in any case, the ordering of the calculated energies always corresponds to the observed one within a *J*-matrix. Table 2 also lists the first three *LS*-components for each level. We can note that, as expected, most of the even-parity states are very strongly mixed and, as already pointed out by Ryabtsev *et al.*, the *jj*-coupling scheme given by these authors appears a bit more appropriate than the *LS* one, with average eigenvector purities of 45% and 32%, respectively. It is also worth mentioning that, if *LS* purities of 100% were reported by Ryabtsev *et al.*, for the four levels belonging to the $4f^{l^3}5s^25p^6$ and $4f^{l^4}5s^25p^5$ odd-parity configurations, it is no more the case in our extended configuration interaction model which gives slightly reduced purities of 97%–98% for those levels. In spite of their very strong mixing, the first *LS*-component of each level is given in boldface in Table 2.

Table 1. Numerical values (in cm^{-1}) of the radial energy parameters adopted in the Hartree-Fock (HFR) calculations.

Configuration	Parameter	Fit	Unc.	Note ^a	Fit/HFR
Odd parity					
$4f^{l^3}5s^25p^6$	E_{av}	29,053	0		
	$\zeta(4f)$	4971	0		0.988
$4f^{l^4}5s^25p^5$	E_{av}	51,968	0		
	$\zeta(5p)$	59,148	0		1.003
Even parity					
$4f^{l^4}5s5p^6$	E_{av}	377,512		f	
$4f^{l^3}5s^25p^55d$	E_{av}	403,242	249		
	$\zeta(4f)$	5022	48	r11	0.995
	$\zeta(5p)$	60,705	127	r2	0.984
	$\zeta(5d)$	4716	109	r10	0.988
	$F^2(4f,5p)$	52,909	1606	r12	0.785
	$F^2(4f,5d)$	35,345	2124	r4	0.780
	$F^4(4f,5d)$	17,165	1031	r4	0.780
	$F^2(5p,5d)$	63,984	2700	r7	0.815

Table 1. Cont.

Configuration	Parameter	Fit	Unc.	Note ^a	Fit/HFR
	G ² (4f,5p)	28,161	1313	r3	1.025
	G ⁴ (4f,5p)	23,435	1092	r3	1.025
	G ¹ (4f,5d)	13,991	413	r5	0.876
	G ³ (4f,5d)	13,111	387	r5	0.876
	G ⁵ (4f,5d)	10,482	309	r5	0.876
	G ¹ (5p,5d)	67,786	607	r1	0.711
	G ³ (5p,5d)	42,728	383	r1	0.711
4f ¹³ 5s ² 5p ⁵ 6d	E _{av}	775,400		f	
4f ¹³ 5s ² 5p ⁵ 6s	E _{av}	542,642	139		
	ζ(4f)	5033	48	r11	0.995
	ζ(5p)	61,895	130	r2	0.984
	F ² (4f,5p)	53,429	1622	r12	0.785
	G ² (4f,5p)	28,352	1322	r3	1.025
	G ⁴ (4f,5p)	23,664	1103	r3	1.025
	G ³ (4f,6s)	6873	2032		1.294
	G ¹ (5p,6s)	9385	742	r13	0.881
4f ¹³ 5s ² 5p ⁵ 7s	E _{av}	813,134		f	
4f ¹⁴ 5s ² 5p ⁴ 5d	E _{av}	420,745	400		
	F ² (5p,5p)	77,035	2775	r14	0.834
	ζ(5p)	58,775	123	r2	0.984
	ζ(5d)	4465	103	r10	0.988
	F ² (5p,5d)	62,865	2653	r7	0.815
	G ¹ (5p,5d)	66,467	595	r1	0.711
	G ³ (5p,5d)	41,892	375	r1	0.711
4f ¹⁴ 5s ² 5p ⁴ 6d	E _{av}	778,313		f	
4f ¹⁴ 5s ² 5p ⁴ 6s	E _{av}	550,299	268		
	F ² (5p,5p)	77,932	2807	r14	0.838
	ζ(5p)	59,932	126	r2	0.984
	G ¹ (5p,6s)	9397	743	r13	0.881
4f ¹⁴ 5s ² 5p ⁴ 7s	E _{av}	813,793		f	
4f ¹⁴ 5s5p ⁵ 6p	E _{av}	992,590		f	
4f ¹⁴ 5s5p ⁵ 5f	E _{av}	1092,223		f	
4f ¹² 5s ² 5p ⁶ 5d	E _{av}	429,283	138		
	F ² (4f,4f)	149,065	2553		0.843
	F ⁴ (4f,4f)	111,500	6763		0.991
	F ⁶ (4f,4f)	77,044	3283		0.947
	α	22		f	
	β	−1000		f	
	γ	−70		f	
	ζ(4f)	5200	49	r11	0.995
	ζ(5d)	4977	115	r10	0.988
	F ² (4f,5d)	36,300	1467	r6	0.785
	F ⁴ (4f,5d)	17,592	711	r6	0.785

Table 1. Cont.

Configuration	Parameter	Fit	Unc.	Note ^a	Fit/HFR	
4f ¹² 5s ² 5p ⁶ 6d 4f ¹² 5s ² 5p ⁶ 6s	G ¹ (4f,5d)	13,832	408	r5	0.876	
	G ³ (4f,5d)	13,147	388	r5	0.876	
	G ⁵ (4f,5d)	10,564	312	r5	0.876	
	E _{av}	819,431		f		
	E _{av}	579,803		f		
	F ² (4f,4f)	147,636		f	0.833	
	F ⁴ (4f,4f)	110,752		f	0.982	
	F ⁶ (4f,4f)	78,585		f	0.963	
	α	22		f		
	β	−1000		f		
	γ	−70		f		
4f ¹³ 5s ² 5p ⁵ 5d – 4f ¹⁴ 5s ² 5p ⁴ 5d	ζ(4f)	5161		f	0.985	
	G ³ (4f,6s)	3974		f	0.758	
	D ² (4f,5p;4f,4f)	−5660	51	r8	0.864	
	D ⁴ (4f,5p;4f,4f)	−309	3	r8	0.864	
	D ² (5p,5p;4f,5p)	−34,864	312	r8	0.864	
	D ² (5p,5d;4f,5d)	−27,246	244	r8	0.864	
	D ⁴ (5p,5d;4f,5d)	−17,855	160	r8	0.864	
	E ¹ (5p,5d;4f,5d)	−24,107	216	r8	0.864	
	E ³ (5p,5d;4f,5d)	−18,067	162	r8	0.864	
	4f ¹³ 5s ² 5p ⁵ 5d – 4f ¹² 5s ² 5p ⁶ 5d	D ² (4f,4f;4f,5p)	−3792	8	r9	0.827
		D ⁴ (4f,4f;4f,5p)	858	2	r9	0.827
D ² (4f,5p;5p,5p)		−32,556	68	r9	0.827	
D ² (4f,5d;5p,5d)		−25,604	54	r9	0.827	
D ⁴ (4f,5d;5p,5d)		−16,845	35	r9	0.827	
E ¹ (4f,5d;5p,5d)		−22,393	47	r9	0.827	
E ³ (4f,5d;5p,5d)		−16,982	36	r9	0.827	
4f ¹⁴ 5s ² 5p ⁴ 5d – 4f ¹² 5s ² 5p ⁶ 5d	D ² (4f,4f;5p,5p)	24,592	52	r9	0.827	
	D ⁴ (4f,4f;5p,5p)	20,291	43	r9	0.827	
4f ¹³ 5s ² 5p ⁵ 6s – 4f ¹⁴ 5s ² 5p ⁴ 6s	D ² (4f,5p,4f,4f)	−6391		f	1.000	
	D ⁴ (4f,5p;4f,4f)	−244		f	1.000	
	D ² (5p,5p;4f,5p)	−40,487		f	1.000	

^a f. fixed parameter from [13]; r n : parameters linked by their corresponding HFR ratios.

Table 2. Comparison between the energy levels computed in the present work and the experimentally known values available in seven times ionized tungsten (W VIII). Energies are given in cm^{-1} .

Index	E_{exp}^a	E_{calc}^b	ΔE^c	J	Percentage Composition in LS-Coupling ^d
Odd Parity					
1°	0	0	0	7/2	98 $4f^{13}5p^6\ ^2F$
2°	1233	1233	0	3/2	98 $4f^{14}5p^5\ ^2P$
3°	17,410	17,410	0	5/2	98 $4f^{13}5p^6\ ^2F$
4°	89,123	89,123	0	1/2	97 $4f^{14}5p^5\ ^2P$
Even Parity					
1	377,119	377,140	-21	9/2	28 $4f^{13}5p^5(^3F)5d\ ^2H$ + 23 $4f^{13}5p^5(^1D)5d\ ^2G$ + 8 $4f^{13}5p^5(^3F)5d\ ^2G$
2	377,288	376,992	296	3/2	25 $4f^{13}5p^5(^1D)5d\ ^2P$ + 18 $4f^{13}5p^5(^3D)5d\ ^4F$ + 15 $4f^{13}5p^5(^3D)5d\ ^4P$
3	377,867	377,714	153	5/2	21 $4f^{13}5p^5(^3D)5d\ ^4F$ + 12 $4f^{14}5p^4(^1S)5d\ ^2D$ + 9 $4f^{13}5p^5(^3F)5d\ ^2F$
4	380,899	381,127	-228	9/2	18 $4f^{13}5p^5(^1G)5d\ ^2G$ + 18 $4f^{13}5p^5(^3G)5d\ ^2G$ + 14 $4f^{13}5p^5(^3F)5d\ ^2G$
5	382,019	382,285	-266	7/2	22 $4f^{13}5p^5(^1D)5d\ ^2F$ + 15 $4f^{13}5p^5(^3D)5d\ ^2G$ + 13 $4f^{13}5p^5(^3F)5d\ ^2F$
6	383,133	383,535	-402	5/2	18 $4f^{13}5p^5(^3D)5d\ ^2F$ + 17 $4f^{13}5p^5(^1D)5d\ ^2D$ + 10 $4f^{14}5p^4(^1S)5d\ ^2D$
7	384,400	383,622	778	9/2	24 $4f^{13}5p^5(^1G)5d\ ^2H$ + 20 $4f^{13}5p^5(^3G)5d\ ^4H$ + 11 $4f^{13}5p^5(^3D)5d\ ^4G$
8	386,704	386,497	207	5/2	16 $4f^{13}5p^5(^3F)5d\ ^2D$ + 11 $4f^{13}5p^5(^3G)5d\ ^4D$ + 9 $4f^{13}5p^5(^3F)5d\ ^4P$
9	391,541	392,282	-741	9/2	14 $4f^{13}5p^5(^1D)5d\ ^2G$ + 13 $4f^{12}5p^6(^3H)5d\ ^2G$ + 5 $4f^{13}5p^5(^3G)5d\ ^2H$
10	393,992	393,539	453	7/2	18 $4f^{12}5p^6(^3H)5d\ ^2F$ + 14 $4f^{13}5p^5(^3G)5d\ ^2F$
11	395,276	395,201	75	5/2	19 $4f^{13}5p^5(^3D)5d\ ^2F$ + 17 $4f^{13}5p^5(^3D)5d\ ^4D$ + 16 $4f^{13}5p^5(^3D)5d\ ^4F$
12	395,471	395,624	-153	7/2	14 $4f^{12}5p^6(^3F)5d\ ^4F$ + 11 $4f^{13}5p^5(^3F)5d\ ^2G$ + 8 $4f^{12}5p^6(^3F)5d\ ^4D$
13	395,474	395,124	350	1/2	38 $4f^{14}5p^4(^3P)5d\ ^4P$ + 17 $4f^{13}5p^5(^3D)5d\ ^2S$ + 8 $4f^{14}5p^4(^3P)5d\ ^2P$
14	396,505	396,147	358	7/2	20 $4f^{13}5p^5(^3D)5d\ ^4F$ + 14 $4f^{13}5p^5(^3F)5d\ ^2G$ + 8 $4f^{13}5p^5(^3D)5d\ ^2F$
15	396,894	396,671	22	3/2	17 $4f^{13}5p^5(^3F)5d\ ^2P$ + 17 $4f^{14}5p^4(^3P)5d\ ^4P$ + 16 $4f^{14}5p^4(^3P)5d\ ^4F$
16	397,612	397,709	-97	5/2	19 $4f^{12}5p^6(^1G)5d\ ^2D$ + 19 $4f^{12}5p^6(^3F)5d\ ^4D$
17	398,707	398,269	438	9/2	15 $4f^{13}5p^5(^1G)5d\ ^2G$ + 15 $4f^{13}5p^5(^3G)5d\ ^4G$ + 13 $4f^{13}5p^5(^1G)5d\ ^2H$
18	400,203	400,110	93	9/2	19 $4f^{12}5p^6(^3F)5d\ ^4G$ + 14 $4f^{12}5p^6(^1G)5d\ ^2H$ + 13 $4f^{12}5p^6(^3F)5d\ ^4F$
19	401,984	402,399	-415	5/2	20 $4f^{14}5p^4(^3P)5d\ ^4F$ + 17 $4f^{13}5p^5(^3G)5d\ ^2D$ + 8 $4f^{14}5p^4(^1D)5d\ ^2F$
20	405,907	405,757	150	9/2	41 $4f^{12}5p^6(^3H)5d\ ^4G$ + 25 $4f^{12}5p^6(^3H)5d\ ^4H$ + 8 $4f^{12}5p^6(^3H)5d\ ^4F$
21	408,086	407,948	138	7/2	42 $4f^{12}5p^6(^3H)5d\ ^2F$ + 7 $4f^{12}5p^6(^3F)5d\ ^2F$ + 7 $4f^{12}5p^6(^1G)5d\ ^2F$
22	408,833	409,199	-366	3/2	21 $4f^{12}5p^6(^1G)5d\ ^2D$ + 17 $4f^{12}5p^6(^1D)5d\ ^2D$ + 8 $4f^{12}5p^6(^3F)5d\ ^2D$
23	409,362	409,047	315	5/2	38 $4f^{12}5p^6(^3H)5d\ ^4F$ + 25 $4f^{12}5p^6(^3F)5d\ ^4F$ + 10 $4f^{12}5p^6(^1G)5d\ ^2D$
24	409,676	409,619	57	5/2	18 $4f^{12}5p^6(^3F)5d\ ^4P$ + 16 $4f^{12}5p^6(^3F)5d\ ^4G$ + 10 $4f^{12}5p^6(^3H)5d\ ^2F$
25	410,258	409,885	373	3/2	17 $4f^{12}5p^6(^3F)5d\ ^2D$ + 13 $4f^{13}5p^5(^3G)5d\ ^4F$ + 12 $4f^{13}5p^5(^1G)5d\ ^2D$
26	410,654	410,270	384	7/2	13 $4f^{12}5p^6(^3F)5d\ ^4G$ + 9 $4f^{12}5p^6(^3H)5d\ ^2G$ + 8 $4f^{13}5p^5(^3D)5d\ ^2G$
27	411,819	412,499	-680	5/2	18 $4f^{12}5p^6(^3H)5d\ ^2F$ + 10 $4f^{13}5p^5(^3G)5d\ ^4G$ + 10 $4f^{12}5p^6(^3F)5d\ ^4G$
28	411,832	411,499	333	7/2	23 $4f^{12}5p^6(^3F)5d\ ^4D$ + 21 $4f^{12}5p^6(^3F)5d\ ^4H$ + 14 $4f^{12}5p^6(^1G)5d\ ^2G$
29	413,450	413,503	-53	9/2	28 $4f^{12}5p^6(^3H)5d\ ^2G$ + 13 $4f^{12}5p^6(^3F)5d\ ^4H$ + 12 $4f^{12}5p^6(^3H)5d\ ^4I$
30	414,888	414,853	35	7/2	39 $4f^{12}5p^6(^3F)5d\ ^4G$ + 11 $4f^{12}5p^6(^3F)5d\ ^2F$ + 10 $4f^{12}5p^6(^3F)5d\ ^4H$
31	415,852	415,874	-22	5/2	27 $4f^{12}5p^6(^3F)5d\ ^4G$ + 16 $4f^{12}5p^6(^1G)5d\ ^2F$ + 13 $4f^{12}5p^6(^3F)5d\ ^4P$
32	416,481	416,737	-256	9/2	29 $4f^{12}5p^6(^3F)5d\ ^2G$ + 18 $4f^{12}5p^6(^3H)5d\ ^4I$ + 10 $4f^{12}5p^6(^1G)5d\ ^2G$
33	417,394	417,333	61	3/2	42 $4f^{12}5p^6(^3F)5d\ ^2P$ + 16 $4f^{12}5p^6(^1G)5d\ ^2D$
34	418,403	418,274	129	9/2	28 $4f^{12}5p^6(^3F)5d\ ^4H$ + 28 $4f^{12}5p^6(^3H)5d\ ^2G$ + 18 $4f^{12}5p^6(^3H)5d\ ^4G$
35	419,585	419,953	-368	7/2	35 $4f^{12}5p^6(^3H)5d\ ^4G$ + 11 $4f^{12}5p^6(^3F)5d\ ^4F$ + 10 $4f^{12}5p^6(^3H)5d\ ^4F$

Table 2. Cont.

Index	E _{exp} ^a	E _{calc} ^b	ΔE ^c	J	Percentage Composition in LS-Coupling ^d
36	419,811	419,829	−18	5/2	25 4f ¹² 5p ⁶ (³ H)5d ⁴ F + 14 4f ¹² 5p ⁶ (³ H)5d ² F
37	424,781	424,776	5	5/2	26 4f ¹² 5p ⁶ (³ H)5d ⁴ G + 19 4f ¹² 5p ⁶ (³ F)5d ⁴ P + 15 4f ¹² 5p ⁶ (¹ G)5d ² D
38	425,843	425,913	−70	3/2	38 4f ¹² 5p ⁶ (³ H)5d ⁴ F + 27 4f ¹² 5p ⁶ (³ F)5d ² P + 11 4f ¹² 5p ⁶ (³ F)5d ⁴ P
39	428,199	427,900	299	3/2	42 4f ¹² 5p ⁶ (³ F)5d ⁴ P + 11 4f ¹² 5p ⁶ (³ H)5d ⁴ F + 6 4f ¹² 5p ⁶ (³ F)5d ² P
40	428,216	428,371	−155	7/2	30 4f ¹² 5p ⁶ (³ F)5d ² G + 10 4f ¹² 5p ⁶ (³ H)5d ² F + 7 4f ¹² 5p ⁶ (³ H)5d ² G
41	428,777	428,727	50	7/2	26 4f ¹² 5p ⁶ (³ F)5d ² F + 17 4f ¹² 5p ⁶ (³ F)5d ⁴ F + 11 4f ¹² 5p ⁶ (³ H)5d ⁴ H
42	430,708	430,640	68	7/2	20 4f ¹⁴ 5p ⁴ (³ P)5d ⁴ F + 16 4f ¹² 5p ⁶ (¹ G)5d ² F + 10 4f ¹² 5p ⁶ (³ H)5d ⁴ H
43	432,963	433,564	−601	5/2	13 4f ¹² 5p ⁶ (³ P)5d ⁴ D + 10 4f ¹⁴ 5p ⁴ (³ P)5d ⁴ F + 9 4f ¹⁴ 5p ⁴ (¹ D)5d ² F
44	435,561	435,879	−318	5/2	15 4f ¹² 5p ⁶ (¹ D)5d ² F + 14 4f ¹² 5p ⁶ (¹ G)5d ² D + 8 4f ¹⁴ 5p ⁴ (¹ D)5d ² F
45	435,658	435,516	142	7/2	14 4f ¹² 5p ⁶ (³ H)5d ² G + 12 4f ¹² 5p ⁶ (¹ G)5d ² G
46	437,149	437,658	−509	5/2	14 4f ¹² 5p ⁶ (³ H)5d ² F + 14 4f ¹² 5p ⁶ (³ H)5d ⁴ G + 11 4f ¹² 5p ⁶ (¹ G)5d ² D
47	439,561	439,318	243	7/2	15 4f ¹² 5p ⁶ (³ H)5d ² G + 13 4f ¹² 5p ⁶ (³ P)5d ² F + 12 4f ¹² 5p ⁶ (¹ G)5d ² F
48	445,286	445,209	77	5/2	15 4f ¹² 5p ⁶ (³ P)5d ² D + 13 4f ¹² 5p ⁶ (¹ D)5d ² D + 5 4f ¹⁴ 5p ⁴ (¹ D)5d ² D
49	447,909	447,860	49	5/2	19 4f ¹² 5p ⁶ (¹ G)5d ² F + 14 4f ¹² 5p ⁶ (³ P)5d ⁴ D + 13 4f ¹² 5p ⁶ (³ F)5d ² F
50	452,821	452,511	310	3/2	24 4f ¹² 5p ⁶ (³ P)5d ⁴ P + 11 4f ¹³ 5p ⁵ (¹ G)5d ² D + 10 4f ¹² 5p ⁶ (³ P)5d ² P
51	454,067	454,016	51	7/2	66 4f ¹² 5p ⁶ (¹ I)5d ² G + 7 4f ¹³ 5p ⁵ (³ G)5d ⁴ H + 5 4f ¹² 5p ⁶ (³ H)5d ² G
52	457,652	457,245	407	5/2	17 4f ¹³ 5p ⁵ (¹ G)5d ² F + 14 4f ¹³ 5p ⁵ (³ G)5d ² F + 9 4f ¹² 5p ⁶ (¹ D)5d ² D
53	457,815	457,776	39	9/2	64 4f ¹² 5p ⁶ (¹ I)5d ² H + 7 4f ¹³ 5p ⁵ (¹ G)5d ² G + 6 4f ¹³ 5p ⁵ (³ D)5d ² G
54	458,380	458,337	43	3/2	16 4f ¹² 5p ⁶ (³ P)5d ² P + 12 4f ¹² 5p ⁶ (³ P)5d ⁴ P
55	459,570	460,304	−734	5/2	22 4f ¹² 5p ⁶ (³ P)5d ² D + 6 4f ¹² 5p ⁶ (³ P)5d ² F
56	462,927	463,121	−194	3/2	24 4f ¹² 5p ⁶ (³ P)5d ² D + 14 4f ¹³ 5p ⁵ (¹ D)5d ² D + 10 4f ¹³ 5p ⁵ (³ F)5d ⁴ F
57	466,219	466,223	−4	5/2	33 4f ¹² 5p ⁶ (³ P)5d ² F + 10 4f ¹² 5p ⁶ (¹ D)5d ² D + 7 4f ¹² 5p ⁶ (³ P)5d ⁴ F
58	468,034	467,620	414	5/2	23 4f ¹² 5p ⁶ (³ P)5d ² F + 9 4f ¹³ 5p ⁵ (¹ D)5d ² F + 6 4f ¹³ 5p ⁵ (³ F)5d ⁴ G
59	468,523	468,312	211	5/2	52 4f ¹² 5p ⁶ (³ P)5d ⁴ P + 5 4f ¹² 5p ⁶ (¹ D)5d ² D + 5 4f ¹³ 5p ⁵ (³ G)5d ⁴ F
60	475,117	475,279	−162	3/2	15 4f ¹⁴ 5p ⁴ (¹ D)5d ² P + 9 4f ¹⁴ 5p ⁴ (³ P)5d ⁴ F
61	481,035	480,441	594	5/2	26 4f ¹⁴ 5p ⁴ (³ P)5d ² D + 16 4f ¹⁴ 5p ⁴ (¹ D)5d ² D + 9 4f ¹³ 5p ⁵ (¹ D)5d ² D
62	481,473	481,921	−448	5/2	65 4f ¹⁴ 5p ⁴ (³ P)6s ⁴ P + 23 4f ¹⁴ 5p ⁴ (¹ D)6s ² D
63	483,243	483,385	−142	3/2	18 4f ¹³ 5p ⁵ (¹ D)5d ² P + 16 4f ¹⁴ 5p ⁴ (¹ D)5d ² P
64	485,175	486,300	−1125	5/2	22 4f ¹³ 5p ⁵ (¹ D)5d ² D + 11 4f ¹³ 5p ⁵ (¹ D)5d ² F + 7 4f ¹³ 5p ⁵ (³ F)5d ⁴ F
65	487,901	487,064	837	3/2	50 4f ¹⁴ 5p ⁴ (³ P)6s ² P + 27 4f ¹⁴ 5p ⁴ (¹ D)6s ² D + 13 4f ¹⁴ 5p ⁴ (³ P)6s ⁴ P
66	492,337	493,284	−947	1/2	32 4f ¹⁴ 5p ⁴ (¹ D)5d ² P + 21 4f ¹⁴ 5p ⁴ (¹ D)5d ² S + 16 4f ¹⁴ 5p ⁴ (³ P)5d ² P
67	495,690	495,041	649	9/2	27 4f ¹³ 5p ⁵ (³ D)5d ² G + 18 4f ¹³ 5p ⁵ (³ F)5d ² G + 10 4f ¹³ 5p ⁵ (³ G)5d ² G
68	498,037	499,096	−1059	5/2	29 4f ¹³ 5p ⁵ (³ G)5d ² D + 14 4f ¹³ 5p ⁵ (¹ G)5d ² D + 9 4f ¹² 5p ⁶ (³ P)5d ² D
69	498,541	498,826	−285	3/2	26 4f ¹⁴ 5p ⁴ (¹ D)5d ² D + 13 4f ¹² 5p ⁶ (¹ S)5d ² D + 10 4f ¹⁴ 5p ⁴ (³ P)5d ² D
70	498,792	499,045	−253	7/2	18 4f ¹³ 5p ⁵ (³ G)5d ² F + 15 4f ¹³ 5p ⁵ (³ F)5d ² F + 13 4f ¹³ 5p ⁵ (¹ G)5d ² F
71	500,313	500,013	300	5/2	56 4f ¹³ 5p ⁵ (¹ F)6s ² F + 19 4f ¹³ 5p ⁵ (³ D)6s ² D + 11 4f ¹³ 5p ⁵ (³ D)6s ⁴ D
72	503,071	502,605	466	7/2	47 4f ¹³ 5p ⁵ (³ F)6s ² F + 16 4f ¹³ 5p ⁵ (¹ F)6s ² F + 10 4f ¹³ 5p ⁵ (³ F)6s ⁴ F
73	504,615	504,586	29	9/2	71 4f ¹³ 5p ⁵ (³ G)6s ² G + 24 4f ¹³ 5p ⁵ (³ G)6s ⁴ G
74	504,691	505,845	−1154	3/2	32 4f ¹² 5p ⁶ (¹ S)5d ² D + 14 4f ¹³ 5p ⁵ (³ G)5d ² D + 7 4f ¹³ 5p ⁵ (³ F)5d ² D
75	512,790	512,628	162	7/2	17 4f ¹³ 5p ⁵ (¹ D)5d ² G + 15 4f ¹³ 5p ⁵ (³ F)5d ² G + 14 4f ¹³ 5p ⁵ (³ G)5d ² G
76	514,063	514,203	−140	5/2	49 4f ¹³ 5p ⁵ (¹ D)6s ² D + 26 4f ¹³ 5p ⁵ (³ D)6s ⁴ D + 10 4f ¹³ 5p ⁵ (³ D)6s ² D
77	514,413	514,677	−264	7/2	37 4f ¹³ 5p ⁵ (³ F)6s ⁴ F + 22 4f ¹³ 5p ⁵ (³ F)6s ² F + 15 4f ¹³ 5p ⁵ (¹ F)6s ² F
78	514,628	515,153	−525	5/2	50 4f ¹³ 5p ⁵ (³ F)6s ⁴ F + 16 4f ¹³ 5p ⁵ (³ G)6s ⁴ G + 14 4f ¹³ 5p ⁵ (¹ F)6s ² F
79	516,493	515,725	768	5/2	24 4f ¹³ 5p ⁵ (³ G)5d ² F + 14 4f ¹³ 5p ⁵ (³ F)5d ² F + 11 4f ¹³ 5p ⁵ (¹ D)5d ² F

Table 2. Cont.

Index	E _{exp} ^a	E _{calc} ^b	ΔE ^c	J	Percentage Composition in LS-Coupling ^d
80	521,876	522,299	-423	5/2	35 4f ¹² 5p ⁶ (¹ S)5d ² D + 26 4f ¹³ 5p ⁵ (³ F)6s ² F + 10 4f ¹³ 5p ⁵ (³ D)6s ⁴ D
81	522,610	521,487	1123	5/2	36 4f ¹² 5p ⁶ (¹ S)5d ² D + 25 4f ¹³ 5p ⁵ (³ F)6s ² F + 10 4f ¹³ 5p ⁵ (³ D)6s ⁴ D
82	522,881	522,986	-105	3/2	41 4f ¹² 5p ⁶ (¹ S)5d ² D + 26 4f ¹³ 5p ⁵ (³ G)5d ² D + 7 4f ¹² 5p ⁶ (³ P)5d ² D
83	527,376	527,853	-477	7/2	46 4f ¹³ 5p ⁵ (¹ G)6s ² G + 29 4f ¹³ 5p ⁵ (³ G)6s ⁴ G + 23 4f ¹³ 5p ⁵ (³ G)6s ² G
84	528,462	528,388	74	1/2	28 4f ¹⁴ 5p ⁴ (¹ D)5d ² S + 17 4f ¹⁴ 5p ⁴ (³ P)5d ² P + 8 4f ¹³ 5p ⁵ (³ D)5d ² S
85	528,652	528,582	70	3/2	65 4f ¹³ 5p ⁵ (³ D)6s ² D + 30 4f ¹³ 5p ⁵ (³ D)6s ⁴ D
86	567,191	565,985	1206	3/2	28 4f ¹⁴ 5p ⁴ (³ P)5d ² D + 28 4f ¹⁴ 5p ⁴ (¹ S)5d ² D + 10 4f ¹⁴ 5p ⁴ (³ P)5d ² P
87	568,644	567,872	772	3/2	77 4f ¹⁴ 5p ⁴ (³ P)6s ⁴ P + 13 4f ¹⁴ 5p ⁴ (³ P)6s ² P
88	572,004	572,684	-680	1/2	66 4f ¹⁴ 5p ⁴ (³ P)6s ² P + 32 4f ¹⁴ 5p ⁴ (³ P)6s ⁴ P
89	581,635	582,142	-507	5/2	60 4f ¹⁴ 5p ⁴ (¹ D)6s ² D + 18 4f ¹⁴ 5p ⁴ (³ P)6s ⁴ P + 7 4f ¹² 5p ⁶ (³ F)6s ² F
90	583,560	583,744	-184	3/2	60 4f ¹⁴ 5p ⁴ (¹ D)6s ² D + 23 4f ¹⁴ 5p ⁴ (³ P)6s ² P + 8 4f ¹² 5p ⁶ (³ F)6s ⁴ F
91	594,941	594,876	65	7/2	56 4f ¹³ 5p ⁵ (³ D)6s ⁴ D + 23 4f ¹³ 5p ⁵ (³ F)6s ⁴ F + 11 4f ¹³ 5p ⁵ (¹ F)6s ² F
92	597,436	597,803	-367	5/2	49 4f ¹³ 5p ⁵ (³ D)6s ² D + 14 4f ¹³ 5p ⁵ (³ F)6s ⁴ F + 13 4f ¹³ 5p ⁵ (³ D)6s ⁴ D
93	598,904	598,949	-45	7/2	39 4f ¹³ 5p ⁵ (¹ G)6s ² G + 21 4f ¹³ 5p ⁵ (³ F)6s ² F + 20 4f ¹³ 5p ⁵ (³ G)6s ⁴ G
94	599,423	599,274	149	9/2	44 4f ¹³ 5p ⁵ (¹ G)6s ² G + 25 4f ¹³ 5p ⁵ (³ G)6s ⁴ G + 19 4f ¹³ 5p ⁵ (³ F)6s ⁴ F
95	609,206	609,104	102	5/2	73 4f ¹³ 5p ⁵ (³ G)6s ⁴ G + 18 4f ¹³ 5p ⁵ (¹ F)6s ² F
96	611,283	611,555	-272	7/2	50 4f ¹³ 5p ⁵ (³ G)6s ² G + 27 4f ¹³ 5p ⁵ (³ G)6s ⁴ G + 16 4f ¹³ 5p ⁵ (¹ F)6s ² F
97	621,343	620,931	412	5/2	39 4f ¹³ 5p ⁵ (¹ D)6s ² D + 19 4f ¹³ 5p ⁵ (³ F)6s ² F + 14 4f ¹³ 5p ⁵ (³ D)6s ⁴ D
98	622,123	621,607	516	3/2	40 4f ¹³ 5p ⁵ (¹ D)6s ² D + 28 4f ¹³ 5p ⁵ (³ F)6s ⁴ F + 9 4f ¹³ 5p ⁵ (³ D)6s ⁴ D

^a From [13]. ^b This work : model HFR(F). ^c ΔE = E_{exp} - E_{calc}. ^d Only the first three LS components larger then 5% are given.

The calculated oscillator strengths (log gf) and transition probabilities (gA) obtained in the present work are given in Table 3 for all the W VIII spectral lines with log gf-values greater than -4. These parameters are only given in the length form, the HFR code of Cowan not allowing the calculation of radiative decay rates in the velocity form. Observed wavelengths (λ_{exp}) taken from the work of Ryabtsev *et al.* [13] are also given in the same table together with the 'Ritz' wavelengths (λ_{Ritz}) deduced from the experimental energy levels identified by the same authors. When looking in detail at the table, one can see that forty listed lines were not observed in [13]. If most of those lines are characterized by rather weak transition probabilities, three of them appear to be strong enough, *i.e.*, with gA-values greater than 10¹⁰ s⁻¹, to be experimentally observed, according to our calculations. These are located at λ = 191.700 Å (gA = 1.46 × 10¹⁰ s⁻¹), λ = 229.402 Å (gA = 1.16 × 10¹⁰ s⁻¹) and λ = 244.249 Å (gA = 1.33 × 10¹¹ s⁻¹) and correspond respectively to transitions from the lower odd level at 1233 cm⁻¹ (J = 3/2), to the upper even level at 522,881 cm⁻¹ (J = 3/2), from the lower odd level at 1233 cm⁻¹ (J = 3/2) to the upper even level at 437,149 cm⁻¹ (J = 5/2), and from the lower odd level at 89,123 cm⁻¹ (J = 1/2) to the upper even level at 498,541 cm⁻¹ (J = 3/2).

Table 3. Oscillator strengths and transition probabilities in W VIII ($\log gf > -4$). A table entry $6.81E + 08$ means 6.81×10^8 .

Indexes ^a	Wavelength ^b		Lower Odd Level ^c		Upper Even Level ^c		$\log gf^d$	$gA (s^{-1})^d$	CF ^e
	$\lambda_{exp} (\text{\AA})$	$\lambda_{Ritz} (\text{\AA})$	E (cm^{-1})	J	E (cm^{-1})	J			
1° – 97	160.940	160.942	0	3.5	621,343	2.5	–2.58	6.81E + 08	0.003
2° – 98	161.057	161.059	1233	1.5	622,123	1.5	–2.41	1.01E + 09	0.045
2° – 97	161.260	161.262	1233	1.5	621,343	2.5	–1.26	1.40E + 10	0.333
1° – 96	163.596	163.590	0	3.5	611,283	3.5	–2.30	1.24E + 09	0.007
1° – 95	164.143	164.148	0	3.5	609,206	2.5	–2.78	4.15E + 08	0.014
2° – 95	164.479	164.481	1233	1.5	609,206	2.5	–3.29	1.27E + 08	0.226
3° – 98	165.369	165.368	17,410	2.5	622,123	1.5	–0.26	1.34E + 11	0.854
3° – 97	165.583	165.581	17,410	2.5	621,343	2.5	–0.42	9.25E + 10	0.609
1° – 94	166.827	166.827	0	3.5	599,423	4.5	0.15	3.39E + 11	0.872
1° – 93	166.971	166.972	0	3.5	598,904	3.5	–0.22	1.44E + 11	0.558
1° – 92	167.382	167.382	0	3.5	597,436	2.5	–0.04	2.16E + 11	0.721
1° – 91	168.084	168.084	0	3.5	594,941	3.5	–0.56	6.57E + 10	0.820
3° – 96	168.381	168.386	17,410	2.5	611,283	3.5	0.05	2.62E + 11	0.730
3° – 95	168.980	168.977	17,410	2.5	609,206	2.5	–0.59	6.03E + 10	0.778
2° – 90	171.727	171.725	1233	1.5	583,560	1.5	–0.80	3.56E + 10	0.131
1° – 89		171.929	0	3.5	581,635	2.5	–2.76	3.98E + 08	0.038
3° – 93	171.973	171.971	17,410	2.5	598,904	3.5	–1.70	4.48E + 09	0.013
2° – 89	172.295	172.294	1233	1.5	581,635	2.5	–0.19	1.46E + 11	0.641
3° – 91		173.151	17,410	2.5	594,941	3.5	–2.67	4.74E + 08	0.026
2° – 88	175.199	175.202	1233	1.5	572,004	0.5	–0.58	5.76E + 10	0.632
2° – 87	176.237	176.239	1233	1.5	568,644	1.5	–0.80	3.38E + 10	0.039
3° – 90	176.630	176.632	17,410	2.5	583,560	1.5	–1.27	1.15E + 10	0.701
2° – 86	176.694	176.692	1233	1.5	567,191	1.5	–0.75	3.77E + 10	0.030
3° – 89	177.232	177.234	17,410	2.5	581,635	2.5	–1.36	9.27E + 09	0.591
3° – 87	181.410	181.411	17,410	2.5	568,644	1.5	–1.07	1.74E + 10	0.134
3° – 86	181.888	181.891	17,410	2.5	567,191	1.5	–0.67	4.28E + 10	0.176
4° – 98	187.608	187.617	89,123	0.5	622,123	1.5	–1.50	5.93E + 09	0.256
2° – 85		189.603	1233	1.5	528,652	1.5	–2.44	6.70E + 08	0.083
1° – 83	189.616	189.618	0	3.5	527,376	3.5	–1.17	1.25E + 10	0.452
2° – 84	189.667	189.671	1233	1.5	528,462	0.5	–0.59	4.81E + 10	0.030
1° – 81	191.348	191.347	0	3.5	522,610	2.5	–0.67	3.89E + 10	0.082
1° – 80	191.617	191.616	0	3.5	521,876	2.5	–0.46	6.38E + 10	0.102
2° – 82		191.700	1233	1.5	522,881	1.5	–1.10	1.46E + 10	0.069
2° – 81		191.800	1233	1.5	522,610	2.5	–3.00	1.78E + 08	0.001
2° – 80	192.070	192.070	1233	1.5	521,876	2.5	–2.25	1.02E + 09	0.007
1° – 79	193.614	193.613	0	3.5	516,493	2.5	–0.96	1.95E + 10	0.029
2° – 79	194.077	194.077	1233	1.5	516,493	2.5	–1.37	7.51E + 09	0.095
1° – 78	194.315	194.315	0	3.5	514,628	2.5	–2.94	2.05E + 08	0.011
1° – 77	194.397	194.396	0	3.5	514,413	3.5	–0.59	4.58E + 10	0.047
1° – 76	194.527	194.529	0	3.5	514,063	2.5	0.09	2.19E + 11	0.840
2° – 76	194.998	194.996	1233	1.5	514,063	2.5	–1.46	6.02E + 09	0.403
1° – 75	195.021	195.012	0	3.5	512,790	3.5	–1.64	4.01E + 09	0.003

Table 3. Cont.

Indexes ^a	Wavelength ^b		Lower Odd Level ^c		Upper Even Level ^c		log gf ^d	gA (s ⁻¹) ^d	CF ^e
	λ_{exp} (Å)	λ_{Ritz} (Å)	E (cm ⁻¹)	J	E (cm ⁻¹)	J			
3° – 85	195.598	195.602	17,410	2.5	528,652	1.5	0.10	2.19E + 11	0.790
3° – 83	196.093	196.092	17,410	2.5	527,376	3.5	0.20	2.76E + 11	0.866
3° – 82	197.835	197.835	17,410	2.5	522,881	1.5	0.63	7.37E + 11	0.514
3° – 81	197.941	197.941	17,410	2.5	522,610	2.5	-1.91	2.07E + 09	0.005
1° – 73	198.171	198.171	0	3.5	504,615	4.5	0.46	4.87E + 11	0.850
3° – 80	198.229	198.229	17,410	2.5	521,876	2.5	0.49	5.31E + 11	0.659
1° – 72	198.779	198.779	0	3.5	503,071	3.5	0.67	7.94E + 11	0.742
1° – 71	199.875	199.875	0	3.5	500,313	2.5	-1.02	1.58E + 10	0.098
3° – 79	200.367	200.367	17,410	2.5	516,493	2.5	1.04	1.82E + 12	0.555
2° – 71		200.369	1233	1.5	500,313	2.5	-2.31	8.23E + 08	0.183
1° – 70	200.483	200.484	0	3.5	498,792	3.5	1.14	2.31E + 12	0.467
1° – 68	200.787	200.788	0	3.5	498,037	2.5	1.05	1.90E + 12	0.572
2° – 69	201.079	201.083	1233	1.5	498,541	1.5	0.09	2.05E + 11	0.358
3° – 78	201.119	201.119	17,410	2.5	514,628	2.5	-0.85	2.33E + 10	0.219
3° – 77	201.205	201.206	17,410	2.5	514,413	3.5	0.83	1.13E + 12	0.562
2° – 68	201.288	201.287	1233	1.5	498,037	2.5	0.12	2.17E + 11	0.196
3° – 76		201.348	17,410	2.5	514,063	2.5	-2.01	1.61E + 09	0.026
1° – 67	201.739	201.739	0	3.5	495,690	4.5	1.29	3.22E + 12	0.577
3° – 75	201.864	201.865	17,410	2.5	512,790	3.5	0.98	1.56E + 12	0.446
4° – 90	202.250	202.250	89,123	0.5	583,560	1.5	-0.07	1.39E + 11	0.835
2° – 66	203.623	203.623	1233	1.5	492,337	0.5	0.62	6.72E + 11	0.563
3° – 74	205.221	205.220	17,410	2.5	504,691	1.5	0.53	5.37E + 11	0.474
2° – 65	205.479	205.479	1233	1.5	487,901	1.5	0.32	3.29E + 11	0.754
3° – 72		205.905	17,410	2.5	503,071	3.5	-3.56	4.31E + 07	0.000
1° – 64		206.111	0	3.5	485,175	2.5	-1.20	9.98E + 09	0.028
2° – 64	206.634	206.636	1233	1.5	485,175	2.5	0.29	3.08E + 11	0.518
3° – 71		207.081	17,410	2.5	500,313	2.5	-1.64	3.56E + 09	0.020
4° – 88	207.092	207.090	89,123	0.5	572,004	0.5	-0.31	7.59E + 10	0.784
2° – 63	207.466	207.465	1233	1.5	483,243	1.5	0.27	2.86E + 11	0.266
1° – 62	207.690	207.696	0	3.5	481,473	2.5	-0.69	3.20E + 10	0.364
3° – 70	207.736	207.735	17,410	2.5	498,792	3.5	-0.80	2.49E + 10	0.027
3° – 69	207.850	207.844	17,410	2.5	498,541	1.5	-1.23	9.15E + 09	0.025
1° – 61	207.884	207.885	0	3.5	481,035	2.5	-0.37	6.55E + 10	0.216
3° – 68		208.062	17,410	2.5	498,037	2.5	-3.79	2.56E + 07	0.000
2° – 62	208.227	208.229	1233	1.5	481,473	2.5	-0.21	9.49E + 10	0.160
2° – 61	208.420	208.419	1233	1.5	481,035	2.5	0.83	1.04E + 12	0.638
4° – 87	208.543	208.541	89,123	0.5	568,644	1.5	0.42	4.04E + 11	0.534
4° – 86	209.175	209.175	89,123	0.5	567,191	1.5	0.62	6.31E + 11	0.502
2° – 60	211.027	211.022	1233	1.5	475,117	1.5	0.28	2.87E + 11	0.369
1° – 59	213.436	213.437	0	3.5	468,523	2.5	-2.91	1.81E + 08	0.001
1° – 58	213.661	213.660	0	3.5	468,034	2.5	-3.04	1.33E + 08	0.000
3° – 64	213.785	213.783	17,410	2.5	485,175	2.5	-1.03	1.36E + 10	0.024
2° – 59	214.001	214.000	1233	1.5	468,523	2.5	-2.50	4.61E + 09	0.013

Table 3. Cont.

Indexes ^a	Wavelength ^b		Lower Odd Level ^c		Upper Even Level ^c		log gf ^d	gA (s ⁻¹) ^d	CF ^e
	λ_{exp} (Å)	λ_{Ritz} (Å)	E (cm ⁻¹)	J	E (cm ⁻¹)	J			
2° – 58	214.229	214.224	1233	1.5	468,034	2.5	–0.09	1.17E + 11	0.428
1° – 57	214.488	214.491	0	3.5	466,219	2.5	–2.31	7.13E + 08	0.002
2° – 57	215.055	215.060	1233	1.5	466,219	2.5	–0.21	8.80E + 10	0.439
3° – 62	215.496	215.488	17,410	2.5	481,473	2.5	–2.22	8.60E + 08	0.023
3° – 61	215.692	215.692	17,410	2.5	481,035	2.5	–1.75	2.57E + 09	0.012
2° – 56	216.596	216.594	1233	1.5	462,927	1.5	–0.71	2.79E + 10	0.187
1° – 55	217.601	217.595	0	3.5	459,570	2.5	–2.39	5.78E + 08	0.001
2° – 55	218.174	218.180	1233	1.5	459,570	2.5	–2.25	7.95E + 08	0.004
1° – 53	218.429	218.429	0	3.5	457,815	4.5	–0.93	1.66E + 10	0.028
3° – 60	218.477	218.480	17,410	2.5	475,117	1.5	–2.25	7.91E + 08	0.003
1° – 52	218.507	218.507	0	3.5	457,652	2.5	–1.24	8.04E + 09	0.011
2° – 54	218.747	218.748	1233	1.5	458,380	1.5	–0.88	1.85E + 10	0.063
2° – 52	219.097	219.097	1233	1.5	457,652	2.5	–2.89	1.76E + 08	0.002
1° – 51	220.239	220.232	0	3.5	454,067	3.5	–3.13	1.02E + 08	0.000
2° – 50	221.443	221.441	1233	1.5	452,821	1.5	–0.49	4.43E + 10	0.075
3° – 59		221.674	17,410	2.5	468,523	2.5	–2.13	1.01E + 09	0.005
3° – 58	221.908	221.915	17,410	2.5	468,034	2.5	–0.80	2.14E + 10	0.030
3° – 57	222.818	222.812	17,410	2.5	466,219	2.5	–1.15	9.46E + 09	0.018
1° – 49	223.260	223.260	0	3.5	447,909	2.5	–1.33	6.17E + 09	0.028
2° – 49		223.876	1233	1.5	447,909	2.5	–1.59	3.39E + 09	0.048
3° – 56		224.458	17,410	2.5	462,927	1.5	–2.63	3.12E + 08	0.002
1° – 48	224.573	224.575	0	3.5	445,286	2.5	–2.38	5.55E + 08	0.002
2° – 48	225.203	225.198	1233	1.5	445,286	2.5	–1.61	3.22E + 09	0.026
3° – 55		226.162	17,410	2.5	459,570	2.5	–3.04	1.20E + 08	0.000
3° – 54		226.773	17,410	2.5	458,380	1.5	–2.01	1.27E + 09	0.003
3° – 52		227.148	17,410	2.5	457,652	2.5	–2.64	2.96E + 08	0.000
1° – 47	227.497	227.500	0	3.5	439,561	3.5	–0.89	1.64E + 10	0.091
4° – 85	227.519	227.516	89,123	0.5	528,652	1.5	–2.26	7.04E + 08	0.057
4° – 84	227.617	227.615	89,123	0.5	528,462	0.5	0.57	4.79E + 11	0.552
3° – 51	229.011	229.013	17,410	2.5	454,067	3.5	–0.90	1.58E + 10	0.023
2° – 46		229.402	1233	1.5	437,149	2.5	–1.04	1.16E + 10	0.072
1° – 45	229.541	229.538	0	3.5	435,658	3.5	–2.02	1.21E + 09	0.007
1° – 44	229.590	229.589	0	3.5	435,561	2.5	–1.07	1.07E + 10	0.047
3° – 50	229.666	229.668	17,410	2.5	452,821	1.5	–1.53	3.67E + 09	0.007
2° – 44	230.246	230.241	1233	1.5	435,561	2.5	–1.01	1.23E + 10	0.070
4° – 82	230.544	230.543	89,123	0.5	522,881	1.5	–0.60	3.17E + 10	0.107
1° – 43	230.964	230.967	0	3.5	432,963	2.5	–1.44	4.60E + 09	0.019
2° – 43	231.629	231.626	1233	1.5	432,963	2.5	–0.74	2.28E + 10	0.064
1° – 42	232.176	232.176	0	3.5	430,708	3.5	–1.18	8.25E + 09	0.049
3° – 49	232.288	232.289	17,410	2.5	447,909	2.5	–0.84	1.80E + 10	0.084
1° – 41	233.225	233.221	0	3.5	428,777	3.5	–0.81	1.89E + 10	0.073
1° – 40	233.525	233.527	0	3.5	428,216	3.5	–0.49	3.93E + 10	0.161
3° – 48	233.709	233.713	17,410	2.5	445,286	2.5	–0.64	2.77E + 10	0.122

Table 3. Cont.

Indexes ^a	Wavelength ^b		Lower Odd Level ^c		Upper Even Level ^c		log gf ^d	gA (s ⁻¹) ^d	CF ^e
	λ_{exp} (Å)	λ_{Ritz} (Å)	E (cm ⁻¹)	J	E (cm ⁻¹)	J			
2° – 39		234.211	1233	1.5	428,199	1.5	-2.99	1.25E + 08	0.001
1° – 37	235.418	235.415	0	3.5	424,781	2.5	-1.23	7.03E + 09	0.055
2° – 38	235.509	235.510	1233	1.5	425,843	1.5	-2.07	1.02E + 09	0.126
2° – 37		236.101	1233	1.5	424,781	2.5	-2.88	1.59E + 08	0.007
3° – 47	236.884	236.882	17,410	2.5	439,561	3.5	-1.01	1.16E + 10	0.040
1° – 36		238.202	0	3.5	419,811	2.5	-3.32	5.62E + 07	0.000
3° – 46	238.243	238.243	17,410	2.5	437,149	2.5	-0.95	1.32E + 10	0.063
1° – 35	238.330	238.331	0	3.5	419,585	3.5	-2.28	6.19E + 08	0.010
2° – 36		238.904	1233	1.5	419,811	2.5	-3.13	8.56E + 07	0.011
1° – 34	239.004	239.004	0	3.5	418,403	4.5	-1.03	1.08E + 10	0.057
3° – 45	239.089	239.093	17,410	2.5	435,658	3.5	-0.59	3.01E + 10	0.156
3° – 44	239.142	239.148	17,410	2.5	435,561	2.5	-1.21	7.14E + 09	0.035
1° – 32	240.107	240.107	0	3.5	416,481	4.5	-0.47	3.94E + 10	0.240
2° – 33		240.292	1233	1.5	417,394	1.5	-3.24	6.63E + 07	0.004
1° – 31	240.468	240.470	0	3.5	415,852	2.5	-2.40	4.62E + 08	0.007
4° – 74	240.634	240.635	89,123	0.5	504,691	1.5	-0.35	5.14E + 10	0.150
1° – 30	241.037	241.029	0	3.5	414,888	3.5	-1.21	7.09E + 09	0.024
2° – 31	241.183	241.185	1233	1.5	415,852	2.5	-2.36	4.97E + 08	0.065
1° – 29	241.867	241.867	0	3.5	413,450	4.5	-0.27	6.16E + 10	0.193
3° – 42		241.956	17,410	2.5	430,708	3.5	-2.16	7.91E + 08	0.007
1° – 28	242.819	242.817	0	3.5	411,832	3.5	-1.36	4.97E + 09	0.071
1° – 27	242.829	242.825	0	3.5	411,819	2.5	-2.02	1.07E + 09	0.006
3° – 41	243.088	243.092	17,410	2.5	428,777	3.5	-2.11	8.72E + 08	0.007
3° – 40	243.426	243.424	17,410	2.5	428,216	3.5	-1.54	3.23E + 09	0.012
3° – 39	243.434	243.434	17,410	2.5	428,199	1.5	-1.51	3.45E + 09	0.121
1° – 26	243.518	243.514	0	3.5	410,654	3.5	-2.01	1.11E + 09	0.004
2° – 27	243.551	243.554	1233	1.5	411,819	2.5	-1.96	1.23E + 09	0.073
1° – 24		244.095	0	3.5	409,676	2.5	-3.96	1.24E + 07	0.000
4° – 69		244.249	89,123	0.5	498,541	1.5	0.08	1.33E + 11	0.183
1° – 23	244.281	244.283	0	3.5	409,362	2.5	-1.30	5.53E + 09	0.088
2° – 25		244.484	1233	1.5	410,258	1.5	-2.54	3.21E + 08	0.005
2° – 24	244.833	244.832	1233	1.5	409,676	2.5	-1.36	4.86E + 09	0.473
3° – 38	244.839	244.838	17,410	2.5	425,843	1.5	-1.19	7.21E + 09	0.142
1° – 21	245.046	245.046	0	3.5	408,086	3.5	-0.81	1.71E + 10	0.041
2° – 22	245.334	245.339	1233	1.5	408,833	1.5	-2.00	1.11E + 09	0.079
3° – 37	245.474	245.476	17,410	2.5	424,781	2.5	-1.26	6.09E + 09	0.060
1° – 20	246.362	246.362	0	3.5	405,907	4.5	-0.73	2.06E + 10	0.359
4° – 66	248.007	248.007	89,123	0.5	492,337	0.5	-1.01	1.07E + 10	0.016
3° – 36	248.508	248.508	17,410	2.5	419,811	2.5	-0.71	2.11E + 10	0.080
3° – 35	248.649	248.648	17,410	2.5	419,585	3.5	-0.61	2.65E + 10	0.130
1° – 19	248.765	248.766	0	3.5	401,984	2.5	-0.37	4.61E + 10	0.069
2° – 19	249.533	249.532	1233	1.5	401,984	2.5	0.03	1.16E + 11	0.551

Table 3. Cont.

Indexes ^a	Wavelength ^b		Lower Odd Level ^c		Upper Even Level ^c		log gf ^d	gA (s ⁻¹) ^d	CF ^e
	λ_{exp} (Å)	λ_{Ritz} (Å)	E (cm ⁻¹)	J	E (cm ⁻¹)	J			
1° – 18	249.873	249.873	0	3.5	400,203	4.5	-0.65	2.39E + 10	0.152
3° – 33	250.010	250.010	17,410	2.5	417,394	1.5	-1.13	7.92E + 09	0.141
4° – 65		250.766	89,123	0.5	487,901	1.5	-2.70	2.11E + 08	0.002
1° – 17	250.811	250.811	0	3.5	398,707	4.5	-1.06	9.19E + 09	0.031
3° – 31	250.978	250.978	17,410	2.5	415,852	2.5	-1.01	1.03E + 10	0.057
1° – 16	251.500	251.501	0	3.5	397,612	2.5	-1.25	5.87E + 09	0.041
3° – 30	251.584	251.586	17,410	2.5	414,888	3.5	-0.43	3.94E + 10	0.150
1° – 14	252.203	252.204	0	3.5	396,505	3.5	-0.34	4.82E + 10	0.116
2° – 16	252.285	252.284	1233	1.5	397,612	2.5	-1.05	9.30E + 09	0.413
2° – 15	252.740	252.742	1233	1.5	396,894	1.5	0.08	1.27E + 11	0.330
1° – 12	252.862	252.863	0	3.5	395,471	3.5	-1.54	3.04E + 09	0.001
1° – 11	252.989	252.988	0	3.5	395,276	2.5	-1.50	3.31E + 09	0.027
3° – 28	253.534	253.536	17,410	2.5	411,832	3.5	-0.92	1.23E + 10	0.110
3° – 27	253.541	253.544	17,410	2.5	411,819	2.5	-0.04	9.56E + 10	0.131
2° – 13	253.653	253.652	1233	1.5	395,474	0.5	-0.44	3.73E + 10	0.140
4° – 63	253.726	253.730	89,123	0.5	483,243	1.5	-1.49	3.35E + 09	0.013
2° – 11	253.779	253.779	1233	1.5	395,276	2.5	-2.40	4.08E + 08	0.024
1° – 10	253.812	253.812	0	3.5	393,992	3.5	0.09	1.26E + 11	0.101
3° – 26	254.294	254.295	17,410	2.5	410,654	3.5	0.01	1.04E + 11	0.143
3° – 25	254.551	254.551	17,410	2.5	410,258	1.5	-0.02	9.92E + 10	0.190
3° – 24	254.928	254.929	17,410	2.5	409,676	2.5	-0.92	1.23E + 10	0.039
3° – 23	255.140	255.133	17,410	2.5	409,362	2.5	-2.03	9.57E + 08	0.013
1° – 9	255.401	255.401	0	3.5	391,541	4.5	0.32	2.16E + 11	0.165
3° – 22	255.479	255.478	17,410	2.5	408,833	1.5	-0.99	1.05E + 10	0.076
3° – 21	255.967	255.967	17,410	2.5	408,086	3.5	-0.40	4.09E + 10	0.115
1° – 8	258.592	258.596	0	3.5	386,704	2.5	0.05	1.10E + 11	0.210
4° – 60	259.069	259.071	89,123	0.5	475,117	1.5	-0.86	1.39E + 10	0.048
2° – 8	259.419	259.423	1233	1.5	386,704	2.5	-0.24	5.66E + 10	0.293
3° – 19	260.027	260.028	17,410	2.5	401,984	2.5	-1.63	2.29E + 09	0.015
1° – 7	260.146	260.146	0	3.5	384,400	4.5	-1.54	2.85E + 09	0.009
1° – 6	261.002	261.006	0	3.5	383,133	2.5	-1.45	3.49E + 09	0.029
1° – 5	261.767	261.767	0	3.5	382,019	3.5	-0.93	1.14E + 10	0.027
2° – 6	261.849	261.849	1233	1.5	383,133	2.5	-2.18	6.41E + 08	0.004
1° – 4	262.537	262.537	0	3.5	380,899	4.5	-1.28	5.12E + 09	0.005
3° – 16		263.018	17,410	2.5	397,612	2.5	-2.22	5.79E + 08	0.004
3° – 15	263.521	263.516	17,410	2.5	396,894	1.5	-2.89	1.24E + 08	0.001
3° – 14	263.787	263.786	17,410	2.5	396,505	3.5	-1.41	3.74E + 09	0.014
3° – 12	264.508	264.508	17,410	2.5	395,471	3.5	-1.04	8.63E + 09	0.014
1° – 3	264.644	264.643	0	3.5	377,867	2.5	-1.07	8.00E + 09	0.032
3° – 11	264.644	264.644	17,410	2.5	395,276	2.5	-1.22	5.67E + 09	0.016
1° – 1	265.168	265.168	0	3.5	377,119	4.5	-1.02	8.91E + 09	0.013
2° – 3	265.510	265.510	1233	1.5	377,867	2.5	-1.26	5.18E + 09	0.031

Table 3. Cont.

Indexes ^a	Wavelength ^b		Lower Odd Level ^c		Upper Even Level ^c		log gf ^d	gA (s ⁻¹) ^d	CF ^e
	λ _{exp} (Å)	λ _{Ritz} (Å)	E (cm ⁻¹)	J	E (cm ⁻¹)	J			
2° – 2	265.919	265.919	1233	1.5	377,288	1.5	-1.47	3.16E + 09	0.055
4° – 56	267.518	267.520	89,123	0.5	462,927	1.5	-2.82	1.42E + 08	0.002
3° – 8	270.794	270.787	17,410	2.5	386,704	2.5	-2.53	2.66E + 08	0.001
4° – 54	270.816	270.814	89,123	0.5	458,380	1.5	-1.34	4.11E + 09	0.019
3° – 5		274.266	17,410	2.5	382,019	3.5	-2.84	1.28E + 08	0.000
4° – 50		274.953	89,123	0.5	452,821	1.5	-1.07	7.47E + 09	0.022
3° – 3		277.426	17,410	2.5	377,867	2.5	-1.92	1.03E + 09	0.004
4° – 39		294.919	89,123	0.5	428,199	1.5	-3.08	6.41E + 07	0.003
4° – 38		296.983	89,123	0.5	425,843	1.5	-2.64	1.75E + 08	0.029
4° – 33		304.626	89,123	0.5	417,394	1.5	-2.92	8.72E + 07	0.008
4° – 25		311.396	89,123	0.5	410,258	1.5	-2.23	4.06E + 08	0.008
4° – 22		312.783	89,123	0.5	408,833	1.5	-3.21	4.21E + 07	0.004
4° – 15		324.917	89,123	0.5	396,894	1.5	-2.78	1.04E + 08	0.000
4° – 13		326.423	89,123	0.5	395,474	0.5	-2.44	2.28E + 08	0.002
4° – 2		347.023	89,123	0.5	377,288	1.5	-3.14	3.94E + 07	0.002

^a Indexes of levels as given in Table 2. ^b λ_{exp} are taken from [13] while λ_{Ritz} are deduced from experimental energy levels given by the same authors. ^c From [13]. ^d This work : model HFR(F). ^e Cancellation factor as defined in Equation (6).

On the other hand, one spectral line observed at 198.625 Å by Ryabtsev *et al.* [13] is not present in Table 3. This can be explained by the fact that, for this transition, our calculated oscillator strength is unexpectedly found to be much smaller than the cut-off chosen for drawing up the table (log gf > -4). The reason could be found in the strong cancellation effects affecting the calculation of the line strength corresponding to this transition for which our HFR values are log gf = -4.44 and gA = 6.16E + 06 s⁻¹. As a reminder, in order to calculate gA or gf for a transition between the atomic states γJ and γ'J', we have to compute the value of the line strength

$$S = \left| \langle \gamma J \| P^{(1)} \| \gamma' J' \rangle \right|^2 \tag{1}$$

or that of its square root

$$S^{1/2} = \langle \gamma J \| P^{(1)} \| \gamma' J' \rangle \tag{2}$$

where P⁽¹⁾ is the electric dipole operator. Because of intermediate coupling and configuration interaction mixing, the wavefunctions are expanded in terms of basis functions:

$$|\gamma J\rangle = \sum_{\beta} y_{\beta J}^{\gamma} |\beta J\rangle \tag{3}$$

$$|\gamma' J'\rangle = \sum_{\beta'} y_{\beta' J'}^{\gamma'} |\beta' J'\rangle \tag{4}$$

We may then write Equation (2) in the form

$$S^{1/2} = \sum_{\beta} \sum_{\beta'} y_{\beta J}^{\gamma} \langle \beta J \| P^{(1)} \| \beta' J' \rangle y_{\beta' J'}^{\gamma'} \tag{5}$$

This sum thus represents a mixing of amplitudes rather than line strengths themselves with the consequence that the effect of mixing is not necessarily a tendency to average out the various line strengths. There are frequently destructive interference effects that cause a weak line to become still weaker. In this context, the cancellation factor is given by

$$CF = \left[\frac{\left| \sum_{\beta} \sum_{\beta'} y_{\beta J}^{\gamma} \langle \beta J \| P^{(1)} \| \beta' J' \rangle y_{\beta' J'}^{\gamma'} \right|^2}{\sum_{\beta} \sum_{\beta'} \left| y_{\beta J}^{\gamma} \langle \beta J \| P^{(1)} \| \beta' J' \rangle y_{\beta' J'}^{\gamma'} \right|^2} \right]^2 \tag{6}$$

According to Cowan [18], very small values of this factor (typically when CF is smaller than about 0.02) indicate that the corresponding transition rates may be expected to show large percentage errors. In Table 3, CF -factors are given for each line in order to give an idea of the reliability of the corresponding transition rates. It is clear that many lines with computed gA -values smaller than 10^9 s^{-1} are affected by very small values of CF indicating that the corresponding transition rates must be taken with caution. On the contrary, most of the strongest transitions listed in Table 3, in particular those with $gA > 10^{10} \text{ s}^{-1}$, do not appear to be affected by cancellation effects.

Finally, in Figure 3, we compare our transition probabilities with those reported by Ryabtsev *et al.* [13]. As expected, a rather large scatter is observed between both sets of results. However, as already discussed in Section 3, in view of the much more extended configuration interaction model adopted here in comparison with the rather limited physical model used by Ryabtsev *et al.*, in particular in the odd parity, the decay rates obtained in the present work should indisputably be more accurate.

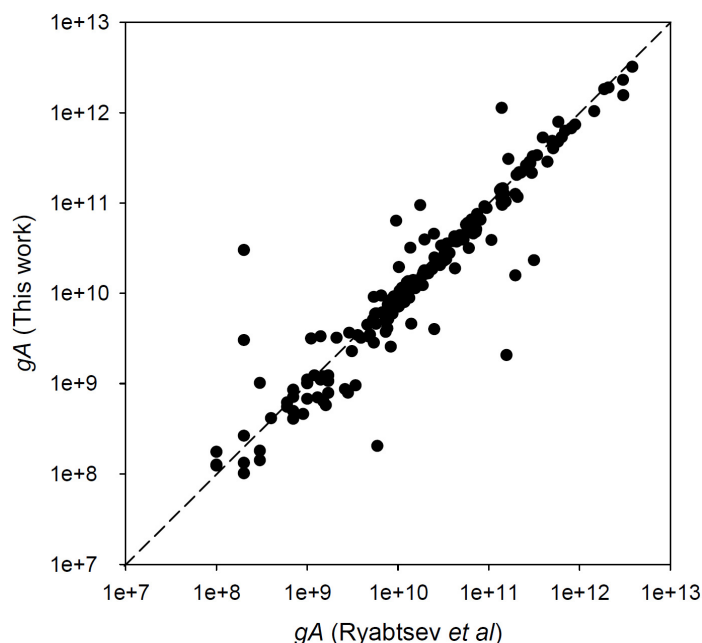


Figure 3. Comparison between the transition probabilities (gA in s^{-1}) computed in the present work and those obtained by Ryabtsev *et al.* [13] for experimentally identified spectral lines in W VIII.

For plasma diagnostic purposes, it is sometimes useful to know the decay rates corresponding to forbidden lines. In the present work, such parameters were thus also computed for magnetic dipole

(M1) and electric quadrupole (E2) transitions involving the four experimentally known levels within the odd parity of W VIII. It was found that only three transitions could be considered as having rather strong transition probabilities. These lines are the following: (1) $\lambda_{\text{vac}} = 1137.79 \text{ \AA}$, $E_{\text{low}} = 1233 \text{ cm}^{-1}$ ($J = 3/2$) – $E_{\text{up}} = 89,123 \text{ cm}^{-1}$ ($J=1/2$), $gA(\text{M1} + \text{E2}) = 2.55 \times 10^4 \text{ s}^{-1}$, (2) $\lambda_{\text{vac}} = 1394.45 \text{ \AA}$, $E_{\text{low}} = 17,410 \text{ cm}^{-1}$ ($J = 5/2$) – $E_{\text{up}} = 89,123 \text{ cm}^{-1}$ ($J=1/2$), $gA(\text{E2}) = 6.54 \times 10^1 \text{ s}^{-1}$, and (3) $\lambda_{\text{air}} = 5742.26 \text{ \AA}$, $E_{\text{low}} = 0 \text{ cm}^{-1}$ ($J = 7/2$) – $E_{\text{up}} = 17,410 \text{ cm}^{-1}$ ($J=5/2$), $gA(\text{M1}) = 4.90 \times 10^2 \text{ s}^{-1}$.

5. Conclusions

A detailed analysis of configuration interaction effects in seven times ionized tungsten allowed us to give a new reliable set of transition probabilities and oscillator strengths for lines of this ion in the spectral range from 160 to 347 Å. The final results were obtained within the framework of an extended physical model based on the pseudo-relativistic Hartree-Fock approach combined with a semi-empirical optimization of the radial energy parameters. Just like our previous studies related to the lowest ionization stages of W, it is expected that the radiative data reported in the present work for the W VIII spectrum will be useful for plasma diagnostics in future fusion reactors where tungsten will be used as a plasma facing material.

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Author Contributions

Both authors were equally involved in the calculations reported in the present paper as well as in the writing of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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