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Atomic Data for He-like Tungsten

Research Article

Sunny Aggarwal[1], A.K. Singh[2] and Man Mohan[3]

[1,3] *Department of Physics and Astrophysics, University of Delhi, Delhi 110007, India*
[2] *Department of Physics, D.D.U. College, University of Delhi, Delhi 110015, India*
Corresponding authors: [1]sunny.kmc87@gmail.com, [3]drmanmohan.05@gmail.com

Abstract. Atomic data on high-Z materials are important for impurity diagnostics due to its possible use in the next generation fusion devices including astrophysics. For this purpose, in the present paper, energies, lifetimes and wave-function compositions have been computed for all level of $1s^2$, 1s2l, 1s3l, 1s4l, 1s5l and 1s6l in highly charged He-like tungsten ion (W LXXIII). Also, we have presented the transition wavelengths, oscillator strengths, transition probabilities and line strengths for the electric dipole (E1) transitions from the levels $1s^2$, 1s2s and 1s2p. Our reported results have been obtained using the fully relativistic GRASP code including the correlations within the $n = 6$ complex. The validity of the method is assessed through the comparison with the other results previously published. The excellent agreement observed between our new GRASP results and those obtained using different approaches confirm the accuracy of our results.

Keywords. Atomic data; Atomic processes

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1. Introduction

Reliable atomic data for the tungsten ions, such as emission line wavelengths and transition probabilities, are of crucial importance both for the diagnostic purposes and the modelling of plasma in fusion reactors. Indeed, because of its high melting point, low tritium retention and erosion rate under plasma loading (see e.g. Pospieszczyk 2006), tungsten will be used as a plasma facing material in the diverter region (Matthews *et al.* (2009), Skinner (2008, 2009), Hawryluk *et al*. (2009)) in the development of future tokamaks, such as ITER. Additionally, tungsten is of interest in astrophysics (Hensberge *et al.* (1986)). Therefore, wavelengths and transition rates in various ionization stages of tungsten must be determined with high confidence from the

experimental measurements or theoretical calculations.

A small numbers of contributions have been devoted, in the past, to the determination of atomic properties for the highly charged He-like tungsten (W LXXIII). Plantae *et al.* (1994) calculated the ionization energies of the ground level and the $n = 2$ levels using relativistic all-order many-body perturbation theory, whose uncertainty has been estimated by Kramida and Shirai (2009). Lin *et al.* (1977) calculated the transition probabilities and oscillator strength for some transition for ground state ($1s^2\ ^1S_0$) and 1s2s ($^1S_0, ^3S_1$) to the $n = 2$ excited levels. Drake (1979) calculated the oscillator strength and transition probabilities for the $1s^2\ ^1S_0$-1s2p($^1P_1, ^3P_1$) transition which was comparable to the Lin *et al*. (1977) results. Additionally, Lifetime for the 1s2p ($^3P_{0,1}$) levels were calculated by (Indelicato *et al.*, 1989). Recently, Kramida and Shirai (2009) provide some transition lines which were derived from the energy level of plantae *et al.* (1994).

The aim of our present work is to extend these works by investigating the electric dipole (E1) transitions involving all of the levels belonging to the $1s^2$, 1s2s and 1s2p configurations of highly charged He-like tungsten. Energy levels for lowest 8 levels for this ion have been compiled by NIST (National Institute of Standards and Technology) and are available at their website `http://www.nist.gov/pml/data/asd.cfm`. To best of our knowledge, there do not appear to be any experimental calculation or a large-scale theoretical calculation for He-like tungsten. Therefore, in present work, we have reported the energy levels and lifetimes for all transitions among the lowest 67 fine-structure levels of W LXXIII, which belong to $1s^2$, 1s2l, 1s3l, 1s4l, 1s5l and 1s6l configurations. Transition probabilities for some electric dipole (E1) transitions are also reported. Accuracy of our results is estimated by comparing energy level with those compiled by NIST and transition probabilities, oscillator strength and lifetime with the other available results in the literature.

The investigations of highly charged He-like tungsten ion considered in present work require the simultaneous consideration of relativistic effects and electronic correlation. For this purpose, our calculations were performed using the fully relativistic GRASP, the general-purpose relativistic atomic structure package, code originally developed by Grant *et al.* (1989) and revised by Norrington (2009). In present calculations, all the orbitals were simultaneously optimized on the average energy of all configurations by using the option of EAL (extended energy level). This procedure produce a compromise set of orbitals describing closely lying states with moderate accuracy. Firstly, zero-order coulomb eigenvectors and energy levels have been calculated. Then, Breit interaction is added to the Hamiltonian and a further diagonalization in the configuration basis produces Breit-corrected eigenvectors and energy levels. Finally, quantum electrodynamics (QED) effects have been estimated and corrected.

2. Excitation Energies

The excitation energies of the 67 fine-structral levels of He-like tungsten belonging to the configurations $1s^2$, 1s2l, 1s3l, 1s4l, 1s5l and 1s6l are presented in Table 1. Here, we have presented the calculated level energies from GRASP 1 (obtained without inclusion of Breit and QED effects) and GRASP2 (obtained with inclusion of Breit and QED effects). Also, we have

presented results for many new spectral lines, which are not listed in the NIST tables. Higher levels corresponding to 1s3l, 1s4l, 1s5l and 1s6l are obtained for the first time. In the column of Table 1 titled "Composition" we first give the percentage of the basis state corresponding to the level's name; next, the second largest percentage together with the related basis state.

Table 1. Energies (in Ryd.), lifetimes (in *s*), and wave-function composition of levels in W LXXIII

Configuration	Level	J	GRASP1	GRASP2	Lifetimes	Composition
$1s^2$	^{1}S	0	0	0		**100**
1s2s	^{3}S	1	4356.53807	4337.06517	9.2336E-14	**100**
1s2p	^{3}P^o	0	4364.96632	4348.79607	1.7984E-10	**100**
1s2s	^{1}S	0	4365.35426	4348.38051	1.8634E-08	**100**
1s2p	^{3}P^o	1	4366.61460	4345.86919	8.3091E-17	**68** + **31**(1s2p ^{1}P$_1$)
1s2p	^{3}P^o	2	4482.20146	4461.53483	2.3956E-14	**100**
1s2p	^{1}P^o	1	4485.26092	4465.46405	4.4434E-17	**68** + **31**(1s2p ^{3}P$_1$)
1s3s	^{3}S	1	5197.37502	5176.85116	3.0371E-15	**100**
1s3s	^{1}S	0	5199.66236	5179.84647	3.1402E-15	**100**
1s3p	^{3}P^o	0	5199.66737	5179.96520	1.2761E-15	**100**
1s3p	^{3}P^o	1	5200.09673	5179.19978	2.6959E-16	**68** + **31**(1s3p ^{1}P$_1$)
1s3p	^{3}P^o	2	5234.53755	5213.64721	1.7587E-15	**100**
1s3p	^{1}P^o	1	5235.41756	5214.81358	1.4564E-16	**68** + **31**(1s3p ^{3}P$_1$)
1s3d	^{3}D	1	5235.47408	5214.73325	4.9104E-16	**100**
1s3d	^{3}D	2	5235.49376	5214.42185	4.7561E-16	**60** + **39**(1s3d ^{1}D$_2$)
1s3d	^{3}D	3	5245.29806	5224.26263	5.4626E-16	**100**
1s3d	^{1}D	2	5245.33085	5224.48380	5.2499E-16	**60** + **39**(1s3d ^{3}D$_2$)
1s4s	^{3}S	1	5485.51406	5464.73695	4.6051E-15	**100**
1s4s	^{1}S	0	5486.42751	5465.94205	4.6576E-15	**100**
1s4p	^{3}P^o	0	5486.44252	5465.98553	2.2159E-15	**100**
1s4p	^{3}P^o	1	5486.61416	5465.67989	6.3533E-16	**68** + **31**(1s4p ^{1}P$_1$)
1s4p	^{3}P^o	2	5501.04094	5480.10742	2.9023E-15	**100**
1s4p	^{1}P^o	1	5501.40618	5480.59661	3.4417E-16	**68** + **31**(1s4p ^{3}P$_1$)
1s4d	^{3}D	1	5501.43064	5480.56503	1.1270E-15	**100**
1s4d	^{3}D	2	5501.44135	5480.43465	1.0806E-15	**60** + **39**(1s4d ^{1}D$_2$)
1s4d	^{3}D	3	5505.60066	5484.60850	1.2658E-15	**100**
1s4d	^{1}D	2	5505.61887	5484.70656	1.1945E-15	**60** + **39**(1s4d ^{3}D$_2$)
1s4f	^{3}F^o	2	5505.62137	5484.69483	2.4146E-15	**100**
1s4f	^{3}F^o	3	5505.62152	5484.63547	2.4123E-15	**57** + **42**(1s4f ^{1}F$_3$)
1s4f	^{3}F^o	4	5507.63612	5486.65608	2.4991E-15	**100**
1s4f	^{1}F^o	3	5507.63635	5486.69911	2.5009E-15	**57** + **42**(1s4f ^{3}F$_3$)
1s5s	^{3}S	1	5616.54495	5595.67791	7.4458E-15	**100**

(*Contd.*)

Configuration	Level	J	GRASP1	GRASP2	Lifetimes	Composition
1s5s	^{1}S	0	5616.99914	5596.27961	7.3794E-15	**100**
1s5p	^{3}P^o	0	5617.00893	5596.29858	3.8185E-15	**100**
1s5p	^{3}P^o	1	5617.09428	5596.14671	1.2263E-15	**68** + **31**(1s5p ^{1}P$_1$)
1s5p	^{3}P^o	2	5624.42634	5603.47877	4.8827E-15	**100**
1s5p	^{1}P^o	1	5624.61158	5603.72805	2.1531E-15	**68** + **31**(1s5p ^{3}P$_1$)
1s5d	^{3}D	1	5624.62407	5603.71223	2.0628E-15	**100**
1s5d	^{3}D	2	5624.63007	5603.64586	2.4317E-15	**60** + **39**(1s5d ^{1}D$_2$)
1s5d	^{3}D	3	5626.76073	5605.78373	2.2800E-15	**100**
1s5d	^{1}D	2	5626.77103	5605.83496	4.6158E-15	**60** + **39**(1s5d ^{3}D$_2$)
1s5f	^{3}F^o	2	5626.77245	5605.82909	4.6132E-15	**100**
1s5f	^{3}F^o	3	5626.77257	5605.79853	4.7889E-15	**57** + **42**(1s5f ^{1}F$_3$)
1s5f	^{3}F^o	4	5627.80752	5606.83655	4.7925E-15	**100**
1s5f	^{1}F^o	3	5627.80771	5606.85880	8.0346E-15	**57** + **42**(1s5f ^{3}F$_3$)
1s5g	^{3}G	3	5627.80774	5606.85605	8.0317E-15	**100**
1s^2	^{1}S	0	0	0		**100**
1s5g	^{3}G	4	5627.80774	5606.83890	8.1579E-15	**55** + **44**(1s5g ^{1}G$_4$)
1s5g	^{3}G	5	5628.42057	5607.45317	8.1604E-15	**100**
1s5g	^{1}G	4	5628.42057	5607.46665	1.1628E-14	**55** + **44**(1s5g ^{3}G$_4$)
1s6s	^{3}S	1	5686.79189	5665.88513	1.1435E-14	**100**
1s6s	^{1}S	0	5687.05038	5666.22878	6.1267E-15	**100**
1s6p	^{3}P^o	0	5687.05607	5666.23750	2.1039E-15	**100**
1s6p	^{3}P^o	1	5687.10461	5666.15115	7.7605E-15	**68** + **31**(1s6p ^{1}P$_1$)
1s6p	^{3}P^o	2	5691.32136	5670.36785	1.1372E-15	**100**
1s6p	^{1}P^o	1	5691.42800	5670.51172	3.6748E-15	**68** + **31**(1s6p ^{3}P$_1$)
1s6d	^{3}D	1	5691.43505	5670.50247	3.5166E-15	**100**
1s6d	^{3}D	2	5691.43867	5670.46423	4.1452E-15	**60** + **39**(1s6d ^{1}D$_2$)
1s6d	^{3}D	3	5692.67066	5671.70030	3.8924E-15	**100**
1s6d	^{1}D	2	5692.67691	5671.73024	7.8380E-15	**60** + **39**(1s6d ^{3}D$_2$)
1s6f	^{3}F^o	2	5692.67778	5671.72688	7.8438E-15	**100**
1s6f	^{3}F^o	3	5692.67786	5671.70916	8.1525E-15	**57** + **42**(1s6f ^{1}F$_3$)
1s6f	^{3}F^o	4	5693.27742	5672.31050	8.1492E-15	**100**
1s6f	^{1}F^o	3	5693.27755	5672.32344	1.3703E-14	**57** + **42**(1s6f ^{3}F$_3$)
1s6g	^{3}G	3	5693.27758	5672.32184	1.3702E-14	**100**
1s6g	^{3}G	4	5693.27758	5672.31188	1.3929E-14	**55** + **44**(1s6g ^{1}G$_4$)
1s6g	^{3}G	5	5693.63294	5672.66808	1.3930E-14	**100**
1s6g	^{1}G	4	5693.63294	5672.67591	2.1531E-15	**55** + **44**(1s6g ^{3}G$_4$)

In our calculation, we found that level 1s5g ^{3}G$_4$ is actually coupled with 1s5g^{1}G$_4$ with their compositions as 55% and 44% respectively. We noted configuration mixing for the ^{3}F$_3$ and ^{1}F$_3$ terms belonging to the configuration 1s4f, 1s5f and 1s6f. Similarly, we found configuration

mixing for the $^3D_2$ and $^1D_2$ terms belonging to the configuration 1snd ($n = 3-6$). Similarly, as can be seen, mixing among some other levels are also strong. As a result of this, the identification of a particular level is not unique, and is not based on the strength of the dominant eigenvector alone. Therefore, the configuration and the J values given in Table 1 are definite, but the corresponding LSJ designation provided for a level is liable to interchange.

In Table 2, we have compared our energy levels obtained with the GRASP code with energy values compiled in National Institute of Standards and Technology (NIST) database from the calculations of plantae *et al.* (1994). The energy levels are compared with respect to the ground level energies of the corresponding data sets. From Table 2, one can see that our results obtained without inclusion of Breit and QED effects (GRASP 1) differs largely from the NIST values. Also, the ordering slightly differs in a few instances. Also, after the inclusion of Breit and QED effects (GRASP2) our results are some what lower than the NIST values. Furthermore, the ordering of GRASP 2 results is same as ordering of data listed in NIST. Therefore, our GRASP2 results are much closer to the NIST listings than the GRASP1 as we have included the Breit and QED effects in GRASP2. Overall we can state that there is no major discrepancy between our calculated level energies and NIST compiled results of He-like tungsten. Therefore, we recommend that our energy levels from the GRASP2 calculations should be taken in the modelling applications.

Table 2. Comparison of our calculated level energies with the other available results (energies in Ryd.)

Configuration	Level	J	GRASP1	GRASP2	NIST
$1s^2$	^1S	0	0	0	0
1s2s	^3S	1	4356.53807	4337.06517	4335.87
1s2p	$^3P^o$	0	4364.96632	4348.79607	4347.21
1s2s	^1S	0	4365.35426	4348.38051	4347.04
1s2p	$^3P^o$	1	4366.61460	4345.86919	4344.31
1s2p	$^3P^o$	2	4482.20146	4461.53483	4459.96
1s2p	$^1P^o$	1	4485.26092	4465.46405	4463.89

3. Radiatives Rates

The absorption oscillator strength (f_{ij}) with the radiative rate A_{ji} (in s^{-1}) for a transition $i \rightarrow j$ is related by following expression:

$$f_{ij} = \frac{mc\omega_j}{8\pi^2 e^2 \omega_j} \lambda_{ji}^2 A_{ji} \,. \tag{1a}$$

After using the value of $\frac{mc}{8\pi^2 e^2} = 1.49 \times 10^{-16}$, eq. (1a) becomes

$$f_{ij} = 1.49 \times 10^{-16} \frac{\omega_j}{\omega_i} \lambda_{ji}^2 A_{ji} \,. \tag{1b}$$

Where c is the velocity of light, e and m are the electron charge and mass, respectively. Also, λ_{ji} is the transition wavelength (in Å), ω_i and ω_j are the statistical weights of the lower and upper

levels respectively. We may also define the other related parameter which is line strength as

$$S = S(i,j) = S(j,i) = |R_{ij}|^2 \tag{2a}$$

where

$$R_{ij} = |\langle \psi_j | P | \psi_i \rangle| . \tag{2b}$$

In eq. (2b) ψ_i and ψ_j represent the initial and final state wavefunctions, and R_{ij} represent the transition matrix element of the appropriate multipole operator P. we can relate the dimensionless oscillator strength f_{ij} and line strength (in a.u.) by the following equations:

For the electric dipole ($E1$) transitions:

$$A_{ji} = \frac{2.0261 \times 10^{18}}{\omega_j \lambda_{ji}^3} S_{E1} \quad \text{and} \quad f_{ij} = \frac{303.75}{\lambda_{ji} \omega_i} S_{E1} . \tag{3}$$

For the magnetic dipole ($M1$) transitions

$$A_{ji} = \frac{2.6974 \times 10^{13}}{\omega_j \lambda_{ji}^3} S_{M1} \quad \text{and} \quad f_{ij} = \frac{4.044 \times 10^{-3}}{\lambda_{ji} \omega_i} S_{M1} . \tag{4}$$

For the electric quadrupole ($E2$) transitions

$$A_{ji} = \frac{1.1199 \times 10^{18}}{\omega_j \lambda_{ji}^5} S_{E2} \quad \text{and} \quad f_{ij} = \frac{167.89}{\lambda_{ji}^3 \omega_i} S_{E2} . \tag{5}$$

For the magnetic quadrupole ($M2$) transitions

$$A_{ji} = \frac{1.4910 \times 10^{13}}{\omega_j \lambda_{ji}^5} S_{M2} \quad \text{and} \quad f_{ij} = \frac{2.236 \times 10^{-3}}{\lambda_{ji}^3 \omega_i} S_{M2} . \tag{6}$$

Since the electric dipole ($E1$) transitions are relatively more important than the other transitions, and most of the results presented in the literature are confined to these transitions alone, therefore, in Table 3, we have presented the transition wavelengths (in Å), transition probabilities (in s^{-1}), oscillator strengths (dimensionless) and line strength (in a.u) obtained with the GRASP code for all electric dipole ($E1$) transitions from the ground state $1s^2\ {}^1S_0$ and some excited states ($1s2s\ {}^1S_0$, ${}^3S_1$ and $1s2p\ {}^3P_{0,1,2}$, ${}^1P_1$) of He-like tungsten. We have also included in this table are the ratio of the velocity and length forms of the f-values from the GRASP calculations, because to have an additional indicator of accuracy of our results.

In our calculations, the difference between both forms for strong $E1$ type transitions ($f > 0.1$) does not exceed 4%. For 68% of the electric dipole transitions, the value of velocity and length forms is identical who indicates that our transition characterstics are quite accurate and reliable. Additionally, difference between velocity and length forms for some weaker transitions ($f < 0.1$) can sometimes be large, see for example ($1s2s\ {}^3S_1$-$1s6f\ {}^3F_4$) transition. All such weak transitions being sensitive to the mixing coefficients, do not affect the overall accuracy of the calculations.

Table 3. Transition data for E1 transitions from $1s^2$, 1s2s and 1s2p levels and 2J for lower level i, upper level j, wavelength λ (in Å), line strength S (length form, oscillator strength f (length form), transition rate A_{ji} (length form) in s^{-1}

Levels		2J		λ (in Å)	A_{ji} (s^{-1})	f_{ij}	S_{ij} (au)	Vel/len
i	j	i	k					
$1s^2\ ^1S$	$1s2p\ ^3P$	0	2	0.20969	1.204E+16	2.380E-01	1.643E-04	1.00E+00
$1s^2\ ^1S$	$1s2p\ ^1P$	0	2	0.20407	2.250E+16	4.214E-01	2.831E-04	1.00E+00
$1s^2\ ^1S$	$1s3p\ ^3P$	0	2	0.17595	2.918E+15	4.063E-02	2.354E-05	1.00E+00
$1s^2\ ^1S$	$1s3p\ ^1P$	0	2	0.17475	6.307E+15	8.662E-02	4.983E-05	1.00E+00
$1s^2\ ^1S$	$1s4p\ ^3P$	0	2	0.16673	1.119E+15	1.399E-02	7.680E-06	1.00E+00
$1s^2\ ^1S$	$1s4p\ ^1P$	0	2	0.16627	2.562E+15	3.185E-02	1.743E-05	1.00E+00
$1s^2\ ^1S$	$1s5p\ ^3P$	0	2	0.16284	5.517E+14	6.579E-03	3.527E-06	1.00E+00
$1s^2\ ^1S$	$1s5d\ ^3D$	0	2	0.16262	1.298E+15	1.543E-02	8.263E-06	1.00E+00
$1s^2\ ^1S$	$1s6p\ ^3P$	0	2	0.16083	3.129E+14	3.640E-03	1.927E-06	1.00E+00
$1s^2\ ^1S$	$1s6p\ ^1P$	0	2	0.1607	7.494E+14	8.705E-03	4.605E-06	1.00E+00
$1s2s\ ^3S$	$1s2p\ ^3P$	2	0	77.681	5.560E+09	1.677E-03	1.286E-03	1.10E+00
$1s2s\ ^3S$	$1s2p\ ^3P$	2	2	103.51	1.588E+09	2.551E-03	2.607E-03	1.60E+00
$1s2s\ ^3S$	$1s2p\ ^3P$	2	4	7.3212	7.723E+12	1.034E-01	7.478E-03	1.00E+00
$1s2s\ ^3S$	$1s2p\ ^1P$	2	2	7.0972	2.752E+12	2.078E-02	1.457E-03	1.00E+00
$1s2s\ ^3S$	$1s3p\ ^3P$	2	0	1.0811	7.800E+14	4.556E-02	4.864E-04	1.00E+00
$1s2s\ ^3S$	$1s3p\ ^3P$	2	2	1.0821	5.305E+14	9.313E-02	9.953E-04	1.00E+00
$1s2s\ ^3S$	$1s3p\ ^3P$	2	4	1.0396	5.511E+14	1.488E-01	1.528E-03	1.00E+00
$1s2s\ ^3S$	$1s3p\ ^1P$	2	2	1.0382	1.759E+14	2.843E-02	2.915E-04	1.00E+00
$1s2s\ ^3S$	$1s4p\ ^3P$	2	0	0.8072	3.255E+14	1.060E-02	8.450E-05	1.00E+00
$1s2s\ ^3S$	$1s4p\ ^3P$	2	2	0.80742	2.205E+14	2.155E-02	1.719E-04	1.00E+00
$1s2s\ ^3S$	$1s4p\ ^3P$	2	4	0.79723	2.569E+14	4.079E-02	3.212E-04	1.00E+00
$1s2s\ ^3S$	$1s4p\ ^1P$	2	2	0.79689	8.260E+13	7.864E-03	6.189E-05	1.00E+00
$1s2s\ ^3S$	$1s4f\ ^3F$	2	4	0.79405	5.359E+05	8.442E-11	6.621E-13	6.20E-02
$1s2s\ ^3S$	$1s5s\ ^1S$	2	0	0.72367	1.633E+14	4.273E-03	3.054E-05	1.00E+00
$1s2s\ ^3S$	$1s5p\ ^3P$	2	2	0.72376	1.103E+14	8.662E-03	6.192E-05	1.00E+00
$1s2s\ ^3S$	$1s5p\ ^3P$	2	4	0.71957	1.342E+14	1.736E-02	1.234E-04	1.00E+00
$1s2s\ ^3S$	$1s5d\ ^3D$	2	2	0.71943	4.338E+13	3.366E-03	2.391E-05	1.00E+00
$1s2s\ ^3S$	$1s5f\ ^3F$	2	4	0.71823	7.235E+05	9.326E-11	6.615E-13	3.20E-02
$1s2s\ ^3S$	$1s6p\ ^3P$	2	0	0.68559	9.436E+13	2.216E-03	1.501E-05	1.00E+00
$1s2s\ ^3S$	$1s6p\ ^3P$	2	2	0.68564	6.327E+13	4.459E-03	3.019E-05	9.90E-01
$1s2s\ ^3S$	$1s6p\ ^3P$	2	4	0.68347	7.883E+13	9.201E-03	6.211E-05	1.00E+00
$1s2s\ ^3S$	$1s6p\ ^1P$	2	2	0.68339	2.557E+13	1.791E-03	1.209E-05	1.00E+00
$1s2s\ ^3S$	$1s6f\ ^3F$	2	4	0.68277	2.983E+07	3.475E-09	2.343E-11	5.00E-03
$1s2p\ ^3P$	$1s3s\ ^3S$	0	2	1.1005	2.675E+13	1.457E-02	5.278E-05	9.80E-01
$1s2p\ ^3P$	$1s3d\ ^3D$	0	2	1.0524	1.148E+15	5.717E-01	1.981E-03	1.00E+00

(*Contd.*)

Levels		2J		λ (in Å)	A_{ji} (s^{-1})	f_{ij}	S_{ij} (au)	Vel/len
i	j	i	k					
1s2p ^{3}P	1s4s ^{3}S	0	2	0.81659	1.089E+13	3.267E-03	8.783E-06	9.60E-01
1s2p ^{3}P	1s4d ^{3}D	0	2	0.80517	3.974E+14	1.159E-01	3.072E-04	1.00E+00
1s2p ^{3}P	1s5s ^{3}S	0	2	0.73084	5.476E+12	1.315E-03	3.165E-06	9.40E-01
1s2p ^{3}P	1s5d ^{3}D	0	4	0.72616	1.868E+14	4.430E-02	1.059E-04	1.00E+00
1s2p ^{3}P	1s6s ^{3}S	0	2	0.69188	2.999E+12	6.457E-04	1.471E-06	9.60E-01
1s2p ^{3}P	1s6d ^{3}D	0	2	0.68946	1.023E+14	2.187E-02	4.964E-05	1.00E+00
1s2s ^{1}S	1s2p ^{1}P	0	2	7.7831	4.369E+12	1.190E-01	3.050E-03	9.90E-01
1s2s ^{1}S	1s3p ^{3}P	0	2	1.0968	2.567E+14	1.389E-01	5.015E-04	1.00E+00
1s2s ^{1}S	1s3p ^{1}P	0	2	1.0517	3.784E+14	1.883E-01	6.519E-04	1.00E+00
1s2s ^{1}S	1s4p ^{3}P	0	2	0.8156	1.070E+14	3.200E-02	8.592E-05	9.90E-01
1s2s ^{1}S	1s4p ^{1}P	0	2	0.80485	1.788E+14	5.208E-02	1.380E-04	9.90E-01
1s2s ^{1}S	1s5p ^{3}P	0	2	0.73032	5.383E+13	1.291E-02	3.105E-05	9.80E-01
1s2s ^{1}S	1s5d ^{3}D	0	2	0.72591	9.520E+13	2.256E-02	5.392E-05	9.70E-01
1s2s ^{1}S	1s6p ^{3}P	0	2	0.69152	2.958E+13	6.361E-03	1.448E-05	1.00E+00
1s2s ^{1}S	1s6p ^{1}P	0	2	0.68924	5.405E+13	1.155E-02	2.620E-05	1.00E+00
1s2p ^{3}P	1s3s ^{3}S	2	2	1.0966	5.214E+13	9.400E-03	1.018E-04	1.00E+00
1s2p ^{3}P	1s3s ^{1}S	2	0	1.0927	7.164E+13	4.274E-03	4.613E-05	9.80E-01
1s2p ^{3}P	1s3d ^{3}D	2	2	1.0488	5.844E+14	9.637E-02	9.982E-04	1.00E+00
1s2p ^{3}P	1s3d ^{3}D	2	4	1.0492	1.721E+15	4.735E-01	4.906E-03	1.00E+00
1s2p ^{3}P	1s3d ^{1}D	2	4	1.0372	2.271E+11	6.103E-05	6.252E-07	1.00E+00
1s2p ^{3}P	1s4s ^{3}S	2	2	0.81446	2.090E+13	2.079E-03	1.672E-05	1.00E+00
1s2p ^{3}P	1s4s ^{1}S	2	0	0.81358	2.964E+13	9.803E-04	7.877E-06	9.70E-01
1s2p ^{3}P	1s4d ^{3}D	2	2	0.8031	2.026E+14	1.959E-02	1.554E-04	1.00E+00
1s2p ^{3}P	1s4d ^{3}D	2	4	0.80319	5.955E+14	9.599E-02	7.615E-04	1.00E+00
1s2p ^{3}P	1s4d ^{1}D	2	4	0.80018	7.124E+10	1.140E-05	9.007E-08	1.10E+00
1s2p ^{3}P	1s5s ^{3}S	2	2	0.72913	1.031E+13	8.221E-04	5.920E-06	1.00E+00
1s2p ^{3}P	1s5p ^{3}P	2	0	0.72878	1.501E+13	3.985E-04	2.868E-06	9.50E-01
1s2p ^{3}P	1s5d ^{3}D	2	4	0.72447	9.516E+13	7.488E-03	5.358E-05	1.00E+00
1s2p ^{3}P	1s5p ^{1}P	2	2	0.72451	2.793E+14	3.663E-02	2.621E-04	1.00E+00
1s2p ^{3}P	1s5d ^{1}D	2	4	0.72325	3.183E+10	4.160E-06	2.972E-08	1.10E+00
1s2p ^{3}P	1s6s ^{3}S	2	2	0.69035	5.856E+12	4.184E-04	2.853E-06	1.00E+00
1s2p ^{3}P	1s6s ^{1}S	2	0	0.69017	8.353E+12	1.988E-04	1.355E-06	9.80E-01
1s2p ^{3}P	1s6d ^{3}D	2	2	0.68794	5.271E+13	3.739E-03	2.541E-05	1.00E+00
1s2p ^{3}P	1s6d ^{3}D	2	4	0.68796	1.537E+14	1.817E-02	1.235E-04	1.00E+00
1s2p ^{3}P	1s6d ^{1}D	2	4	0.6873	2.611E+10	3.082E-06	2.092E-08	7.30E-01
1s2p ^{3}P	1s3s ^{3}S	4	2	1.2739	2.056E+14	3.001E-02	6.294E-04	1.00E+00
1s2p ^{3}P	1s3d ^{3}D	4	2	1.2099	5.009E+13	6.595E-03	1.313E-04	1.00E+00
1s2p ^{3}P	1s3d ^{3}D	4	4	1.2104	2.708E+14	5.946E-02	1.185E-03	1.00E+00

(*Contd.*)

Levels		2J		λ (in Å)	A_{ji} (s^{-1})	f_{ij}	S_{ij} (au)	Vel/len
i	j	i	k					
1s2p ^{3}P	1s3d ^{3}D	4	6	1.1948	1.819E+15	5.449E-01	1.072E-02	1.00E+00
1s2p ^{3}P	1s3d ^{1}D	4	4	1.1944	1.822E+14	3.897E-02	7.661E-04	1.00E+00
1s2p ^{3}P	1s4s ^{3}S	4	2	0.90836	7.863E+13	5.836E-03	8.726E-05	1.00E+00
1s2p ^{3}P	1s4d ^{3}D	4	2	0.89425	1.544E+13	1.111E-03	1.635E-05	1.00E+00
1s2p ^{3}P	1s4d ^{3}D	4	4	0.89437	8.329E+13	9.989E-03	1.471E-04	1.00E+00
1s2p ^{3}P	1s4d ^{3}D	4	6	0.89072	5.891E+14	9.809E-02	1.438E-03	1.00E+00
1s2p ^{3}P	1s4d ^{1}D	4	4	0.89063	5.903E+13	7.020E-03	1.029E-04	1.00E+00
1s2p ^{3}P	1s5s ^{3}S	4	2	0.80349	3.810E+13	2.213E-03	2.926E-05	1.00E+00
1s2p ^{3}P	1s5d ^{3}D	4	4	0.79784	6.943E+12	3.976E-04	5.221E-06	9.90E-01
1s2p ^{3}P	1s5p ^{1}P	4	2	0.79788	3.732E+13	3.562E-03	4.678E-05	1.00E+00
1s2p ^{3}P	1s5d ^{3}D	4	6	0.79639	2.697E+14	3.590E-02	4.706E-04	1.00E+00
1s2p ^{3}P	1s5d ^{1}D	4	4	0.79636	2.704E+13	2.571E-03	3.370E-05	1.00E+00
1s2p ^{3}P	1s5g ^{3}G	4	6	0.79565	1.328E+05	1.764E-11	2.310E-13	1.50E+00
1s2p ^{3}P	1s6s ^{3}S	4	2	0.75665	2.155E+13	1.110E-03	1.382E-05	1.00E+00
1s2p ^{3}P	1s6d ^{3}D	4	2	0.75376	3.767E+12	1.925E-04	2.389E-06	9.90E-01
1s2p ^{3}P	1s6d ^{3}D	4	4	0.75378	2.021E+13	1.721E-03	2.136E-05	1.00E+00
1s2p ^{3}P	1s6d ^{3}D	4	6	0.75301	1.477E+14	1.758E-02	2.179E-04	1.00E+00
1s2p ^{3}P	1s6d ^{1}D	4	4	0.75299	1.483E+13	1.260E-03	1.562E-05	1.00E+00
1s2p ^{3}P	1s6g ^{3}G	4	6	0.75263	3.992E+06	4.747E-10	5.880E-12	5.10E-02
^{1}P	^{3}S	2	2	1.281	4.032E+13	9.918E-03	1.255E-04	9.90E-01
1s2p ^{1}P	1s3s ^{1}S	2	0	1.2756	2.468E+14	2.007E-02	2.528E-04	9.80E-01
1s2p ^{1}P	1s3d ^{3}D	2	2	1.2162	2.422E+14	5.370E-02	6.451E-04	1.00E+00
1s2p ^{1}P	1s3d ^{3}D	2	4	1.2167	3.501E+13	1.295E-02	1.556E-04	1.00E+00
1s2p ^{1}P	1s3d ^{1}D	2	4	1.2006	1.630E+15	5.869E-01	6.959E-03	1.00E+00
1s2p ^{1}P	1s4s ^{3}S	2	2	0.91193	1.553E+13	1.936E-03	1.744E-05	9.90E-01
1s2p ^{1}P	1s4s ^{1}S	2	0	0.91083	9.765E+13	4.048E-03	3.642E-05	9.60E-01
1s2p ^{1}P	1s4d ^{3}D	2	2	0.89771	7.433E+13	8.980E-03	7.962E-05	1.00E+00
1s2p ^{1}P	1s4d ^{3}D	2	4	0.89783	1.069E+13	2.154E-03	1.910E-05	9.90E-01
1s2p ^{1}P	1s4d ^{1}D	2	4	0.89407	5.273E+14	1.053E-01	9.300E-04	1.00E+00
1s2p ^{1}P	1s5s ^{3}S	2	2	0.80628	7.575E+12	7.382E-04	5.878E-06	9.90E-01
1s2p ^{1}P	1s5p ^{3}P	2	0	0.80585	4.906E+13	1.592E-03	1.267E-05	9.40E-01
1s2p ^{1}P	1s5d ^{3}D	2	4	0.80059	3.328E+13	3.198E-03	2.529E-05	1.00E+00
1s2p ^{1}P	1s5p ^{1}P	2	2	0.80064	4.806E+12	7.698E-04	6.087E-06	9.80E-01
1s2p ^{1}P	1s5d ^{1}D	2	4	0.7991	2.418E+14	3.857E-02	3.044E-04	1.00E+00
1s2p ^{1}P	1s6s ^{3}S	2	2	0.75913	4.184E+12	3.614E-04	2.710E-06	1.00E+00
1s2p ^{1}P	1s6s ^{1}S	2	0	0.75891	2.719E+13	7.824E-04	5.864E-06	9.60E-01
1s2p ^{1}P	1s6d ^{3}D	2	2	0.75622	1.787E+13	1.532E-03	1.144E-05	1.00E+00
1s2p ^{1}P	1s6d ^{3}D	2	4	0.75624	2.495E+12	3.565E-04	2.662E-06	1.00E+00
1s2p ^{1}P	1s6d ^{1}D	2	4	0.75545	1.307E+14	1.864E-02	1.391E-04	1.00E+00

In Table 4, we have presented the transition wavelength (in Å) compiled by NIST and estimated by Kramida and Shirai (2009) for comparison. For the transition $1s^2\ ^1S_0$-$1s2p\ ^1P_1$, the value of wavelength listed in NIST tables is found to be 0.20407, whereas our calculated value for this transition is 0.20414. Also, one can see from Table 4, the wavelength for all transitions agree with the NIST data. The largest differences for the wavelengths are predicted for transition between energy levels which showed largest discrepancies from NIST energies.

Table 4. Comparison of computed wavelengths from observed wavelengths for the available transitions

Levels		2J		λ (in Å) calculated	λ (in Å) NIST
I	J	I	J		
$1s^2\ ^1S$	$1s2p\ ^1P$	0	2	0.20407	0.20414
$1s^2\ ^1S$	$1s2p\ ^3P$	0	2	0.20969	0.20976
$1s2s\ ^3S$	$1s2p\ ^1P$	2	2	7.0972	7.1185
$1s2s\ ^3S$	$1s2p\ ^3P$	2	4	7.3212	7.3438
$1s2s\ ^1S$	$1s2p\ ^1P$	0	2	7.7831	7.7991
$1s2s\ ^3S$	$1s2p\ ^3P$	2	0	77.681	80.39
$1s2s\ ^3S$	$1s2p\ ^3P$	2	2	103.51	107.99

Table 5. Computed lifetimes for W LXXIII

Configuration	Level	J	Lifetimes (s)	
			This work	Indelicato *et al.* (1989)
1s2p	^3P	0	1.798E-10	1.974E-10
1s2p	^3P	1	8.309E-17	8.250E-17

We have also compared our results of oscillator strength and transition probabilities for some transition, with those from results of Lin *et al.* (1977) and Drake (1979) in Table 6 and 7 respectively. From Table 6 and 7, it can be seen, for all transitions, our calculated values of transition probabilities and oscillator strength are in reasonable agreement with other available results. The closeness of our results with the calculated values of Lin *et al.* (1977) and Drake (1979) giving its credit to the accuracy of our results. Therefore, we recommend the use of our calculated GRASP results for these transition probabilities, oscillator strengths and other data.

A general criterion to check the accuracy of the A-values and f-values is to compare their length and velocity forms. These ratios are used as indicators of the accuracy of calculated transition probabilities and oscillator strengths. Such comparisons are desirable, but are not fully sufficient tests to check the accuracies, because different calculations can give comparable A-values and f-values in two forms, but different results in magnitude. The length form is used for electric transitions, as they are less sensitive to the accuracy of wavefunction compared with results obtained in the velocity form of the transition operator and we would normally recommend the length results. Also, because in the dipole length form relativistic corrections

are included automatically but extra term should be added to the gradient matrix element to restore the equivalence relation between length and velocity forms (Hibbert 2004). Therefore, we discuss the two forms in order to show the accuracy of our results.

Table 6. A comparison of the transition Probability (in S^{-1}) calculated in this work with those previously published

Transition	This work	Lin et al. (1977)	Drake (1979)
$1s^2\,{}^1S_0 - 1s2p\,{}^3P_1$	1.204E+16	1.21E+16	1.202E+16
$1s^2\,{}^1S_0 - 1s2p\,{}^1P_1$	2.250E+16	2.24E+16	2.237E+16
$1s^2\,{}^1S_0 - 1s2p\,{}^3P_2$	3.400E+13	3.47E+13	
$1s2s\,{}^1S_0 - 1s2p\,{}^3P_2$	3.887E+06	4.11E+06	
$1s2s\,{}^3S_1 - 1s2p\,{}^3P_2$	7.723E+12	7.93E+12	
$1s2s\,{}^3S_1 - 1s2p\,{}^3P_1$	1.588E+09	2.51E+09	
$1s2s\,{}^3S_1 - 1s2p\,{}^3P_0$	5.560E+09	7.85E+09	
$1s2s\,{}^1S_0 - 1s2p\,{}^1P_1$	4.369E+12	4.53E+12	
$1s2s\,{}^3S_1 - 1s2p\,{}^1P_1$	2.752E+12	2.84E+12	
$1s2s\,{}^3S_1 - 1s2s\,{}^1S_0$	9.663E+05	4.50E+05	
$1s^2\,{}^1S_0 - 1s2s\,{}^3S_1$	1.083E+13	1.10E+13	

Table 7. A comparison of the oscillator strength calculated in this work with those previously published

Transition	This work	Lin et al. (1977)	Drake (1979)
$1s^2\,{}^1S_0 - 1s2p\,{}^3P_1$	0.2380	0.237	0.2366
$1s^2\,{}^1S_0 - 1s2p\,{}^1P_1$	0.4214	0.418	0.4173
$1s2s\,{}^3S_1 - 1s2p\,{}^3P_2$	0.1034	0.187	
$1s2s\,{}^3S_1 - 1s2p\,{}^3P_1$	0.00255	0.0089	
$1s2s\,{}^3S_1 - 1s2p\,{}^3P_0$	0.0167	0.017	
$1s2s\,{}^1S_0 - 1s2p\,{}^1P_1$	0.119	0.121	
$1s2s\,{}^3S_1 - 1s2p\,{}^1P_1$	0.02078	0.0630	

4. Lifetimes

The mean lifetime of a level is the reciprocal of the sum of all the probabilities of emmision transitions from that level. We have presented our calculated lifetimes for all excited levels, which include contributions from electric dipole ($E1$), magnetic dipole ($M1$), electric quadrupole ($E2$) and magnetic quadrupole ($M2$) transitions.

In Table 5, we compare our calculated lifetimes of 1s2p ($^3P_0$ and $^3P_1$) levels with the results of (Indelicato *et al.* 1989). There is excellent agreement in the two sets of results. To best of our knowledge, no other calcuations or measurements are available in the literature for lifetime in W LXXIII. We hope that our calculated value of lifetimes will be useful to experimentalists to measure lifetimes in their future work.

5. Conclusion

Multiconfiguration Dirac-Fock energy levels, as well as some of the electric dipole transition probabilities, line and oscillator strengths have been computed for He-like tungsten. The lowest 67 energy levels are considered. Calculated values have been compared with the data compiled by NIST. Furthermore, we have compared the results for transition probabilities, oscillator strength, transition wavelengths and lifetimes, where previously published work exists.

Lifetimes for all excited levels of W LXXIII are listed, but comparison with the other theoretical results have been possible for only two levels, for which there are no discrepancies between our results and other available result.

Good agreement between our energy levels and radiative transition characterstics for He-like tungsten and the available NIST data, allows us to conclude that the achieved accuracy of the present calculations is higher than those available to date. We hope that our data will be useful in fusion plasma and other applications.

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