Relativistic atomic data for W XLVII

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Energy levels, radiative rates, and lifetimes are calculated for all levels of $3s^23p$, $3s^23d$, $3s3p^2$, $3s3d^2$, $3s3p3d$, $3p^23d$, $3s3d^2$, $3p3d^2$, $3p^3$, and $3d^3$ configurations of Al-like tungsten ion (W XLVII). Multiconfigurational Dirac–Fock (MCDF) method is adopted for calculating energy levels and radiative rates. Oscillator strengths, radiative rates, and line strengths are reported for some E1 transitions from the ground level. Comparisons are made with the available data in the literature and good agreement has been found which confirms the reliability of our results.

Keywords: atomic data, multiconfigurational Dirac–Fock method, transition probability

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1. Introduction

Spectroscopic parameters of tungsten ions are essential for exploring the physical conditions in tokamak plasmas such as ITER in which tungsten is currently considered to be a promising candidate for the plasma-facing material in the divertor region.[1] As sputtering at the surfaces with plasma contact cannot be avoided completely, tungsten will be an intrinsic impurity in these plasmas. The electron temperatures in ITER will range from below 0.1 keV at the edge up to about 30 keV in the core of the plasma. The measured spectra often contain many spectral lines from several ionization stages forming spectral features. To understand its influence as a plasma impurity, reliable atomic data are needed for many ionic stages of tungsten.

Many investigations have been carried out for the Al-like tungsten in the last two decades both theoretically as well as experimentally. For instance, on the theoretical side, Feng *et al.*[2] have presented a comprehensive study of atomic characteristics of ten tungsten ions including W XLVII in a broad range of wavelengths, energy levels and transition probabilities. They have also presented results of multiconfiguration Dirac–Fock and relativistic configuration interaction calculations including the Breit interaction. Safronova and Safronova[3] have calculated the excitation energies for Al-like W^{61+} of the $[2p^6]3s^23p$, $3s3p^2$, $3d^23d$, $3s3p3d$, and $3p^3$ levels and radiative rates of the E1 transitions between them. Further, Huang[4] has tabulated transition rates and oscillator strengths for Al-like ions, calculated by the multiconfiguration Dirac–Fock (MCDF) method. Relativistic many-body calculations of electric dipole lifetimes, transition rates and oscillator strengths for $n = 3$ states in Al-like ions were presented by Safronova *et al.*[5] They calculated the transition rates, oscillator strengths, and line strengths for electric-dipole (E1) transitions between even-parity $3s3p^2$, $3s^23d$, $3p^23d$, $3d^23s$, and $3d^3$ states and odd-parity $3s^23p$, $3p^3$, $3s3p3d$, and $3d^23p$ states in Al-like ions with the nuclear charges ranging from $Z = 15$ to 100.[5] Further, Lavin *et al.*[6] have reported oscillator strengths corresponding to dipole-allowed transitions for a group of Al-like ions ($Z = 13$–103).

On the experimental side, Ralchenko *et al.*[7] reported the measurements of extreme ultraviolet (EUV) spectra (4–20 nm) of highly-charged tungsten ions W^{54+} to W^{63+}obtained with an electron beam ion trap (EBIT) facility at the National Institute of Standards and Technology (NIST). The three levels $^2P_{1/2}$, $^2P_{3/2}$ of $3s^23p$, and $^4P_{1/2}$ of $3s3p^2$ of Al-like tungsten were found using EBIT at NIST.

The aim of this work is to upgrade the database of energy levels, oscillator strengths, transition probabilities, and lifetimes of Al-like tungsten ion. The investigations of highly charged Al-like tungsten ion considered in the present work require the simultaneous consideration of electronic correlation and relativistic effects. For this purpose, we use MCDF technology which was originally developed by Grant *et al.*[8] and revised by Norrington.[9] It includes the most important configuration effects as well as quantum electrodynamics (QED) correction and has been applied successfully to calculate atomic data for highly charged ions.[10–18] In our calculations, all the orbitals are simultaneously optimized on the average energy of all configurations by using the option of EAL (extended average level).

The rest of this paper is organized as follows. In Section 2, we present the method of calculations, then the energy levels and wavefunction compositions are presented in Section 3. In Section 4, we report the radiative rates for electric dipole (E1) and magnetic quadrupole (M2) transition. In Section 5, we present the lifetimes of excited states. Finally, the conclu-

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sion is given in Section 6.

2. Calculation method

We obtain results using the multiconfiguration Dirac–Fock method employed in the GRASP code of Grant *et al.*,[8] revised by Norrington[9] and recently used by various authors.[10–18] In the MCDF approach, the Hamiltonian for an N-electron atom or ion Dirac–Coulomb Hamiltonian is given by

$$\hat{H}^{\mathrm{DC}} = \sum_{i=1}^{N} \hat{H}_i + \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \left|\hat{\boldsymbol{r}}_i - \hat{\boldsymbol{r}}_j\right|^{-1}, \tag{1}$$

where

$$\hat{H} = c \sum_{i=1}^{3} \boldsymbol{\alpha}_i \boldsymbol{p}_i + \beta c^2 + V_{\mathrm{nuc}}(\boldsymbol{r}) \tag{2}$$

is the single particle Hamiltonian consisting of kinetic energy and its interaction with the nucleus. In Eq. (1), α and β represent 4×4 Dirac matrices where c is the speed of light. The N-electron wavefunction is constructed from central-field Dirac orbitals given by

$$\phi_{nkm} = \frac{1}{\boldsymbol{r}} \begin{pmatrix} P_{nk}(\boldsymbol{r}) & \chi_{km}(\theta,\phi,\sigma) \\ -\mathrm{i}Q_{nk}(\boldsymbol{r}) & \chi_{-km}(\theta,\phi,\sigma) \end{pmatrix}, \tag{3}$$

where k is the Dirac angular quantum number, $k = \pm(j+1/2)$ for $l = j \pm 1/2$, so $j = k - 1/2$, m is the projection of the angular momentum j, and P_{nk} and Q_{nk} are radial functions. The spin angular momentum $\chi_{km}(\theta, \phi)$ is a 2 component function defined by

$$\chi_{km}(\theta,\phi) = \sum_{\sigma=\pm 1/2} \left\langle l\, m-\sigma\, \frac{1}{2}\sigma \middle| l\, \frac{1}{2}\, jm \right\rangle Y_l^{m-\sigma}(\theta,\phi)\phi^{\sigma}. \tag{4}$$

An atomic state function (ASF) can now be formed for an N-electron system with the given total angular momentum J, M and parity P is approximated by a linear combination of n_{c} electronic configuration state functions (CSFs)

$$|\psi_\alpha(PJM)\rangle = \sum_{i=1}^{n_{\mathrm{c}}} C_i(\alpha)\,|\gamma_i(PJM)\rangle\,, \tag{5}$$

where n_{c} is the number of CSFs included in the expansion, $C_i(\alpha)$ are the expansion mixing co-efficients, and α represents all information such as orbital occupation numbers, coupling, etc. The CSFs are usually chosen to be orthonormal, so that

$$C_i(\alpha) + C_j(\alpha) = \delta_{ij}. \tag{6}$$

For expectation of the Dirac–Hamiltonian, we get the energy of the N-electron system as

$$\begin{aligned} E_\alpha^{PJM} &= \left\langle \Psi_\alpha(PJM) \middle| H^{\mathrm{DC}} \middle| \Psi_\alpha(PJM) \right\rangle \\ &= \sum_{ij} C_i^*(\alpha) C_i(\alpha) \left\langle \gamma_i(PJM) \middle| H^{\mathrm{DC}} \middle| \gamma_j(PJM) \right\rangle \\ &= \left(C_\alpha^{\mathrm{DC}}\right)^+ H^{\mathrm{DC}} C_\alpha^{\mathrm{DC}}. \end{aligned} \tag{7}$$

The Hamiltonian matrix, H^{DC} has elements

$$H_{rs}^{\mathrm{DC}} = \left\langle \gamma_r(PJM) \middle| H^{\mathrm{DC}} \middle| \gamma_s(PJM) \right\rangle. \tag{8}$$

Using the normalization condition

$$(H^{\mathrm{DC}} - E_\alpha^{\mathrm{DC}}\, \boldsymbol{I}) C_\alpha^{\mathrm{DC}} = 0, \tag{9}$$

where $\boldsymbol{I}$ is the $n_{\mathrm{c}} \times n_{\mathrm{c}}$ unit matrix. Thus the predicted atomic energy level E_α^{PJM} can be taken to be eigenvalues of H^{DC}. In the present calculation, QED corrections (including vacuum polarization and self energy), are considered in the first order of perturbation theory. One-electron excitations from 3s and 3p orbitals of $3s^2 3p$ configuration as well as two electron excitations from orbitals with $n = 3$ to all possible combinations of one or two electrons in the shells up to $n = 4$ were employed to generate one-electron wavefunctions as a basis set for CSFs in the MCDF method. Therefore, we use [$1s^2 2s^2 2p^6$] $3s^2 3p$, $3p^3$, $3p3d^2$, $3p4s^2$, $3p4f^2$, $3p4d^2$, $3s^2 4p$, $3s^2 4f$, $3p^2 4p$, $3p^2 4f$, $3s3p^2$, $3s^2 3d$, $3p^2 3d$, $3s3d^2$, $3d^3$, $3s^2 4s$, $3d4s^2$, $3d4p^2$, $3d4d^2$, $3d4f^2$, $3s\,^2 4d$, $3p^2 4s$, $3s3p3d$, $3s3p4s$, $3s3p4p$, $3s3p4d$, $3s3p4f$, $3s3d4s$, $3s3d4p$, $3s3d4d$, $3s3d4f$, $3p3d4s$, $3p3d4p$, $3p3d4d$, and $3p3d4f$ configurations. We also present a detailed comparison of our theoretical calculations with the data recommended from the NIST database.

3. Energy levels

We have performed calculations on transitions energies for the 148 fine structural levels belong to $3s^2 3p$, $3s^2 3d$, $3s3p^2$, $3s3d^2$, $3s3p3d$, $3p^2 3d$, $3s3d^2$, $3p3d^2$, $3p^3$, and $3d^3$ configurations of Al-like tungsten. The Ne-like ($1s^2 2s^2 2p^6$) core was treated as an inactive core. Energy levels of all the fine structural levels generated by above configurations have been calculated by the fully relativistic Multiconfigurational Dirac–Fock method. The flexible atomic code (FAC), which is also fully relativistic and based on the jj-coupling scheme has been used to generate all relevant atomic data.

The energy levels with their labels obtained using MCDF and FAC lifetimes of excited levels for Al-like tungsten are presented in Table 1. The calculation includes ([$1s^2 2s^2 2p^6$]$3s^2 3p$, $3p^3$, $3p3d^2$, $3p4s^2$, $3p4f^2$, $3p4d^2$,$3s^2 4p$, $3s^2 4f$, $3p^2 4p$, $3p^2 4f$, $3s3p^2$, $3s^2 3d$, $3p^2 3d$, $3s3d^2$, $3d^3$, $3s^2 4s$, $3d4s^2$, $3d4p^2$, $3d4d^2$, $3d4f^2$, $3s\,^2 4d$, $3p^2 4s$, $3s3p3d$, $3s3p4s$, $3s3p4p$, $3s3p4d$, $3s3p4f$, $3s3d4s$, $3s3d4p$, $3s3d4d$, $3s3d4f$, $3p3d4s$, $3p3d4p$, $3p3d4d$, and $3p3d4f$) configurations, which generate 894 energy levels, of which 148 are listed in Table 1. As QED corrections are important for transition energy calculations, therefore we present the QED corrections in our results. Further, we show the contributions to the excitation energies arising from different parts of the Hamiltonian and compare our level energies calculated by MCDF (included Breit and QED effects) with the FAC.

Table 1. Dirac–Coulomb (DC), Breit, and quantum electrodynamics (QED) contributions to the MCDF energy (in Rydberg) as a function of the orbital set. The sum (total) is compared with FAC. All energies are relative to the ground state.

S. No.	Configuration	Term	J	MCDF				FAC	Lifetime
				DC	Breit	QED	Total		
1	$3s^2\ 3p$	$^2P^o$	(1/2)	0	0	0	0	0	–
2	$3s\ 3p^2(^3P)$	^4P	(1/2)	12.4452	0.325	–0.314	12.4556	12.3288	2.54×10^{-11}
3	$3s^2\ 3p$	$^2P^o$	(3/2)	27.0064	–0.333	0.0284	26.7019	26.7411	4.58×10^{-9}
4	$3s3p^2(^3P)$	^4P	(3/2)	37.1833	–0.0166	–0.28	36.8867	36.8079	8.85×10^{-11}
5	$3s3p^2(^1D)$	^2D	(5/2)	38.6017	–0.0791	–0.278	38.2449	38.1613	6.99×10^{-11}
6	$3s3p^2(^1D)$	^2D	(3/2)	40.1414	–0.111	–0.233	39.7977	39.7204	1.51×10^{-12}
7	$3s3p^2(^3P)$	^2P	(1/2)	40.8939	–0.0122	–0.283	40.5984	40.5014	3.53×10^{-13}
8	$3s^2\ 3d$	^2D	(3/2)	44.4263	–0.339	–0.0651	44.0223	43.9728	2.58×10^{-13}
9	$3s^2\ 3d$	^2D	(5/2)	49.9195	–0.574	–0.0184	49.3267	49.303	3.43×10^{-12}
10	$3p^3$	$^2P^o$	(3/2)	52.3	0.0962	–0.471	51.9247	51.7734	6.61×10^{-7}
11	$3s3p(^3P)\ 3d$	$^4F^o$	(3/2)	53.3083	0.0359	–0.406	52.9380	52.7457	3.39×10^{-7}
12	$3s\ 3p(^3P)3d$	$^4F^o$	(5/2)	54.249	–0.142	–0.324	53.7833	53.6247	9.26×10^{-4}
13	$3s\ 3p(^3P)3d$	$^4D^o$	(1/2)	56.1705	–0.0769	–0.323	55.7705	55.6171	8.51×10^{-6}
14	$3s\ 3p(^3P)3d$	$^4D^o$	(3/2)	56.6942	–0.0651	–0.35	56.2795	56.1207	4.41×10^{-5}
15	$3s\ 3p(^3P)3d$	$^4P^o$	(5/2)	60.3773	–0.26	–0.324	59.7935	59.6518	2.69×10^{-6}
16	$3s\ 3p(^3P)3d$	$^4F^o$	(7/2)	61.511	–0.331	–0.323	60.8569	60.7115	5.34×10^{-12}
17	$3s\ 3p(^3P)3d$	$^2F^o$	(5/2)	62.2414	–0.29	–0.325	61.6267	61.4807	8.53×10^{-6}
18	$3s\ 3p(^3P)3d$	$^2D^o$	(3/2)	62.5673	–0.219	–0.339	62.0089	61.8571	5.22×10^{-6}
19	$3s3p^2(^3P)$	^4P	(5/2)	65.1299	–0.38	–0.249	64.5008	64.4575	1.40×10^{-12}
20	$3s3p^2(^3P)$	^2S	(1/2)	67.8754	–0.33	–0.251	67.2946	67.2421	1.32×10^{-10}
21	$3p^23d$	$^4F^o$	(3/2)	68.1109	0.329	–0.586	67.8533	67.4099	3.50×10^{-8}
22	$3s3p^2$	^2P	(3/2)	68.4861	–0.453	–0.3	67.7327	67.8118	4.35×10^{-10}
23	$3p^23d$	$^4F^o$	(5/2)	75.4611	0.0435	–0.635	74.8695	74.5782	9.39×10^{-9}
24	$3p^3(^2D)$	$^2D^o$	(5/2)	78.8571	–0.213	–0.476	78.1680	78.03	6.38×10^{-7}
25	$3p^3(^4S)$	$^4S^o$	(3/2)	79.2019	–0.0761	–0.545	78.5810	78.4271	1.33×10^{-4}
26	$3p^3(^2P)$	$^2P^o$	(1/2)	80.4362	–0.112	–0.509	79.8149	79.673	1.52×10^{-5}
27	$3s\ 3p(^3P)3d$	$^4P^o$	(3/2)	81.2342	–0.416	–0.298	80.5197	80.4059	1.40×10^{-6}
28	$3s\ 3p(^3P)3d$	$^4P^o$	(1/2)	81.3392	–0.38	–0.305	80.6538	80.5357	1.24×10^{-6}
29	$3s\ 3p(^3P)3d$	$^4D^o$	(5/2)	81.595	–0.397	–0.341	80.8567	80.7327	5.19×10^{-4}
30	$3s\ 3p(^3P)3d$	$^4D^o$	(7/2)	81.8294	–0.505	–0.291	81.0329	80.9224	6.11×10^{-13}
31	$3s\ 3p(^3P)3d$	$^2D^o$	(3/2)	83.8718	–0.44	–0.3	83.1325	83.0127	1.19×10^{-5}
32	$3s\ 3p(^3P)3d$	$^2F^o$	(5/2)	84.8819	–0.434	–0.314	84.1338	83.989	1.36×10^{-3}
33	$3s\ 3p(^3P)3d$	$^2P^o$	(1/2)	85.2375	–0.377	–0.321	84.5394	84.4149	3.82×10^{-5}
34	$3s\ 3p(^3P)3d$	$^4F^o$	(9/2)	85.9295	–0.657	–0.291	84.9810	84.8806	4.85×10^{-9}
35	$3s\ 3p(^3P)3d$	$^2D^o$	(5/2)	87.5944	–0.602	–0.298	86.6934	86.5886	7.47×10^{-6}
36	$3s\ 3p(^3P)3d$	$^2F^o$	(7/2)	88.2682	–0.627	–0.291	87.3493	87.2476	9.17×10^{-12}
37	$3s\ 3p(^3P)3d$	$^2P^o$	(3/2)	88.474	–0.571	–0.3	87.6032	87.4976	1.19×10^{-4}
38	$3s\ 3p(^1P)3d$	$^2F^o$	(7/2)	89.7242	–0.627	–0.293	88.8049	88.6935	3.27×10^{-11}
39	$3s\ 3p(^3P)3d$	$^2P^o$	(1/2)	90.3355	–0.533	–0.305	89.4975	89.3899	1.28×10^{-3}
40	$3s\ 3p(^1P)3d$	$^2P^o$	(3/2)	91.1687	–0.574	–0.292	90.3022	90.1939	1.59×10^{-6}
41	$3s\ 3p(^1P)3d$	$^2D^o$	(5/2)	91.3831	–0.594	–0.302	90.4877	90.3748	5.50×10^{-6}
42	$3p^2(^1D)3d$	^2F	(5/2)	93.224	–0.178	–0.585	92.4619	92.2134	1.75×10^{-8}
43	$3p^2(^3P)\ 3d$	^4D	(3/2)	93.7989	–0.121	–0.604	93.0733	92.8152	2.47×10^{-9}
44	$3p^2(^3P)\ 3d$	^4D	(1/2)	93.9714	–0.0822	–0.606	93.2836	93.0225	4.57×10^{-9}
45	$3p^2(^1D)\ 3d$	^2G	(7/2)	94.4215	–0.214	–0.6	93.6080	93.3495	2.30×10^{-5}
46	$3p^2(^1D)\ 3d$	^2D	(3/2)	96.0891	–0.181	–0.56	95.3485	95.1006	2.73×10^{-9}
47	$3p^2(^3P)\ 3d$	^2D	(5/2)	96.2053	–0.183	–0.574	95.4485	95.19	8.89×10^{-9}
48	$3p^2(^3P)\ 3d$	^4D	(1/2)	96.4082	–0.14	–0.568	95.7004	95.4465	2.58×10^{-7}
49	$3s\ 3d^2(^3F)$	^4F	(3/2)	98.2298	–0.441	–0.372	97.4174	97.19	1.46×10^{-6}
50	$3s\ 3d^2(^3F)$	^4F	(5/2)	99.2798	–0.476	–0.378	98.4267	98.1975	1.03×10^{-9}
51	$3p^2(^3P)\ 3d$	^4F	(7/2)	99.9257	–0.3	–0.601	99.0243	98.7792	2.36×10^{-5}
52	$3p^2(^1D)\ 3d$	^2G	(9/2)	100.6	–0.409	–0.583	99.6073	99.3663	1.29×10^{-12}
53	$3s\ 3d^2(^3P)$	^4P	(1/2)	100.66	–0.413	–0.361	99.8859	99.6457	1.75×10^{-8}
54	$3p^2(^1D)3d$	^2P	(3/2)	100.781	–0.299	–0.592	99.8900	99.656	3.12×10^{-8}
55	$3p^2(^1D)3d$	^2D	(5/2)	101.148	–0.348	–0.585	100.215	99.9733	1.35×10^{-8}
56	$3p^2(^1D)\ 3d$	^2F	(7/2)	102.074	–0.421	–0.554	101.099	100.867	2.49×10^{-5}
57	$3p^2(^3P)3d$	^4P	(5/2)	102.203	–0.306	–0.592	101.305	101.057	2.44×10^{-7}
58	$3p^2(^1D)\ 3d$	^2S	(1/2)	102.94	–0.299	–0.567	102.074	101.822	1.46×10^{-10}
59	$3p^2(^3P)\ 3d$	^2D	(3/2)	103.243	–0.294	–0.589	102.360	102.098	1.06×10^{-10}
60	$3s\ 3d^2(^3F)$	^4F	(7/2)	104.278	–0.663	–0.37	103.245	103.033	6.83×10^{-2}
61	$3s\ 3d^2(^3P)$	^4P	(5/2)	104.406	–0.656	–0.339	103.412	103.206	1.10×10^{-8}

Table 1. (*Continued*).

S. No.	Configuration	Term	J	MCDF				FAC	Lifetime
				DC	Breit	QED	Total		
62	$3s\ 3d^2(^3P)$	^4P	(3/2)	104.792	–0.615	–0.335	103.842	103.642	2.72×10^{-9}
63	$3s\ 3d^2(^1G)$	^2G	(9/2)	105.573	–0.754	–0.353	104.466	104.255	4.49×10^{-13}
64	$3s\ 3d^2(^3F)$	^2F	(5/2)	106.084	–0.63	–0.369	105.085	104.851	1.75×10^{-8}
65	$3s\ 3d^2(^1G)$	^2G	(7/2)	106.136	–0.707	–0.346	105.083	104.865	3.48×10^{-4}
66	$3s\ 3d^2(^1D)$	^2D	(3/2)	106.422	–0.616	–0.359	105.447	105.217	1.02×10^{-10}
67	$3s\ 3d^2(^3P)$	^2P	(1/2)	107.13	–0.534	–0.378	106.218	105.971	7.30×10^{-11}
68	$3p^3(^2D)$	^2D	(3/2)	107.994	–0.385	–0.53	107.079	106.96	1.33×10^{-3}
69	$3p\ 3d^2(^1G)$	^2F	(5/2)	108.874	–0.203	–0.648	108.023	107.699	3.35×10^{-2}
70	$3s3d^2(^3F)$	^4F	(9/2)	110.457	–0.884	–0.336	109.237	109.044	7.27×10^{-12}
71	$3s3d^2(^1D)$	^2D	(5/2)	111.468	–0.809	–0.339	110.321	110.119	3.15×10^{-10}
72	$3p3d^2(^3P)$	^4D	(1/2)	111.968	–0.112	–0.647	111.208	110.738	7.47×10^{-3}
73	$3p3d^2(^3F)$	^2D	(3/2)	112.045	–0.155	–0.646	111.244	110.892	1.11×10^{-3}
74	$3s\ 3d^2(^3F)$	^2F	(7/2)	112.135	–0.825	–0.351	110.958	110.892	9.25×10^{-3}
75	$3s\ 3d^2(^3P)$	^2P	(3/2)	112.545	–0.774	–0.348	111.424	111.206	2.61×10^{-8}
76	$3s\ 3d^2(^1S)$	^2S	(1/2)	113.847	–0.7	–0.342	112.805	112.599	1.81×10^{-9}
77	$3p3d^2(^3F)$	^4G	(7/2)	115.748	–0.398	–0.648	114.702	114.385	2.21×10^{-9}
78	$3p3d^2(^3F)$	^4G	(5/2)	115.983	–0.355	–0.648	114.980	114.664	5.79×10^{-3}
79	$3p3d^2(^3P)$	^4D	(3/2)	116.46	–0.319	–0.648	115.493	115.183	3.42×10^{-4}
80	$3p3d^2(^3P)$	^4P	(1/2)	116.617	–0.272	–0.648	115.697	115.389	7.52×10^{-5}
81	$3p3d^2(^1G)$	^2H	(9/2)	117.019	–0.476	–0.648	115.894	115.577	8.28×10^{-6}
82	$3p3d^2(^3F)$	^4F	(5/2)	118.579	–0.355	–0.647	117.577	117.243	5.87×10^{1}
83	$3p3d^2(^1G)$	^2F	(7/2)	119.038	–0.392	–0.647	117.999	117.657	3.28×10^{-8}
84	$3p3d^2(^3P)$	^4S	(3/2)	119.347	–0.306	–0.647	118.394	118.049	5.11×10^{-5}
85	$3p^23d(^2D)$	^4P	(3/2)	122.272	–0.437	–0.573	121.262	121.043	3.50×10^{-8}
86	$3p^23d(^2D)$	^4D	(5/2)	122.897	–0.492	–0.573	121.831	121.608	1.27×10^{-8}
87	$3p^23d(^2D)$	^2P	(1/2)	123.028	–0.448	–0.572	122.008	121.776	4.77×10^{-9}
88	$3p^23d(^2D)$	^2F	(7/2)	123.235	–0.519	–0.573	122.143	121.92	4.33×10^{-6}
89	$3p3d^2(^3F)$	^4D	(7/2)	123.438	–0.525	–0.648	122.266	121.948	2.75×10^{-8}
90	$3p3d^2(^3F)$	^2G	(9/2)	123.848	–0.608	–0.648	122.592	122.278	3.83×10^{-1}
91	$3p3d^2(^1D)$	^2P	(3/2)	124.21	–0.481	–0.648	123.081	122.768	5.55×10^{-3}
92	$3p3d^2(^3P)$	^4D	(5/2)	124.439	–0.526	–0.648	123.265	122.953	1.23×10^{-3}
93	$3p^23d(^2D)$	^2D	(3/2)	124.583	–0.441	–0.574	123.569	123.346	2.85×10^{-9}
94	$3p^23d(^2D)$	^4D	(1/2)	126.334	–0.408	–0.647	125.278	124.978	1.98×10^{-1}
95	$3p^23d(^2D)$	^4F	(9/2)	127.571	–0.679	–0.574	126.318	126.112	2.75×10^{-9}
96	$3p^23d(^2D)$	^4D	(7/2)	127.6	–0.657	–0.571	126.372	126.162	6.13×10^{-5}
97	$3p^23d(^2D)$	^2P	(1/2)	128.598	–0.607	–0.572	127.419	127.202	1.48×10^{-7}
98	$3p^23d(^2D)$	^2D	(5/2)	129.828	–0.591	–0.574	128.663	128.446	1.49×10^{-10}
99	$3p^23d(^2D)$	^2P	(3/2)	130.745	–0.608	–0.572	129.565	129.329	9.46×10^{-4}
100	$3p^23d(^2D)$	^2F	(5/2)	130.973	–0.631	–0.574	129.768	129.555	3.18×10^{-10}
101	$3p3d^2(^3F)$	^4F	(3/2)	137.718	–0.493	–0.616	136.610	136.325	4.84×10^{-2}
102	$3p3d^2(^3F)$	^2F	(5/2)	138.323	–0.55	–0.616	137.157	136.864	2.73×10^{-3}
103	$3p3d^2(^3F)$	^4D	(1/2)	138.376	–0.507	–0.616	137.253	136.959	1.85×10^{-2}
104	$3p3d^2(^3F)$	^2G	(7/2)	138.475	–0.583	–0.616	137.276	136.987	4.13×10^{-9}
105	$3p3d^2(^3P)$	^4P	(3/2)	140.238	–0.481	–0.616	139.140	138.851	2.73×10^{-3}
106	$3p3d^2(^3F)$	^4G	(9/2)	142.705	–0.751	–0.616	141.338	141.071	3.20×10^{-6}
107	$3p3d^2(^3P)$	^4D	(7/2)	143.064	–0.716	–0.616	141.732	141.467	3.31×10^{-10}
108	$3p3d^2(^3P)$	^4P	(5/2)	143.871	–0.637	–0.616	142.618	142.2	5.42×10^{-5}
109	$3p3d^2(^1G)$	^2H	(11/2)	143.923	–0.841	–0.616	142.466	142.358	2.94×10^{-4}
110	$3p3d^2(^3P)$	^2S	(1/2)	143.993	–0.662	–0.616	142.715	142.451	1.71×10^{-2}
111	$3p3d^2(^3F)$	^4D	(3/2)	144.097	–0.667	–0.616	142.814	142.533	9.28×10^{-3}
112	$3p3d^2(^3F)$	^4D	(5/2)	144.156	–0.691	–0.616	142.849	142.566	2.02×10^{-1}
113	$3p3d^2(^1G)$	^2G	(7/2)	144.569	–0.754	–0.616	143.199	142.928	6.64×10^{-10}
114	$3p3d^2(^3F)$	^4F	(7/2)	145.483	–0.747	–0.616	144.120	143.831	1.81×10^{-9}
115	$3p\ 3d^2(^3P)$	^2D	(5/2)	145.687	–0.701	–0.616	144.370	144.074	2.37×10^{-4}
116	$3p3d^2(^1D)$	^2D	(3/2)	145.86	–0.672	–0.616	144.572	144.28	1.43×10^{-2}
117	$3p3d^2(^1G)$	^2G	(9/2)	146.057	–0.795	–0.616	144.646	144.357	1.03×10^{-5}
118	$3p3d^2(^3P)$	^2D	(3/2)	146.594	–0.636	–0.615	145.343	145.036	2.04×10^{-1}
119	$3p3d^2(^1G)$	^2F	(5/2)	147.007	–0.698	–0.615	145.693	145.382	5.34×10^{-4}
120	$3p3d^2(^3P)$	^2P	(1/2)	147.35	–0.63	–0.615	146.105	145.78	3.23×10^{-2}
121	$3p3d^2(^3F)$	^4G	(11/2)	148.913	–0.932	–0.616	147.366	147.111	1.81×10^{-5}
122	$3p3d^2(^1D)$	^2D	(5/2)	149.668	–0.843	–0.616	148.210	147.953	3.29×10^{-3}
123	$3p\ 3d^2(^1D)$	^2F	(7/2)	149.8	–0.859	–0.616	148.326	148.07	9.14×10^{-10}

Table 1. (*Continued*).

S. No.	Configuration	Term	J	MCDF				FAC	Lifetime
				DC	Breit	QED	Total		
124	$3p\ 3d^2(^3F)$	^4F	(9/2)	150.092	–0.918	–0.616	148.558	148.292	5.21×10^{-5}
125	$3p\ 3d^2(^1D)$	^2P	(1/2)	151.226	–0.818	–0.616	149.792	149.53	8.02
126	$3p\ 3d^2(^3F)$	^2F	(7/2)	152.437	–0.877	–0.616	150.944	150.653	6.02×10^{-9}
127	$3p\ 3d^2(^1S)$	^2P	(3/2)	152.455	–0.758	–0.615	151.082	150.823	7.53×10^{-3}
128	$3p\ 3d^2(^3F)$	^2D	(5/2)	152.609	–0.828	–0.615	151.166	150.869	3.51×10^{-3}
129	$3p3d^2(^3P)$	^2P	(3/2)	153.786	–0.791	–0.615	152.380	152.076	1.11×10^{-2}
130	$3d^3(^4F)$	^4F	(3/2)	154.601	–0.534	–0.657	153.410	152.998	6.38×10^{-7}
131	$3d^3(^4F)$	^4F	(5/2)	159.956	–0.721	–0.657	158.578	158.187	1.08×10^{-6}
132	$3d^3(^4P)$	^4P	(3/2)	160.502	–0.691	–0.657	159.154	158.76	5.31×10^{-5}
133	$3d^3(^2H)$	^2H	(9/2)	160.842	–0.85	–0.657	159.335	158.906	1.96×10^{-9}
134	$3d^3(^2G)$	^2G	(7/2)	160.86	–0.809	–0.657	159.393	158.979	6.02×10^{-3}
135	$3d^3(^4P)$	^4P	(1/2)	161.001	–0.713	–0.657	159.630	159.235	5.77×10^{-6}
136	$3d^3(^2_1D)$	^2D	(5/2)	162.903	–0.708	–0.657	161.538	161.12	8.65×10^{-6}
137	$3d^3(^4F)$	^4F	(7/2)	166.092	–0.919	–0.657	164.516	164.131	5.76×10^{-3}
138	$3d^3(^4F)$	^4F	(9/2)	166.505	–0.999	–0.657	164.849	164.451	4.82×10^{-10}
139	$3d^3(^2_3D)$	^2D	(3/2)	166.939	–0.85	–0.657	165.432	165.051	1.62×10^{-6}
140	$3d^3(^2P)$	^2P	(1/2)	167.24	–0.874	–0.657	165.709	165.15	6.84×10^{-5}
141	$3d^3(^2H)$	^2H	(11/2)	167.301	–0.875	–0.657	165.768	165.325	1.17×10^{-5}
142	$3d^3(^4P)$	^4P	(5/2)	167.303	–1.07	–0.657	165.578	165.377	8.09×10^{-9}
143	$3d^3(^2_3D)$	^2D	(5/2)	168.073	–0.91	–0.657	166.506	166.092	8.94×10^{-6}
144	$3d^3(^2F)$	^2F	(7/2)	168.123	–0.957	–0.657	166.509	166.102	1.27×10^{-2}
145	$3d^3(^2_1D)$	^2D	(3/2)	169.82	–0.826	–0.657	168.337	167.928	1.35×10^{-6}
146	$3d^3(^2G)$	^2G	(9/2)	172.631	–1.13	–0.657	170.840	170.459	1.39×10^{-9}
147	$3d^3(^4P)$	^2P	(3/2)	173.858	–1.03	–0.657	172.173	171.791	2.43×10^{-5}
148	$3d^3(^2F)$	^2F	(5/2)	174.712	–1.01	–0.657	173.049	172.666	5.25×10^{-7}

Table 2. Energy level (in Rydberg) for the lowest 40 levels compared with other available results.

S. No.	Configuration	Term	J	MCDF	FAC	NIST	Ref. [3]
1	$3s^2\ 3p$	$^2P^o$	(1/2)	0	0	0	0
2	$3s\ 3p^2(^3P)$	^4P	(1/2)	12.4556	12.3288	12.308	12.30181
3	$3s^2\ 3p$	$^2P^o$	(3/2)	26.7019	26.7411	26.731	26.70555
4	$3s3p^2(^3P)$	^4P	(3/2)	36.8867	36.8079	36.774	36.77895
5	$3s3p^2(^1D)$	^2D	(5/2)	38.2449	38.1613	38.11	38.11104
6	$3s3p^2(^1D)$	^2D	(3/2)	39.7977	39.7204	39.688	39.66374
7	$3s3p^2(^3P)$	^2P	(1/2)	40.5984	40.5014	40.424	40.40241
8	$3s^2\ 3d$	^2D	(3/2)	44.0223	43.9728	43.904	43.87753
9	$3s^2\ 3d$	^2D	(5/2)	49.3267	49.303	49.26	49.26256
10	$3p^3$	$^2P^o$	(3/2)	51.9247	51.7734		51.72698
11	$3s3p(^3P)\ 3d$	$^4F^o$	(3/2)	52.9380	52.7457		52.67461
12	$3s\ 3p(^3P)3d$	$^4F^o$	(5/2)	53.7833	53.6247		53.58168
13	$3s\ 3p(^3P)3d$	$^4D^o$	(1/2)	55.7705	55.6171		55.53234
14	$3s\ 3p(^3P)3d$	$^4D^o$	(3/2)	56.2795	56.1207		56.02196
15	$3s\ 3p(^3P)3d$	$^4P^o$	(5/2)	59.7935	59.6518		59.62401
16	$3s\ 3p(^3P)3d$	$^4F^o$	(7/2)	60.8569	60.7115		60.66112
17	$3s\ 3p(^3P)3d$	$^2F^o$	(5/2)	61.6267	61.4807		61.41766
18	$3s\ 3p(^3P)3d$	$^2D^o$	(3/2)	62.0089	61.8571		61.77733
19	$3s3p^2(^3P)$	^4P	(5/2)	64.5008	64.4575	64.37	64.37089
20	$3s3p^2(^3P)$	^2S	(1/2)	67.2946	67.2421	67.11	67.11562
21	$3p^23d$	$^4F^o$	(3/2)	67.8533	67.4099		67.48094
22	$3s3p^2$	^2P	(3/2)	67.7327	67.8118	67.48	67.49233
23	$3p^23d$	$^4F^o$	(5/2)	74.8695	74.5782		74.46962
24	$3p^3(^2D)$	$^2D^o$	(5/2)	78.1680	78.03		77.92897
25	$3p^3(^4S)$	$^4S^o$	(3/2)	78.5810	78.4271		78.28445
26	$3p^3(^2P)$	$^2P^o$	(1/2)	79.8149	79.673		79.53945
27	$3s\ 3p(^3P)3d$	$^4P^o$	(3/2)	80.5197	80.4059		80.31812
28	$3s\ 3p(^3P)3d$	$^4P^o$	(1/2)	80.6538	80.5357		80.44761
29	$3s\ 3p(^3P)3d$	$^4D^o$	(5/2)	80.8567	80.7327		80.62003
30	$3s\ 3p(^3P)3d$	$^4D^o$	(7/2)	81.0329	80.9224		80.82706
31	$3s\ 3p(^3P)3d$	$^2D^o$	(3/2)	83.1325	83.0127		82.88087
32	$3s\ 3p(^3P)3d$	$^2F^o$	(5/2)	84.1338	83.989		83.83087
33	$3s\ 3p(^3P)3d$	$^2P^o$	(1/2)	84.5394	84.4149		84.23565
34	$3s\ 3p(^3P)3d$	$^4F^o$	(9/2)	84.9810	84.8806		84.83937
35	$3s\ 3p(^3P)3d$	$^2D^o$	(5/2)	86.6934	86.5886		86.5119
36	$3s\ 3p(^3P)3d$	$^2F^o$	(7/2)	87.3493	87.2476		87.15599
37	$3s\ 3p(^3P)3d$	$^2P^o$	(3/2)	87.6032	87.4976		87.40303
38	$3s\ 3p(^1P)3d$	$^2F^o$	(7/2)	88.8049	88.6935		88.57227
39	$3s\ 3p(^3P)3d$	$^2P^o$	(1/2)	89.4975	89.3899		89.25992
40	$3s\ 3p(^1P)3d$	$^2P^o$	(3/2)	90.3022	90.1939		90.04998

In Table 1, we report many new spectral lines which have not been reported either experimentally or theoretically. Energy values for 13 fine structure levels were compiled by NIST. We present energy values for the fine structural levels belonging to $3s3d^2$, $3p3d^2$, and $3d^3$ configurations, which are reported for the first time. We also present new results for many levels belonging to $3p^3$, $3p^23d$, and 3s3p3d configurations.

In Table 2, we compare our calculated results for energy values from MCDF and FAC with the energy levels compiled by NIST, which are based on the data listed by Kramida.[19] The experimental energy values compiled by NIST were measured by some authors.[3,7,20–22] In Table 2, we also present the calculated values of Safronova.[3] For the levels belonging to $3s^23p$, $3p^23d$, and $3s^23d$ configurations, our calculated energy values with MCDF are in good agreement with the NIST values and other theoretical results.[3] For the level $3s3p^2$, our energy values calculated with MCDF agree well (error 0.2–1.1%) with NIST values. The disagreement between our calculated MCDF energies and FAC energies of the $3s3p^2$ level is about (0.06–0.23%) except for the level $3s3p^2$ ($^4P_{1/2}$) (level 2) for which both calculated results differ by 1%. Further, the calculated energies for the levels $3p^3$ and 3s3p3d by the MCDF method agree well with those calculated by FAC and Safronova.[3] The maximum disagreement between MCDF and FAC results for these levels is 0.36% while between MCDF and results of Safronova[3] is 0.49%. Further, the ordering of Safronova and our calculated results is the same. In our MCDF calculation, we include those configurations which can provide reliable energy levels and whose energy levels interact with other energy levels. Therefore, we conclude that our MCDF results agree well with other available experimental and theoretical results.

4. Radiative rates

In Table 3, we present the transition wavelengths (λ in Å), radiative rates (A_{ji} in s^{-1}, oscillator strengths (f_{ij}, dimensionless), and line strengths (S in a.u. (atomic units)), in length form only, for electric dipole (E1), electric quadrupole (E2), magnetic dipole (M1), and magnetic quadrupole (M2) transitions from the ground state ($3s^23p\ ^2P_{3/2}$) of Al-like W. To show the reliability of our results, in Table 4, we report the transition wavelengths for some levels and compare them with the available experimental and theoretical work. One can see from Table 4 that our transition wavelengths calculated with MCDF are in reasonable agreement with other theoretical and experimental results. For $3s^23p\ ^2P_{1/2}$–$3s3p^2\ ^4P_{1/2}$ transition, our results differ 1.1% from the experimental transition wavelength, while the theoretical results of Pütterich *et al.*[23] differ by 1.8% from experimental results. For all other transitions, our transition wavelength agrees within an error range of 0.02–0.4%. In addition, the mean ratio $\lambda_{\text{This work}}/\lambda_{\text{exp.}}$ is found to be 0.9943. This is a clear indication of the accuracy of our calculated results.

Table 3. Transition data for E1, E2, M1, and M2 transitions from $3s^23p\ ^2P_{3/2}$: levels and $2J$ for lower level i, upper level k, wavelength λ (in Å), line strength S (length form), oscillator strength f (length form), transition rate A_{ji} (length form) calculated using MCDF.

Level		λ/Å	A_{ji}/s^{-1}	f_{ij}	S_{ij}/a.u.	Type
i	k					
1	2	7.32×10^{1}	3.94×10^{10}	3.16×10^{-2}	1.52×10^{-2}	E1
1	3	3.41×10^{1}	2.18×10^{8}	7.62×10^{-5}	1.29	M1
1	3	3.41×10^{1}	6.27×10^{6}	2.19×10^{-6}	1.04×10^{-3}	E2
1	4	2.47×10^{1}	1.13×10^{10}	2.07×10^{-3}	3.36×10^{-4}	E1
1	4	2.47×10^{1}	2.14×10^{5}	3.91×10^{-8}	5.28×10^{-1}	M2
1	5	2.38×10^{1}	3.04×10^{5}	7.75×10^{-8}	9.38×10^{-1}	M2
1	6	2.29×10^{1}	6.63×10^{11}	1.04×10^{-1}	1.57×10^{-2}	E1
1	6	2.29×10^{1}	2.13×10^{4}	3.35×10^{-9}	3.60×10^{-2}	M2
1	7	2.24×10^{1}	2.83×10^{12}	2.14×10^{-1}	3.16×10^{-2}	E1
1	8	2.07×10^{1}	3.88×10^{12}	4.99×10^{-1}	6.79×10^{-2}	E1
1	8	2.07×10^{1}	1.57×10^{4}	2.01×10^{-9}	1.60×10^{-2}	M2
1	9	1.85×10^{1}	1.30×10^{5}	1.99×10^{-8}	1.12×10^{-1}	M2
1	10	1.76×10^{1}	1.51×10^{6}	1.40×10^{-7}	1.21×10^{-3}	M1
1	10	1.76×10^{1}	5.04×10^{7}	4.66×10^{-6}	3.00×10^{-4}	E2
1	11	1.72×10^{1}	2.95×10^{6}	2.62×10^{-7}	2.23×10^{-3}	M1
1	11	1.72×10^{1}	9.38×10^{6}	8.33×10^{-7}	5.06×10^{-5}	E2
1	12	1.69×10^{1}	9.74×10^{7}	1.26×10^{-5}	7.28×10^{-4}	E2
1	13	1.63×10^{1}	1.18×10^{5}	4.70×10^{-9}	3.80×10^{-5}	M1
1	14	1.62×10^{1}	2.27×10^{4}	1.78×10^{-9}	1.43×10^{-5}	M1
1	14	1.62×10^{1}	4.74×10^{7}	3.73×10^{-6}	1.89×10^{-4}	E2
1	15	1.52×10^{1}	4.27×10^{7}	4.46×10^{-6}	1.88×10^{-4}	E2
1	17	1.48×10^{1}	3.84×10^{8}	3.78×10^{-5}	1.46×10^{-3}	E2
1	18	1.47×10^{1}	1.92×10^{5}	1.24×10^{-8}	9.02×10^{-5}	M1
1	18	1.47×10^{1}	4.32×10^{8}	2.80×10^{-5}	1.06×10^{-3}	E2
1	19	1.41×10^{1}	1.14×10^{3}	1.03×10^{-10}	2.59×10^{-4}	M2
1	20	1.35×10^{1}	7.57×10^{9}	2.08×10^{-4}	1.85×10^{-5}	E1
1	21	1.34×10^{1}	2.86×10^{7}	1.55×10^{-6}	1.37×10^{-7}	E1
1	21	1.34×10^{1}	6.06×10^{3}	3.28×10^{-10}	7.10×10^{-4}	M2
1	22	1.35×10^{1}	2.30×10^{9}	1.25×10^{-4}	1.10×10^{-5}	E1
1	22	1.35×10^{1}	7.73×10^{3}	4.20×10^{-10}	9.14×10^{-4}	M2
1	23	1.22×10^{1}	8.37×10^{2}	5.58×10^{-11}	9.00×10^{-5}	M2
1	24	1.17×10^{1}	1.04×10^{7}	6.35×10^{-7}	1.20×10^{-5}	E2
1	25	1.16×10^{1}	7.50×10^{3}	3.03×10^{-10}	1.74×10^{-6}	M1
1	25	1.16×10^{1}	1.50×10^{7}	6.04×10^{-7}	1.12×10^{-5}	E2
1	26	1.14×10^{1}	6.57×10^{4}	1.28×10^{-9}	7.25×10^{-6}	M1
1	27	1.13×10^{1}	7.14×10^{5}	2.74×10^{-8}	1.53×10^{-4}	M1
1	27	1.13×10^{1}	3.86×10^{4}	1.48×10^{-9}	2.56×10^{-8}	E2
1	28	1.13×10^{1}	8.04×10^{5}	1.54×10^{-8}	8.60×10^{-5}	M1
1	29	1.13×10^{1}	1.97×10^{6}	1.13×10^{-7}	1.92×10^{-6}	E2
1	31	1.10×10^{1}	8.38×10^{4}	3.02×10^{-9}	1.64×10^{-5}	M1
1	31	1.10×10^{1}	4.53×10^{6}	1.63×10^{-7}	2.56×10^{-6}	E2
1	32	1.08×10^{1}	2.89×10^{4}	1.52×10^{-9}	2.31×10^{-8}	E2
1	33	1.08×10^{1}	2.62×10^{4}	4.57×10^{-10}	2.43×10^{-6}	M1
1	35	1.05×10^{1}	2.17×10^{5}	1.08×10^{-8}	1.49×10^{-7}	E2
1	37	1.04×10^{1}	8.39×10^{3}	2.72×10^{-10}	1.40×10^{-6}	M1
1	37	1.04×10^{1}	1.28×10^{6}	4.14×10^{-8}	5.55×10^{-7}	E2
1	39	1.02×10^{1}	7.82×10^{2}	1.22×10^{-11}	6.12×10^{-8}	M1
1	40	1.01×10^{1}	6.31×10^{5}	1.93×10^{-8}	9.61×10^{-5}	M1
1	40	1.01×10^{1}	3.14×10^{5}	9.59×10^{-9}	1.17×10^{-7}	E2
1	41	1.01×10^{1}	5.64×10^{6}	2.57×10^{-7}	3.13×10^{-6}	E2
1	42	9.86	1.90×10^{2}	8.31×10^{-12}	7.12×10^{-6}	M2
1	43	9.79	4.05×10^{8}	1.16×10^{-5}	7.50×10^{-7}	E1
1	43	9.79	4.41×10^{2}	1.27×10^{-11}	1.06×10^{-5}	M2
1	44	9.77	2.19×10^{8}	3.13×10^{-6}	2.01×10^{-7}	E1
1	46	9.56	3.66×10^{8}	1.00×10^{-5}	6.31×10^{-7}	E1
1	46	9.56	3.23×10^{3}	8.85×10^{-11}	6.91×10^{-5}	M2
1	47	9.55	3.56×10^{2}	1.46×10^{-11}	1.14×10^{-5}	M2
1	48	9.52	3.87×10^{6}	5.26×10^{-8}	3.30×10^{-9}	E1

Table 3. (*Continued*).

Level		λ/Å	A_{ji}/s^{-1}	f_{ij}	S_{ij}/a.u.	Type
i	*k*					
1	49	9.35	6.84×10^{5}	1.79×10^{-8}	1.10×10^{-9}	E1
1	49	9.35	7.50×10^{2}	1.97×10^{-11}	1.44×10^{-5}	M2
1	50	9.26	5.94×10^{3}	2.29×10^{-10}	1.63×10^{-4}	M2
1	53	9.12	5.73×10^{7}	7.15×10^{-7}	4.29×10^{-8}	E1
1	54	9.12	3.20×10^{7}	8.00×10^{-7}	4.80×10^{-8}	E1
1	54	9.12	3.30×10^{3}	8.23×10^{-11}	5.59×10^{-5}	M2
1	55	9.09	1.95×10^{3}	7.25×10^{-11}	4.88×10^{-5}	M2
1	57	9.00	3.85×10^{1}	1.40×10^{-12}	9.12×10^{-7}	M2
1	58	8.93	6.86×10^{9}	8.20×10^{-5}	4.82×10^{-6}	E1
1	59	8.90	9.48×10^{9}	2.25×10^{-4}	1.32×10^{-5}	E1
1	59	8.90	9.70	2.30×10^{-13}	1.46×10^{-7}	M2
1	61	8.81	7.85×10^{2}	2.74×10^{-11}	1.68×10^{-5}	M2
1	62	8.78	3.68×10^{8}	8.49×10^{-6}	4.91×10^{-7}	E1
1	62	8.78	8.89×10^{-1}	2.05×10^{-14}	1.24×10^{-8}	M2
1	64	8.67	1.88×10^{3}	6.37×10^{-11}	3.72×10^{-5}	M2
1	66	8.64	9.78×10^{9}	2.19×10^{-4}	1.25×10^{-5}	E1
1	66	8.64	1.79×10^{3}	4.01×10^{-11}	2.31×10^{-5}	M2
1	67	8.58	1.37×10^{10}	1.51×10^{-4}	8.54×10^{-6}	E1
1	68	8.51	7.53×10^{2}	1.64×10^{-11}	6.88×10^{-8}	M1
1	68	8.51	4.81	1.04×10^{-13}	7.67×10^{-13}	E2
1	69	8.44	2.85×10^{6}	9.11×10^{-8}	6.51×10^{-7}	E2
1	71	8.26	8.97×10^{2}	2.75×10^{-11}	1.39×10^{-5}	M2
1	72	8.19	1.34×10^{2}	1.35×10^{-12}	5.46×10^{-9}	M1
1	73	8.19	9.05×10^{2}	1.82×10^{-11}	7.37×10^{-8}	M1
1	73	8.19	2.13×10^{6}	4.30×10^{-8}	2.81×10^{-7}	E2
1	75	8.18	3.83×10^{7}	7.68×10^{-7}	4.14×10^{-8}	E1
1	75	8.18	5.27×10^{3}	1.06×10^{-10}	5.17×10^{-5}	M2
1	76	8.08	5.52×10^{8}	5.40×10^{-6}	2.87×10^{-7}	E1
1	78	7.93	6.40×10^{5}	1.81×10^{-8}	1.07×10^{-7}	E2
1	79	7.89	2.92×10^{3}	5.46×10^{-11}	2.13×10^{-7}	M1
1	79	7.89	8.38×10^{5}	1.57×10^{-8}	9.16×10^{-8}	E2
1	80	7.88	1.33×10^{4}	1.24×10^{-10}	4.82×10^{-7}	M1
1	82	7.75	3.66×10^{5}	9.89×10^{-9}	5.48×10^{-8}	E2
1	84	7.70	1.96×10^{4}	3.47×10^{-10}	1.32×10^{-6}	M1
1	84	7.70	5.10×10^{5}	9.06×10^{-9}	4.92×10^{-8}	E2
1	85	7.51	2.86×10^{7}	4.84×10^{-7}	2.39×10^{-8}	E1
1	85	7.51	8.27	1.40×10^{-13}	5.32×10^{-8}	M2
1	86	7.48	7.45×10^{1}	1.87×10^{-12}	7.02×10^{-7}	M2
1	87	7.47	2.10×10^{8}	1.76×10^{-6}	8.63×10^{-8}	E1
1	91	7.40	1.80×10^{2}	2.96×10^{-12}	1.08×10^{-8}	M1
1	91	7.40	5.51×10^{6}	9.05×10^{-8}	4.38×10^{-7}	E2
1	92	7.39	5.48×10^{6}	1.35×10^{-7}	6.48×10^{-7}	E2
1	93	7.37	3.51×10^{8}	5.72×10^{-6}	2.78×10^{-7}	E1
1	93	7.37	8.76×10^{-1}	1.43×10^{-14}	5.13×10^{-9}	M2
1	94	7.27	5.05	4.01×10^{-14}	1.44×10^{-10}	M1
1	97	7.15	6.75×10^{6}	5.17×10^{-8}	2.44×10^{-9}	E1
1	98	7.08	2.38	5.36×10^{-14}	1.70×10^{-8}	M2
1	99	7.03	1.06×10^{3}	1.57×10^{-11}	7.26×10^{-13}	E1
1	99	7.03	4.78×10^{1}	7.09×10^{-13}	2.21×10^{-7}	M2
1	100	7.02	2.98×10^{1}	6.62×10^{-13}	2.05×10^{-7}	M2
1	101	6.67	2.06×10^{1}	2.75×10^{-13}	9.09×10^{-10}	M1
1	101	6.67	6.66×10^{3}	8.88×10^{-11}	3.14×10^{-10}	E2
1	102	6.64	2.60×10^{4}	5.15×10^{-10}	1.80×10^{-9}	E2
1	103	6.64	5.41×10^{1}	3.58×10^{-13}	1.17×10^{-9}	M1
1	105	6.55	3.66×10^{2}	4.70×10^{-12}	1.52×10^{-8}	M1
1	105	6.55	4.97×10^{3}	6.40×10^{-11}	2.14×10^{-10}	E2
1	108	6.39	4.51×10^{2}	8.29×10^{-12}	2.58×10^{-11}	E2
1	110	6.39	5.83×10^{1}	3.57×10^{-13}	1.13×10^{-9}	M1
1	111	6.38	1.08×10^{2}	1.32×10^{-12}	4.15×10^{-9}	M1

Table 3. (*Continued*).

Level		λ/Å	A_{ji}/s^{-1}	f_{ij}	S_{ij}/a.u.	Type
i	*k*					
1	111	6.38	1.35×10^{4}	1.65×10^{-10}	5.10×10^{-10}	E2
1	112	6.38	9.51×10^{3}	1.74×10^{-10}	5.38×10^{-10}	E2
1	115	6.31	1.33×10^{5}	2.38×10^{-9}	7.13×10^{-9}	E2
1	116	6.30	7.02×10^{1}	8.36×10^{-13}	2.61×10^{-9}	M1
1	116	6.30	8.53×10^{4}	1.02×10^{-9}	3.03×10^{-9}	E2
1	118	6.27	4.90	5.77×10^{-14}	1.79×10^{-10}	M1
1	118	6.27	9.85×10^{4}	1.16×10^{-9}	3.41×10^{-9}	E2
1	119	6.25	5.52×10^{4}	9.72×10^{-10}	2.83×10^{-9}	E2
1	120	6.24	3.10×10^{1}	1.81×10^{-13}	5.57×10^{-10}	M1
1	122	6.15	1.04×10^{4}	1.77×10^{-10}	4.91×10^{-10}	E2
1	125	6.08	1.25×10^{-1}	6.92E-16	2.08×10^{-12}	M1
1	127	6.03	1.33×10^{2}	1.45×10^{-12}	4.32×10^{-9}	M1
1	127	6.03	7.09×10^{2}	7.74×10^{-12}	2.02×10^{-11}	E2
1	128	6.03	1.19×10^{4}	1.94×10^{-10}	5.07×10^{-10}	E2
1	129	5.98	9.02×10^{1}	9.68×10^{-13}	2.86×10^{-9}	M1
1	129	5.98	2.07×10^{4}	2.22×10^{-10}	5.65×10^{-10}	E2
1	130	5.94	1.57×10^{6}	1.66×10^{-8}	6.49×10^{-10}	E1
1	130	5.94	1.67×10^{1}	1.77×10^{-13}	3.32×10^{-8}	M2
1	131	5.75	5.33	7.92×10^{-14}	1.34×10^{-8}	M2
1	132	5.73	1.88×10^{4}	1.85×10^{-10}	6.97×10^{-12}	E1
1	132	5.73	3.40	3.34×10^{-14}	5.62×10^{-9}	M2
1	135	5.71	1.73×10^{5}	8.46×10^{-10}	3.18×10^{-11}	E1
1	136	5.64	2.01	2.87×10^{-14}	4.62×10^{-9}	M2
1	139	5.51	6.17×10^{5}	5.61×10^{-9}	2.04×10^{-10}	E1
1	139	5.51	5.61×10^{1}	5.10×10^{-13}	7.63×10^{-8}	M2
1	140	5.50	1.46×10^{4}	6.63×10^{-11}	2.40×10^{-12}	E1
1	141	5.50	4.11	5.59×10^{-14}	8.31×10^{-9}	M2
1	143	5.47	1.12×10^{2}	1.51×10^{-12}	2.21×10^{-7}	M2
1	145	5.41	7.40×10^{5}	6.50×10^{-9}	2.32×10^{-10}	E1
1	145	5.41	6.60	5.80×10^{-14}	8.23×10^{-9}	M2
1	147	5.29	4.11×10^{4}	3.46×10^{-10}	1.20×10^{-11}	E1
1	147	5.29	2.50	2.10×10^{-14}	2.79×10^{-9}	M2
1	148	5.27	1.20	1.50×10^{-14}	1.96×10^{-9}	M2

Table 4. Comparison of computed wavelengths (in Å) from different theories with observed wavelengths for transitions from $3s^23p\ ^2P_{1/2}$ to selected upper levels.

Upper	$2J_i$	$2J_k$	This work (MCDF)	Experimental	Other theory
$3s3p^2\ ^4P_{1/2}$	1	1	73.20	74.04[a]	72.687[b]
					73.95[a]
					74.08[e]
$3s^23p\ ^2P_{3/2}$	1	3	34.10	34.110[c]	34.08[d]
					34.123[e]
$3s^23d\ ^2D_{3/2}$	1	3	20.700	20.756[f]	20.721[f]
$3s3p^2\ ^2P_{1/2}$	1	1	22.446	22.543[f]	22.506[f]
$3s3p^2\ ^2P_{3/2}$			22.898	22.961[f]	22.950[f]
$3s3p^2\ ^4P_{3/2}$			24.705	24.78[f]	24.77[f]

[a]Ralchenko;[7] [b]Pütterich;[23] [c]Lennartsson;[24] [d]Quinet;[10] [e]Safronova;[3] [f]Clementson.[22]

In Table 5, we compare our calculated transition probabilities for some transitions with other theoretical results. For $3s^23p\ ^2P_{1/2}$–$3s3p^2\ ^4P_{1/2}$ transition, the results of Pütterich *et al.*[23] differ by an order of magnitude from the results of Ralchenko *et al.*[7] as well as other theoretical results. Our calculated transition probability agrees well (within 1%) with Ralchenko *et al.*[7] for the $3s^23p\ ^2P_{1/2}$–$3s3p^2\ ^4P_{1/2}$ transition.

The A-value calculated by Quinet[10] differs by an order of magnitude with all available theoretical results. From Table 5, it can be seen that our calculated value of transition probabilities are in good agreement with the other available results for all transitions.

Table 5. Comparison of computed transition probabilities (in s^{-1}) from different theories for transitions from $3s^23p\ ^2P_{1/2}$ to selected upper levels.

Upper	$2J_i$	$2J_k$	This work (MCDF)	Other theory
$3s3p^2\ ^4P_{1/2}$	1	1	3.94×10^{10}	3.5×10^{10} [b]
				3.88×10^{10} [a]
$3s^23p\ ^2P_{3/2}$	1	3	2.18×10^{8}	2.85×10^{8} [d]
				2.24×10^{8} [c]
				2.13×10^{8} [e]

[a]Ralchenko;[7] [b]Pütterich;[23] [c]Huang;[4] [d]Quinet;[10] [e]Charro.[25]

Our calculated oscillator strength using MCDF for some transitions with other theoretical results are compared in Table 6. For the transition $3s^23p\ ^2P_{1/2}$–$3s^23d\ ^2D_{3/2}$, we compare our results with the results of Lavin *et al.*[6] who calculated f-values using three different approaches (QDO, RQDO, and MCDF-EAL). From Table 6, it can be seen that our MCDF f-values for the $3s^23p\ ^2P_{1/2}$–$3s^23d\ ^2D_{3/2}$ transition is in close agreement with their MCDF-EAL results.[6] For the $3s^23p\ ^2P_{1/2}$–$3s^23p\ ^2P_{3/2}$ transition, the maximum disagreement between our calculated f-value and the other available f-value is about 5%. It shows that our results are quite reliable.

Table 6. Comparison of computed oscillator strengths from different theories for transitions from $3s^23p\ ^2P_{1/2}$ to selected upper levels.

Upper	$2J_i$	$2J_k$	This work (MCDF)	Other theory
$3s^23d\ ^2D_{3/2}$	1	1	4.99×10^{-1}	1.75×10^{-1} [a1]
				2.57×10^{-1} [a2]
				4.84×10^{-1} [a3]
$3s^23p\ ^2P_{3/2}$	1	3	7.62×10^{-5}	7.219×10^{-5} [b]
				7.603×10^{-5} [c]

[a1]Lavin using QDO;[6] [a2]Lavin using RQDO;[6]

[a3]Lavin using MCDF-EAL;[6] [b]Charro;[25] [c]Huang.[4]

5. Lifetimes

The lifetime (τ) for a level j is defined as

$$\tau_j = \frac{1}{\sum_i A_{ji}}. \tag{10}$$

Calculations for transition probabilities have become advanced and require relativistic effects to be included. All possible E1 (electric dipole), E2 (electric quadrupole), M1 (magnetic dipole), and M2 (magnetic quadrupole) transitions are computed from which the lifetimes of levels have been determined. To the best of our knowledge, no calculations or measurements are available in the literature for lifetimes in Al-like tungsten. We hope that our calculated values of lifetimes will be beneficial to experimentalists in their future work.

6. Conclusion

In this paper, we have presented the energies of $3s^23p$, $3s^23d$, $3s3p^2$, $3s3d^2$, $3s3p3d$, $3p^23d$, $3s3d^2$, $3p3d^2$, $3p^3$, and $3d^3$ configurations of Al-like tungsten ion (W XLVII) levels and E1, E2, M1, and M2 transitions from the ground state by taking into account the various checks for accuracy of wavefunctions. We have also estimated the lifetimes of all excited levels. Our results may be useful for plasma physicists for interpretation of spectra emitted by plasmas produced in fusion reactors.

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