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E1, E2 and M1 transitions between n=3 levels in magnesium-like tungsten

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Abstract

Electric dipole (E1) transitions of 3s-3p and 3p-3d, and electric quadrupole (E2) and magnetic dipole (M1) transitions between fine structure levels of 3s3p and $3p^2$ in Mg-like tungsten (W^{62+}) have been studied by multiconfiguration Hartree-Fock (MCHF) method. Multielectron ions of high-Z elements are of interest in atomic structure theory. In this work Breit-Pauli relativistic contributions and correlation effects have been considered. The magnesium-like tungsten lines obtained from this work are compared with other theoretical and experimental results.

Keywords: MCHF method; allowed and forbidden transitions; transition rates; wavelengths

1. Introduction

Highly charged ions (HCI) are of interest in atomic physics, astrophysics, and high-temperature plasma diagnostics (Podpaly et al. 2009). Since tungsten is a high-Z element, it is a promising material in future magnetic confinement fusion reactors such as the ITER (Aymar et al. 2002). Tungsten's desirable properties are low hydrogen retention, high melting point, and high thermal conductivity.

Multielectron ions of high-Z elements are important in atomic structure theory. Magnesium like ions which have only a few valence electrons outside the closed shell are useful for testing QED calculations in multielectron systems. Accurate atomic data for Mg-like tungsten have been recently presented in literature. The results of MCDF and relativistic configuration interaction calculations for some tungsten ions were presented by Hu et al. (2011).

Safronova and co-workers (2000, 2009, 2010) reported the results from various calculations using the relativistic many-body perturbation theory (RMBPT code), the Hartree-Fock–relativistic method (Cowan code), multiconfiguration Dirac-Fock theory (MCDF code) and the multiconfiguration relativistic Hebrew University Lawrence Atomic Code (HULLAC code) for some Mg-like ions. Zou and Fischer (2001) calculated the forbidden transitions between ground states and first excited levels for some Mg-like ions using the multiconfiguration Hartree-Fock-Dirac (MCDHF) method. Curtis (1989) presented a semiempirical work on E1 and M1 transitions for He, Mg, Ne, Si and S isoelectronic sequences. Wavelength measurements of n=3 to n=3 transitions in highly charged tungsten ions were given by Clementson and Beiersdorfer (2010). The works on fusion plasmas including tungsten ions published by Clementson (2010), Biedermann et al. (2009), and Kramida and Shirai (2009) presented the energy levels and spectral lines of tungsten ions (W III-WLXXIV). And, Ralchenko et al. (2008) reported EUV spectra of highly-charged tungsten ions. Other previous works including calculations and measurements on Mg-like tungsten can be found in NIST (2014).

The present work focuses on the wavelengths and transition probabilities between n=3 levels in Mg-like tungsten (W^{62+}) using the MCHF atomic code (Fischer, 2000) based on multiconfiguration Hartree-Fock method (MCHF) (Fischer et al. 1997) developed by Fischer. Atomic radiative transition (especially, E1, E2 and M1) is one of the fundamental processes in plasmas. The numerical simulation of atomic kinetics in laboratory as well as astrophysical plasmas requires accurate radiative transition rates (or probabilities) (Zou and Fischer, 2001). Although the atomic kinetics depends on, in particular, optical allowed transitions (E1) the weak forbidden transitions (E2 and M1) are of great interest for the plasma diagnostics since the photons from such transitions may carry information from large optical depths within the plasma (Hu et al. 2011). The ground state configuration of Mg-like

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tungsten (Z=74) is [Ne] $3s^2$. The correlation and relativistic effects are important atomic systems, in particular for heavy atoms and ions. The consideration of both intervalence (valence-valence) and core-valence correlation is very important for atomic structure calculations, in particular multiply ionized system. In this work we have investigated the intervalence correlation where one or two valence orbitals are only excited, and core-valence correlation where one core orbital, here 2p core orbital, and one valence orbital are excited. Also calculations include the Breit-Pauli relativistic corrections. In the MCHF method in the framework of the Breit-Pauli Hamiltonian the relativistic effects captures the spin-orbit, spin-other-orbit, spin-spin contact, orbit-orbit interactions, and mass and Darwin corrections (one- and two- body). These relativistic corrections are included as first-order correction to the MCHF approximation. Hence, we selected the configurations of $2p^63s^2$, $2p^63s3d$, $2p^63s4s$, $2p^63s4d$, $2p^63s5s$, $2p^63s6s$, $2p^63p^2$, $2p^63p4p$, $2p^63p4f$, $2p^63d^2$, $2p^53s^23p$, $2p^53s^24p$, $2p^53s^25p$, $2p^53s3p3d$, $2p^53s3p4s$, $2p^53s3p5s$, $2p^53s3d4p$, and $2p^53p^3$ for even-parity; and $2p^53p^3$, $2p^63s3p$, $2p^63s4p$, $2p^63s4f$, $2p^63s5p$, $2p^63p3d$, $2p^63p4s$, $2p^53s3p^2$, $2p^53s^23d$, $2p^53p^23d$, $2p^53d^3$, $2p^53s3d^2$, and $2p^53s3d4s$ for odd-parity, outside $1s^22s^2$ core, for considering correlation effects.

2. Calculation method

Detailed information on the multiconfiguration Hartree-Fock method (MCHF) can be found in (Fischer et al. 1997). In this method the Hamiltonian *H* may be a non-relativistic Hamiltonian or a low-order relativistic Breit–Pauli Hamiltonian. The resulting wavefunctions are atomic state functions (ASFs). ASFs are expansions in terms of configuration state functions (CSFs). The coefficients of the CSFs in the expansion are obtained from a variational solution of the wave equation in terms of the basis of CSFs. The multiconfiguration Hartree–Fock (MCHF) method varies some or all the radial functions defining the CSFs. When the non-relativistic MCHF method is used to obtain radial functions, a subsequent configuration interaction calculation in terms of the Breit–Pauli Hamiltonian is performed in order to include relativistic effects in *LSJ* coupling. The total energies are eigenvalues of an interaction matrix and the associated eigenvector defines the wave function expansion.

Radiative properties of atoms are described on electromagnetic transition between two states, characterized by the angular momentum and parity of the corresponding photon. If the emitted or absorbed photon has angular momentum k and parity $\pi = (-1)^k$, then the transition is an electric multipole transition (Ek). However, if the photon has parity $\pi = (-1)^{k+1}$ the transition is a magnetic multipole transition (Mk). Once initial and final state functions have been calculated, the radiative matrix element for radiative properties computation can be obtained from

$$O_{if} = \langle \psi(i) | \boldsymbol{O}^{(1)} | \psi(f) \rangle \quad (1)$$

where $\boldsymbol{O}^{(1)}$ is either the electric dipole interaction for allowed transition (E1) or the electric quadrupole or magnetic dipole interaction for forbidden transition (E2 and M1). For spontaneous emissions, transition probability (or transition rate) from an upper state to a lower state is defined as

$$A^{\pi k}(\gamma' J', \gamma J) = 2C_k \left[\alpha (E_{\gamma' J'} - E_{\gamma J}\right]^{2k+1} \frac{S^{\pi k}(\gamma J, \gamma' J')}{g_{J'}} \quad (2)$$

where $g_{J'}$, is the statistical weight of the upper level $g_{J'} = 2J' + 1$, α is fine-structure constant(α=1/137), $C_k = \frac{(2k+1)(k+1)}{k((2k+1)!!)^2}$ and $S^{\pi k}$ line strengths, $|\langle \gamma J | O^{\pi k} | \gamma' J' \rangle|^2$.

3. Results and Discussion

In this work, the calculations of wavelengths, λ(in Å), and transition rates (or probabilities), A_{ki} (in s^{-1}), have been obtained for electric dipole (E1) of 3s-3p and 3p-3d, and electric quadrupole (E2) and magnetic dipole(M1) between fine structure levels of 3s3p and $3p^2$ according to selected configurations of $2p^63s^2$, $2p^63s3d$, $2p^63s4s$, $2p^63s4d$, $2p^63s5s$, $2p^63s6s$, $2p^63p^2$, $2p^63p4p$, $2p^63p4f$, $2p^63d^2$, $2p^53s^23p$, $2p^53s^24p$, $2p^53s^25p$, $2p^53s3p3d$, $2p^53s3p4s$, $2p^53s3p5s$, $2p^53s3d4p$, and $2p^53p^3$ for even-parity; and $2p^53p^3$, $2p^63s3p$, $2p^63s4p$, $2p^63s4f$, $2p^63s5p$, $2p^63p3d$, $2p^63p4s$ $2p^53s3p^2$, $2p^53s^23d$, $2p^53p^23d$, $2p^53d^3$, $2p^53s3d^2$, and $2p^53s3d4s$ for odd-parity. We have here used the MCHF atomic code (Fischer, 2000) for calculations.

Atomic radiative transitions are important, especially in plasmas and astrophysics. The largest transition probability (or rates) is general, for electric dipole (E1) radiation, dominated by the least factor $1/\alpha^2$ over other types of transitions (E2, E3, M1, M2, etc.). Therefore E1 transitions are referred 'allowed' whereas higher order electric and all magnetic transitions are called as 'forbidden'. Hence, M1 and E2 transition probabilities are of several orders of magnitude smaller than those for E1 transitions with a similar-energy level separation Generally, lowest-order metastable levels relatively decay correspond to M1 and E2 transitions

(Trabert, 2000). We have presented the electric dipole transitions (E1) of 3s-3p and 3p-3d in Table 1. In addition, we have also reported electric quadrupole (E2) and magnetic dipole (M1) transitions between fine structure levels of 3s3p and $3p^2$ levels in Table 2. In the tables, the number in brackets represents the power of 10. However, only odd-parity states are indicated by "o" superscript, and the core $1s^22s^22p^6$ is omitted in tables. References for other comparison values are typed below the table with a superscript lowercase letter. The results include correlation effects and Breit-Pauli relativistic effects. Our MCHF results are in agreement with other available works, in generally. In Table 2, we have given only transition probabilities larger than 10^{-1} s^{-1}. There is little data on E1 and, especially E2 and M1 for magnesium-like tungsten in literature. We had studied level energies and transition parameters for W^{62+} using different configuration sets and atomic code (Özdemir et al., 2013).

In conclusion, the main purpose of this work was to perform MCHF calculations including correlation and Breit-Pauli relativistic corrections for obtaining a description of highly ionized tungsten (W^{62+}). Accurate atomic data including information on atomic transitions for large range of charge states of tungsten are needed to develop diagnostics for measuring tungsten concentration in fusion plasmas and to provide support for modeling. In particular, the accurate transition rates are also required for astrophysical plasmas. Consequently, we hope that our results obtained using the MCHF method will be useful for research in these fields and other works in the future for magnesium-like tungsten.

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Table 1. Transition probabilities, A_{ki} (s^{-1}), wavelengths, $\lambda(\text{Å})$, of allowed lines (E1) in W^{62+} calculated using the MCHF code. In table, a(b) denotes ax10^b. U and L indicate upper and lower level, respectively

Transitions		A_{ki} [s^{-1}]		λ[Å]	
U	L	This work	Other works	This work	Other works
$3s3p\ ^3P^o_1$	$3s^2\ ^1S_0$	5.47(10)	1.80(10) [B], 2.67(10) [C], 2.14(10) [D] 1.82(10) [E], 1.81(10)[H], 1.89(10)[K]	55.98	79.86 [B], 78.89 [C], 78.73 [D], 79.90 [E] 79.91[G], 79.94 [H], 79.497 [K]
$3p^2\ ^3P_0$	$3s3p\ ^3P^o_1$	2.76(11)	1.28(11) [A], 1.50(11) [K]	54.20	69.665[A], 67.034 [K]
$3s3p\ ^1P^o_1$	$3s^2\ ^1S_0$	2.39(12)	2.57(12) [A,B], 3.28(12) [C], 2.59(12)[D] 2.55(12) [H], 2.58(12) [K]	23.56	22.712 [A], 22.71 [B], 22.65 [C], 22.73 [D] 22.80 [G], 22.74 [H], 22.714 [K]
$3p^2\ ^1D_2$	$3s3p\ ^3P^o_1$	1.30(12)	4.72(11) [A], 4.76(11) [K]	24.87	23.347 [A], 23.214 [K]
$3p^2\ ^1D_2$	$3s3p\ ^3P^o_2$	1.82(10)	3.17(10) [B], 3.61(10) [C], 3.57(10) [D,K]	53.71	69.87 [B], 69.07 [C], 69.17 [D], 68.190 [K]
$3p^2\ ^1D_2$	$3s3p\ ^1P^o_1$	3.98(09)	9.01(09) [K]	64.00	85.987 [K]
$3p^2\ ^3P_1$	$3s3p\ ^3P^o_0$	9.63(11)	1.20(12) [A,B], 1.29(12) [C], 1.27(12)[D] 1.24(12)[K]	24.81	22.599 [A], 22.60 [B], 22.54 [C] 22.52 [D], 22.436 [K]
$3p^2\ ^3P_1$	$3s3p\ ^3P^o_1$	4.83(11)	6.50(11) [A,B], 5.90(11) [C], 6.39(11) [D] 6.53(11) [K]	25.60	23.260 [A,B], 23.23 [C], 23.15 [D] 23.122 [K]
$3p^2\ ^3P_1$	$3s3p\ ^3P^o_2$	9.12(10)	5.50(10) [K]	57.23	67.394 [K]
$3p^2\ ^3P_1$	$3s3p\ ^1P^o_1$	7.75(09)	4.45(09) [K]	69.06	84.724 [K]
$3s3d\ ^3D_1$	$3s3p\ ^3P^o_0$	5.36(11)	1.09(12) [A,B], 1.16(12) [C], 1.05(12) [D] 1.11(12) [K]	26.38	21.275 [A], 21.28[B], 21.25 [C] 21.63 [D], 21.246 [K]
$3s3d\ ^3D_1$	$3s3p\ ^3P^o_1$	2.81(11)	5.03(11) [A,B], 4.62(11) [C], 5.30(11) [D] 5.29(11) [K]	27.27	21.860 [A,B], 21.86 [C], 22.21 [D] 21.860 [K]
$3s3d\ ^3D_1$	$3s3p\ ^3P^o_2$	1.83(09)	2.31(09) [K]	66.35	57.688 [K]
$3s3d\ ^3D_1$	$3s3p\ ^1P^o_1$	3.16(09)	5.34(09) [K]	82.79	69.932 [K]
$3s3d\ ^3D_2$	$3s3p\ ^3P^o_1$	3.68(11)	2.73(12) [A,B], 2.81(12) [C], 2.82(12) [D] 2.78(12) [K]	27.27	21.375 [A], 21.38 [B], 21.34 [C] 21.69 [D], 21.337 [K]
$3s3d\ ^3D_2$	$3s3p\ ^3P^o_2$	1.64(10)	8.67(08) [K]	66.35	54.185 [K]
$3s3d\ ^3D_3$	$3s3p\ ^3P^o_2$	2.31(11)	2.48(11) [A,B], 2.52(11) [C], 2.33(11) [D] 2.60(11) [K]	42.61	41.775 [A], 41.78 [B], 41.58 [C], 42.97 [D] 41.163 [K]
$3s3d\ ^1D_2$	$3s3p\ ^3P^o_1$	6.12(11)	2.15(11) [A], 2.08(11) [K]	21.72	18.566 [A], 18.462 [K]
$3s3d\ ^1D_2$	$3s3p\ ^3P^o_2$	1.21(11)	7.32(10) [B], 7.89(10) [C], 6.73(10) [D] 7.82(10) [K]	40.92	39.46 [B], 39.26 [C], 40.73 [D], 38.827 [K]
$3s3d\ ^1D_2$	$3s3p\ ^1P^o_1$	2.45(11)	2.02(11) [A], 2.13(11) [K]	46.63	44.735 [A], ,44.013 [K]
$3p3d\ ^3F^o_2$	$3p^2\ ^1D_2$	2.22(09)	3.22(10) [K]	69.81	63.159 [K]
$3p3d\ ^3F^o_2$	$3s3d\ ^3D_1$	6.65(10)	2.53(10) [K]	55.95	75.969 [K]
$3p3d\ ^3F^o_2$	$3s3d\ ^3D_2$	7.53(10)	9.75(09) [K]	55.95	83.039 [K]
$3p3d\ ^3D^o_1$	$3s^2\ ^1S_0$	2.54(09)	7.02(07) [K]	13.29	13.473 [K]
$3p3d\ ^3D^o_1$	$3p^2\ ^3P_0$	1.38(12)	2.25(12) [K]	25.69	21.400 [K]
$3p3d\ ^3D^o_1$	$3p^2\ ^1D_2$	1.32(10)	5.20(09) [K]	58.29	53.849 [K]
$3p3d\ ^3D^o_1$	$3p^2\ ^3P_1$	1.85(10)	1.32(12) [A], 1.59(10) [B], 1.57(10) [C] 1.37(10) [D], 1.83(10) [K]	54.64	21.471 [A], 56.57 [B], 56.08[C], 59.68 [D] 54.357[K]
$3p3d\ ^3D^o_1$	$3s3d\ ^3D_1$	3.69(10)	1.49(12) [A], 1.55(10) [K]	48.30	22.819 [A], 62.891 [K]
$3p3d\ ^3D^o_1$	$3s3d\ ^3D_2$	1.51(11)	5.22(11) [A], 6.10(10) [K]	48.30	23.372[A], 67.660 [K]
$3p3d\ ^3D^o_1$	$3s3d\ ^1D_2$	1.74(09)	2.82(08) [K]	88.21	133.697 [K]
$3p3d\ ^3P^o_2$	$3p^2\ ^1D_2$	6.43(10)	1.45(12) [A], 3.87(10) [K]	22.87	21.794 [A], 41.341 [K]
$3p3d\ ^3P^o_2$	$3p^2\ ^3P_1$	2.16(11)	7.20(11) [A], 2.08(11) [B], 2.22(11) [C] 1.94(11) [D], 2.33(11) [K]	43.59	21.871 [A], 43.23 [B], 43.12 [C] 44.62 [D], 41.639 [K]
$3p3d\ ^3P^o_2$	$3s3d\ ^3D_1$	1.21(10)	8.76(11) [A], 4.44(06) [K]	21.15	23.272 [A], 46.470 [K]
$3p3d\ ^3P^o_2$	$3s3d\ ^3D_2$	2.64(10)	2.57(11) [A], 7.12(09) [K]	39.46	23.848[A], 49.023 [K]
$3p3d\ ^3P^o_2$	$3s3d\ ^3D_3$	8.85(10)	4.20(10) [B], 4.33(10) [C], 4.70(10) [D] 4.31(11)[&],4.39(11)[+],4.33(11)[*],5.56(10)[K]	59.02	73.16 [B],72.62 [C], 72.49 [D], 23.25[&] 23.23 [+], 23.20 [*], 68.679 [K]
$3p3d\ ^3P^o_2$	$3s3d\ ^1D_2$	5.75(09)	8.35(09) [K]	62.60	76.346 [K]
$3p3d\ ^3F^o_3$	$3p^2\ ^1D_2$	2.04(10)	1.45(11) [A], 3.58(11) [B], 3.79(11) [C] 2.94(11) [D], 1.62(11) [K]	25.83	42.491 [A], 21.41 [B], 21.36 [C] 21.75 [D], 40.835 [K]

3p3d $^3F^o_3$	3s3d $^3D_2$	3.79(10)	1.82(09) [K]	39.14	48.313 [K]
3p3d $^3F^o_3$	3s3d $^3D_3$	4.00(10)	2.52(10) [B], 2.62(10) [C], 2.82(10) [D] 3.16(10)[&], 3.20(10)[+], 2.72(10) [*], 3.35(10) [K]	29.54	71.90 [B],70.98 [C], 71.13 [D], 26.97[&] 26.85 [+],26.91 [*], 67.294 [K]
3p3d $^3F^o_3$	3s3d $^1D_2$	1.01(11)	3.92(10) [K]	61.79	74.637 [K]
3p^2 $^3P_2$	3s3p $^3P^o_1$	5.44(09)	1.66(08) [K]	16.41	13.630 [K]
3p^2 $^3P_2$	3s3p $^3P^o_2$	1.26(12)	1.82(12) [A], 1.83(12) [K]	25.43	22.303 [A], 22.244 [K]
3p^2 $^3P_2$	3s3p $^1P^o_1$	1.19(12)	1.84(12) [A], 1.86(12) [K]	27.52	23.895 [A], 23.854 [K]
3p^2 $^3P_2$	3p3d $^3P^o_2$	1.63(11)	7.93(06) [K]	43.45	163.875 [K]
3p^2 $^1S_0$	3s3p $^3P^o_1$	2.41(10)	1.28(10) [K]	15.77	13.352 [K]
3p^2 $^1S_0$	3s3p $^1P^o_1$	2.60(12)	3.57(12) [A], 3.59(12) [K]	25.75	23.046 [A], 23.016 [K]
3p3d $^3D^o_2$	3p^2 $^1D_2$	0.218(12)	1.45(12) [B], 1.55(12) [C], 1.48(12) [D], 1.49(12) [K]	26.47	21.79[B], 21.78 [C], 22.14 [D], 21.817 [K]
3p3d $^3D^o_2$	3p^2 $^3P_1$	5.41(11)	7.20(11) [B], 7.85(11) [C], 7.52(11) [D], 7.75(11) [K]	25.69	21.87[B], 21.85 [C], 22.23 [D], 21.900 [K]
3p3d $^3D^o_2$	3s3d $^3D_1$	7.61(11)	8.71(11) [K]	24.20	23.167 [K]
3p3d $^3D^o_2$	3s3d $^3D_2$	10.8(11)	2.53(11) [K]	24.20	23.784 [K]
3p3d $^3D^o_2$	3s3d $^3D_3$	4.12(09)	4.31(11) [A], 3.10(09) [B], 3.07(09) [C] 2.73(09) [D], 2.92(09) [K]	30.37	23.253 [A], 27.58[B], 27.52 [C] 27.50 [D], 27.620 [K]
3p3d $^3D^o_2$	3s3d $^1D_2$	1.76(10)	1.35(12) [A], 7.71(08) [K]	31.29	24.037 [A], 28.782 [K]
3p3d $^3D^o_2$	3p^2 $^3P_2$	8.62(09)	1.23(11) [A],7.22(09) [K]	58.60	45.236 [A], 64.335 [K]
3p3d $^3P^o_0$	3p^2 $^3P_1$	1.10(12)	1.47(12) [A], 1.58(12) [K]	25.18	21.490 [A], 21.542 [K]
3p3d $^3P^o_0$	3s3d $^3D_1$	1.75(12)	1.98(12) [A], 1.97(12) [K]	23.75	22.841 [A], 22.766 [K]
3p3d $^3P^o_1$	3p^2 $^3P_0$	1.72(09)	2.08(12) [A], 1.28(09) [K]	16.55	21.592 [A], 13.363 [K]
3p3d $^3P^o_1$	3p^2 $^1D_2$	2.35(11)	5.52(10) [K]	25.87	21.424 [K]
3p3d $^3P^o_1$	3p^2 $^3P_1$	0.868(12)	1.32(12) [B], 1.34(12) [C], 1.26(12) [D], 1.37(12) [K]	25.12	21.47[B], 21.45[C], 21.85 [D], 21.504 [K]
3p3d $^3P^o_1$	3s3d $^3D_1$	1.43(12)	1.52(12) [K]	23.69	22.723 [K]
3p3d $^3P^o_1$	3s3d $^3D_2$	2.21(11)	5.40(11) [K]	23.69	23.317 [K]
3p3d $^3P^o_1$	3s3d $^1D_2$	3.46(10)	9.27(09) [K]	30.45	28.101 [K]
3p3d $^3P^o_1$	3p^2 $^3P_2$	1.99(10)	1.33(10) [K]	55.72	61.028 [K]
3p3d $^3P^o_1$	3p^2 $^1S_0$	4.54(09)	4.14(09) [K]	64.73	7.295 [K]
3p3d $^3F^o_4$	3s3d $^3D_3$	1.22(12)	1.62(12) [A,B,K], 1.65(12) [C,D]	26.42	23.78 [A,B], 23.75 [C], 23.69 [D], 23.711 [K]
3p3d $^3D^o_3$	3p^2 $^1D_2$	5.72(10)	3.58(11) [A], 7.72(07) [K]	22.01	21.412 [A], 18.403 [K]
3p3d $^3D^o_3$	3s3d $^3D_2$	1.65(10)	2.59(12) [A], 6.20(08) [K]	20.41	23.391 [A] 19.784 [K]
3p3d $^3D^o_3$	3s3d $^3D_3$	7.43(11)	9.89(11) [K]	24.64	22.367 [K]
3p3d $^3D^o_3$	3s3d $^1D_2$	5.58(11)	6.53(11) [K]	25.24	23.123 [K]
3p3d $^3D^o_3$	3p^2 $^3P_2$	5.39(11)	4.72(11) [K]	40.44	41.586 [K]
3p3d $^1P^o_1$	3s^2 $^1S_0$	1.85(10)	1.40(10) [K]	9.57	9.010 [K]
3p3d $^1P^o_1$	3p^2 $^3P_0$	7.95(09)	4.19(09) [K]	14.66	11.978 [K]
3p3d $^1P^o_1$	3p^2 $^1D_2$	4.89(11)	3.29(10) [K]	21.52	18.074 [K]
3p3d $^1P^o_1$	3p^2 $^3P_1$	3.72(09)	4.53(09) [K]	21.00	18.130 [K]
3p3d $^1P^o_1$	3s3d $^3D_1$	5.89(09)	4.43(09) [K]	19.99	18.990 [K]
3p3d $^1P^o_1$	3s3d $^3D_2$	2.72(09)	5.20(10) [K]	19.99	19.403 [K]
3p3d $^1P^o_1$	3s3d $^1D_2$	1.26(12)	1.85(12) [A], 1.89(12) [K]	24.60	22.665 [A], 22.605 [K]
3p3d $^1P^o_1$	3p^2 $^3P_2$	5.14(10)	4.97(10) [K]	38.82	39.939 [K]
3p3d $^1P^o_1$	3p^2 $^1S_0$	2.73(11)	2.35(11) [A], 2.53(11) [K]	42.99	43.321 [A], 42.531 [K]
3d^2 $^3F_2$	3p3d $^3F^o_2$	1.72(12)	1.62(12) [A], 2.17(12) [K]	20.14	21.169 [A], 19.415 [K]
3d^2 $^3F_2$	3p3d $^3D^o_1$	1.47(12)	1.92(12) [K]	21.36	20.505 [K]
3d^2 $^3F_2$	3p3d $^3P^o_2$	1.43(09)	3.22(09) [K]	23.71	23.174 [K]

$3d^2\ ^3F_2$	$3p3d\ ^3F^o_3$	1.39(09)	1.03(09) [K]	23.83	23.336 [K]
$3d^2\ ^3F_2$	$3p3d\ ^3D^o_2$	3.55(10)	2.15(10) [K]	38.18	46.500 [K]
$3d^2\ ^3F_2$	$3p3d\ ^3P^o_1$	3.29(10)	2.30(12) [A], 2.17(10) [K]	39.51	22.494 [A], 48.396 [K]
$3d^2\ ^3P_0$	$3p3d\ ^3D^o_1$	3.56(12)	4.49(12) [K]	20.41	19.690 [K]
$3d^2\ ^3P_0$	$3p3d\ ^3P^o_1$	1.34(11)	3.30(12) [A], 8.47(10) [K]	36.38	21.456 [A], 44.091 [K]
$3d^2\ ^3F_3$	$3p3d\ ^3P^o_2$	7.64(11)	1.74(11) [A], 8.51(11) [K]	19.66	43.869 [A], 20.060 [K]
$3d^2\ ^3F_3$	$3p3d\ ^3F^o_3$	1.18(12)	8.84(11)[A], 1.22(12) [K]	19.74	22.151 [A], 20.182 [K]
$3d^2\ ^3F_3$	$3p3d\ ^3F^o_4$	2.44(10)	4.88(09) [B,C], 4.58(09) [D], 1.14(10) [K]	33.39	58.83 [B], 58.59[C], 61.19[D], 44.973 [K]
$3d^2\ ^3F_3$	$3p3d\ ^3D^o_3$	2.26(10)	9.70(09) [K]	36.75	50.758 [K]
$3d^2\ ^3P_2$	$3s3p\ ^3P^o_1$	2.05(09)	4.49(09) [K]	8.78	8.473 [K]
$3d^2\ ^3P_2$	$3p3d\ ^3F^o_2$	7.58(09)	1.16(10) [K]	16.85	16.917 [K]
$3d^2\ ^3P_2$	$3p3d\ ^3D^o_1$	2.76(09)	2.21(11) [A], 6.87(09) [K]	17.70	43.624 [A], 17.739 [K]
$3d^2\ ^3P_2$	$3p3d\ ^3P^o_2$	1.60(12)	1.68(12) [K]	19.28	19.702 [K]
$3d^2\ ^3P_2$	$3p3d\ ^3F^o_3$	4.70(11)	3.72(11) [A], 5.13(11) [K]	19.36	21.680 [A], 19.820 [K]
$3d^2\ ^3P_2$	$3p3d\ ^3D^o_2$	2.77(11)	1.73(11) [K]	28.67	34.353 [K]
$3d^2\ ^3P_1$	$3p3d\ ^3P^o_2$	2.09(12)	2.25(12) [K]	19.14	19.556 [K]
$3d^2\ ^3P_1$	$3p3d\ ^3D^o_2$	7.63(10)	4.23(10) [K]	27.58	33.909 [K]
$3d^2\ ^3P_1$	$3p3d\ ^3P^o_0$	3.92(11)	8.30(11) [A], 2.38(11) [K]	28.19	22.841 [A], 34.806 [K]
$3d^2\ ^3P_1$	$3p3d\ ^3P^o_1$	3.75(11)	2.26(11) [K]	28.26	34.906 [K]
$3d^2\ ^3P_1$	$3p3d\ ^1P^o_1$	9.91(09)	4.80(09) [K]	36.27	50.010 [K]
$3d^2\ ^1G_4$	$3p3d\ ^3F^o_3$	1.43(12)	1.70(12) [K]	19.24	19.667 [K]
$3d^2\ ^1G_4$	$3p3d\ ^3F^o_4$	8.91(10)	1.18(11) [A], 2.09(10) [B], 2.14(10) [C] 1.86(10) [D], 4.77(10) [K]	31.96	41.475 [A], 55.10 [B], 54.49[C] 57.24[D], 42.497 [K]
$3d^2\ ^1G_4$	$3p3d\ ^3D^o_3$	3.87(10)	1.05(10) [K]	35.03	47.626 [K]
$3d^2\ ^3F_4$	$3p3d\ ^3F^o_3$	2.75(10)	1.21(12) [A], 1.85(10) [K]	23.04	21.600 [A], 17.539 [K]
$3d^2\ ^3F_4$	$3p3d\ ^3F^o_4$	4.71(11)	1.18(11) [B], 1.19(11) [C], 1.13(11) [D], 2.20(11) [K]	25.37	41.48 [B],41.31 [C], 42.61 [D], 33.670 [K]
$3d^2\ ^3F_4$	$3p3d\ ^3D^o_3$	1.25(12)	2.52(11) [A], 6.02(11) [K]	27.27	43.237 [A], 36.810 [K]
$3d^2\ ^1D_2$	$3s3p\ ^3P^o_2$	3.63(09)	4.55(09) [K]	9.85	10.321 [K]
$3d^2\ ^1D_2$	$3s3p\ ^1P^o_1$	3.69(09)	6.93(09) [K]	10.15	10.655 [K]
$3d^2\ ^1D_2$	$3p3d\ ^3F^o_2$	1.58(09)	1.48(09) [K]	14.58	15.063 [K]
$3d^2\ ^1D_2$	$3p3d\ ^3D^o_1$	1.66(09)	4.95(07) [K]	15.21	15.711 [K]
$3d^2\ ^1D_2$	$3p3d\ ^3P^o_2$	1.26(12)	8.23(07) [K]	25.52	17.232 [K]
$3d^2\ ^1D_2$	$3p3d\ ^3F^o_3$	8.89(09)	9.87(07) [K]	22.62	17.321 [K]
$3d^2\ ^1D_2$	$3p3d\ ^3P^o_1$	1.32(10)	5.65(09) [K]	22.60	28.134 [K]
$3d^2\ ^1D_2$	$3p3d\ ^3D^o_3$	2.74(11)	1.30(11) [K]	26.69	35.863 [K]
$3d^2\ ^1D_2$	$3p3d\ ^1P^o_1$	4.60(11)	1.79(11) [A], 2.16(11) [K]	27.44	46.549 [A], 37.185 [K]
$3d^2\ ^1S_0$	$3s3p\ ^3P^o_1$	2.20(09)	4.71(09) [K]	7.97	7.838 [K]
$3d^2\ ^1S_0$	$3s3p\ ^1P^o_1$	1.88(10)	5.71(10) [K]	9.92	10.402 [K]
$3d^2\ ^1S_0$	$3p3d\ ^3D^o_1$	2.34(10)	6.03(10) [K]	14.69	15.167 [K]
$3d^2\ ^1S_0$	$3p3d\ ^3P^o_1$	2.31(09)	1.29(07) [K]	21.48	26.438 [K]
$3d^2\ ^1S_0$	$3p3d\ ^1P^o_1$	2.26(12)	6.03(11) [A], 1.13(12) [K]	25.81	42.004 [A], 34.280 [K]

A: RMBPT calculations (Safronova and Safronova, 2010)
B: RMBPT calculations (Safronova et al., 2009)
C: HULLAC calculations (Safronova et al., 2009)
D: COWAN calculations (Safronova et al., 2009)
E: EBIT-experiment (Ralchenko et al., 2008)
G: EBIT-experiment (Hu et al., 2011)
H: MCDF+CV calculations (Hu et al., 2011)
K: AUTOSTRUCTURE calculations (Özdemir et al., 2013)

Table 2. Transition probabilities, $A_{ki}(s^{-1})$, and wavelengths, $\lambda(\text{Å})$, of forbidden lines (E2 and M1) in W^{62+}. In table, a(b) denotes ax10^b.U and L indicate upper and lower level, respectively

Transitions		Transition type	A_{ki} [s^{-1}]		λ[Å]	
U	L		This work	Other works	This work	Other works
$3s3p\ ^3P^o_1$	$3s3p\ ^3P^o_0$	M1	2.55(04)	2.60(04)[A] 3.03(04)[K]	805.28	755.95[K]
$3s3p\ ^3P^o_2$	$3s3p\ ^3P^o_0$	E2	0.81(06)	2.91(06)[A] 2.95(06)[K]	43.78	33.63[K]
$3s3p\ ^3P^o_2$	$3s3p\ ^3P^o_1$	E2	1.03(06)	3.86(06)[A] 3.88(06)[K]	46.30	35.20[K]
		M1	1.00(08)	2.19(08)[A] 2.22(08)[K]	46.30	
$3s3p\ ^1P^o_1$	$3s3p\ ^3P^o_0$	M1	0.79(08)	1.67(08)[A] 1.70(08)[K]	38.69	30.52[K]
$3s3p\ ^1P^o_1$	$3s3p\ ^3P^o_2$	E2	3.36(01)	3.49(01)[A] 3.71(01)[K]	332.67	329.48[K]
		M1	1.58(05)	1.63(05)[A] 1.71(05)[K]	332.67	
$3p^2\ ^1D_2$	$3p^2\ ^3P_0$	E2	7.39(05)	3.06(06)[K]	45.95	35.51[K]
$3p^2\ ^3P_1$	$3p^2\ ^3P_0$	M1	1.08(08)	2.79(08)[K]	48.50	35.30[K]
$3p^2\ ^3P_1$	$3p^2\ ^1D_2$	E2	1.34(-01)	2.09(05)[K]	872.19	5770.27[K]
		M1	4.72(03)	3.20(01)[K]	872.19	
$3p^2\ ^3P_2$	$3p^2\ ^3P_0$	E2	7.23(00)	9.77(03)[K]	23.54	17.11[K]
$3p^2\ ^3P_2$	$3p^2\ ^3P_1$	E2	8.80(05)	4.24(06)[K]	45.75	33.20[K]
		M1	8.92(07)	2.31(08)[K]	45.75	
$3p^2\ ^1S_0$	$3p^2\ ^1D_2$	E2	2.98(06)	1.68(07)[K]	43.09	31.43[K]
$3p^2\ ^1S_0$	$3p^2\ ^3P_1$	M1	2.40(08)	5.22(08)[K]	41.06	31.60[K]
$3p^2\ ^1S_0$	$3p^2\ ^3P_2$	E2	1.33(02)	1.13(01)[K]	400.15	655.25[K]

A: MCDHF calculations (Zou and Fischer, 2001)
K: AUTOSTRUCTURE calculations, (Özdemir et al., 2013)