ENERGY LEVELS, WAVELENGTHS, TRANSITION RATES, LINE STRENGTHS, AND LIFETIMES FOR LOW-LYING LEVELS IN Ne-, Na-, Mg-, AND Al-LIKE IONS OF TANTALUM [**]

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Herein the energies of low-lying levels, wavelengths, transition rates, and line strengths for electric dipole allowed (E1) and forbidden (M1) lines in Ne- to Al-like ions of tantalum have been calculated using the GRASP2K package, which is based on the multiconfiguration Dirac–Hartree–Fock (MCDHF) method. From our radiative decay rates, we also calculated the radiative lifetimes of some levels. The present results are in good agreement with other available theoretical and experimental values. We predict new data for several levels where no other theoretical and/or experimental results are available, stipulating the necessity of precise measurements.

***Keywords*:** *low-lying levels, wavelength, transition rate, line strength.*

ЭНЕРГИИ УРОВНЕЙ, ДЛИНЫ ВОЛН, СКОРОСТИ ПЕРЕХОДОВ, ИНТЕНСИВНОСТИ ЛИНИЙ И ВРЕМЯ ЖИЗНИ ДЛЯ НИЗКОЛЕЖАЩИХ УРОВНЕЙ В Ne-, Na-, Mg- И Al-ПОДОБНЫХ ИОНАХ ТАНТАЛА

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Энергии низколежащих уровней, длины волн, скорости переходов и интенсивности линий для электрических дипольных разрешенных (E1) и запрещенных (M1) линий от Ne- до Al-подобных ионов тантала рассчитаны с помощью пакета GRASP2K, основанного на применении многоконфигурационного метода Дирака–Хартри–Фока (MCDHF). На основе данных о скоростях радиационного распада вычислены радиационные времена жизни некоторых уровней, которые хорошо согласуются с другими доступными теоретическими и экспериментальными результатами. Предсказаны новые данные для нескольких уровней, для которых отсутствуют какие-либо теоретические и/или экспериментальные результаты, что обусловливает необходимость точных измерений.

Ключевые слова: *низколежащие уровни, длина волны, скорость перехода, интенсивность линии.*

Introduction. Multi-electron ions of high-*Z* elements are of interest in atomic structure theory [1]. Any accurate modeling of these systems needs to include electron correlation and relativistic effects in addition to

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quantum electrodynamic (QED) corrections [2, 3]. Electron correlation, relativistic effects, and long and short-range configuration interaction may significantly contribute to the term structure. In most cases, all configurations within the lowest complex have to be included in the treatment, and doing so has generally given good agreement with the observations for the $n = 2$ and $n = 3$ systems among lower Z elements (up to 36). However, there is comparatively a paucity of similar data for ions with a higher Z, although W LXV has attracted maximum attention due to its importance as a wall material in the developing ITER project–see [4] and references therein. Recently, Singh et al. [5] have reported the energy levels, radiative rates (A-values) and lifetimes (τ) for four Ne-like ions, namely Hf LXIII, Ta LXIV, WLXV, and Re LXVI. Similarly, Quinet et al. [6] calculated the energy levels and A values for several Ne-like ions, up to $Z = 92$, but not for the ions of the present interest, although they did report the oscillator strengths (f-values) for the 5 $E2$ (electric quadrupole), 6 $M1$ (magnetic dipole), and 6 $M2$ (magnetic quadrupole) transitions of Hf LXIII. For any ion, the most dominant transitions of interest are $E1$ (electric dipole) because of their large magnitudes. Still, virtually the only results available in the literature are those of Singh et al. [5], and unfortunately no measurements have been made for the energy levels of the ions of interest, except for two levels of Hf LXIII by Beiersdorfer [7]. At the same time, the energy levels, radiative rates, and lifetimes were performed and reported by Aggarwal for three Ne-like ions, namely Hf LXIII, Ta LXIV, and Re LXVI [8]. For the calculations Aggarwal adopted two independent atomic structure codes, namely the general-purpose relativistic atomic structure package (GRASP) and the flexible atomic code (FAC) of Gu [9]. The calculations included 121 configurations, namely $2s^22p6$, $2s^22p^53l$, $2s2p^63l$, $2s^22p^54l$, $2s2p^64l$, and $2s^22p^55l$, which generated 93437 levels (or configuration state functions, CSF) in total. Recently, the X-ray emission in atomic decays to the M-shell of Hf, Ta, W, Pt, and Au induced by electrons was studied by Trincavelli et al. [10]. As a result of the investigations, it was found that atomic physics information on the atomic structure, spectra, and collision processes was badly needed but largely lacking. In addition, the spectral data of the highly charged Ne-, Na-, Mg-, and Al-like ions of tantalum are still extremely fragmentary. The purpose of this paper is to fill in this gap. We calculate the energy levels, transition rates, line strengths, and lifetimes for low-lying levels in Ne-, Na-, Mg-, and Al-like ions of tantalum using the full relativistic multiconfiguration Dirac–Hartree–Fock (MCDHF) method. Line identification for such an extension of the database requires isoelectronic extrapolation, which is somewhat risky, or calculations for comparison and interpretational help.

Computational procedure. Our calculations are based on the flexible MCDHF method, which has a particular advantage in dealing with highly charged ions with several valence electrons. The theoretical basis of our present computational approach has been widely discussed elsewhere [11–13], so we will not repeat it. Here we only give a brief description of the background for using the GRASP2K program package. In an MCDHAF calculation, the atomic state functions (ASFs) are represented by a linear combination of configuration state functions (CSFs):

$$\psi\left(\Gamma\, P\, J\, M_J\right) = \sum_{i=1}^{n_{csf}} c_i \Phi_i\left(\gamma_i\, P\, J\, M_J\right), \qquad (1)$$

where c_i are the mixing coefficients for the state i; n_{csf} is the number of CSFs included in the evaluation of the ASFs; J and M_J are the angular quantum numbers; P is parity; γ denotes other appropriate labelling of the CSF. CSFs are built from the products of one-electron Dirac orbitals. In the relativistic self-consistent field procedure, both the radial parts of the Dirac orbitals and the expansion coefficients are optimized to self-consistency. Calculations can be done not only for single levels but also for a portion of a spectrum in an extended optimal level (EOL) where the optimization is on a weighted sum of energies. The advantage of using the EOL scheme is that both the initial and final states are assigned equal weights in the energy expression. The Breit interaction and QED effects, including vacuum polarization and self-energy correction, can be evaluated in subsequent RCI calculations. In the latter, only mixing coefficients are variables. The formulas for self-energy and vacuum polarization can be found elsewhere [14].

Generation of configuration expansions. We performed a series of calculations of increasing complexity as more orbitals and, consequently, more CSFs were added. Then the correlation effects were included by continuing the calculations for a series of expansions generated mainly by single and double (SD) electron replacements from the orbitals occupied in the multireference (MR) set to the unfilled sub-shells with the same LS symmetry. The virtual set was varied in a systematic way by increasing the principal quantum number n by 1 without imposing restrictions on the orbital quantum number. Because Ne- through Al-like ions of tantalum are so highly ionized, the most important contributions are CSFs within the $n = 3$ complex that interact with one or more members of the MR set. The basis consists of the spin orbitals: $2s$, $2p$, $3s$, $3p$, $3d$, $4s$, $4p$, $4d$, $4f$, $5s$, $5p$, $5d$, $5f$, $6s$, $6p$, $6d$, and $6f$ for the tantalum system. However, it was too time-consuming to include

all CSFs for considering the electron correlation effects completely. The double excitations are limited only to configurations such as: {3*snl*}, {3*pnl*}, and {3*dnl*}. That is, one electron was excited from the outermost core shell to the next open shell. All electrons were treated as reference configurations throughout the present calculations. We believe that these configurations are the most appropriate to represent core-valence correlations. Further corrections are included, and the expansions increase in size significantly. As a result of the relatively weak correlations between the core electrons and the valence electrons and between the core electrons for highly charged ions, we included all relativistic orbitals with $n \le 6$, $l \le 3$ except for Na-like Ta ions. For Na-like ions, there is only one valence electron; we therefore considered the core–valence correlation from the $n = 2$ shell and the core correlation in the 2*p* subshell. In the calculations, the same atomic state functions were determined simultaneously in the wave-function expansion for all levels of the group in this EOL calculation. The Breit interaction and QED effects were further included in the subsequent RCI computations. The GRASP2K package was employed to finish these calculations [15].

Results and discussions. In Table 1 we list energies for the levels of Ta LXIV. The listed energies are from the present and earlier calculations of Aggarwal [8] and Singh et al. [5] with GRASP, which are based on 3948 CSFs of 64 configurations. Also, we included the predicted data given by Aggarwal [8] and Singh et al. [5] with the flexible atomic code (FAC)for 3948 and 93 437 levels, respectively. Considering all levels listed in Table 1, our calculations are also generally in excellent agreement with the GRASP results of Aggarwal [8] and Singh et al. [5], the difference being 0.012–0.094% for most cases. Our MCDHF results are in good agreement with FAC data of Aggarwal [8] and Singh et al. [5], the difference being about 0.011–0.662% for most cases. It is in general clear that these kinds of transitions require much work, especially on the experimental side, to explain the differences among different computational methods and to facilitate their use in plasma diagnostics.

TABLE 1. Level Energies for the Low-Lying Excited Configuration of Ne-like Ta Ions with an Atomic Core [He]

Level		Energy, cm^{-1}				
LS term	*jj* term	Present	GRASP [8]	GRASP [5]	FAC [8]	FAC [5]
$2s^22p^6\ {}^1S_0$	$2s_{1/2}^2 2p_{1/2}^2 2p_{1/2}^4$ ($J = 0$)	0	0	0	0	0
$2s^22p^5 3s\ {}^3P_2$	$2s_{1/2}^2 2p_{1/2}^2 2p_{3/2}^3 3s_{1/2}$ ($J = 2$)	65042057	65033977	65030256	65044643	64612600
$2s^22p^5 3s\ {}^1P_1$	$2s_{1/2}^2 2p_{1/2} 2p_{1/2}^4 3s_{1/2}$ ($J = 1$)	65108582	65101015	65097032	65113459	64677400
$2s^22p^5 3s\ {}^3P_0$	$2s_{1/2}^2 2p_{1/2} 2p_{1/2}^4 3s_{1/2}$ ($J = 0$)	75555545	75532249	75525007	75548479	75107700
$2s^22p^5 3s\ {}^3P_1$	$2s_{1/2}^2 2p_{1/2}^2 2p_{3/2}^3 3s_{1/2}$ ($J = 1$)	75582508	75559519	75552002	75576495	75144400
$2s2p^6 3p\ {}^3P_0$	$2s_{1/2} 2p_{1/2}^6 3p_{1/2}$ ($J = 0$)	80563105	80609806	80638634	80592478	80115000
$2s2p^6 3p\ {}^3P_1$	$2s_{1/2} 2p_{1/2}^6 3p_{1/2}$ ($J = 1$)	80573935	80587288	80613493	80574075	80116200
$2s2p^6 3p\ {}^3P_2$	$2s_{1/2} 2p_{1/2}^6 3p_{3/2}$ ($J = 2$)	83450639	83490915	83517537	83475124	83075600
$2s2p^6 3p\ {}^1P_1$	$2s_{1/2} 2p_{1/2}^6 3p_{3/2}$ ($J = 1$)	83500281	83538794	83565218	83523781	83126200
$2s^22p^5 3d\ {}^3P_0$	$2s_{1/2}^2 2p_{1/2}^2 2p_{3/2}^3 3d_{3/2}$ ($J = 0$)	70329518	70352286	70349290	70344099	69953300
$2s^22p^5 3d\ {}^3P_1$	$2s_{1/2}^2 2p_{1/2}^2 2p_{3/2}^3 3d_{5/2}$ ($J = 1$)	70406653	70431231	70428312	70423429	70055500
$2s^22p^5 3d\ {}^3F_3$	$2s_{1/2}^2 2p_{1/2}^2 2p_{3/2}^3 3d_{3/2}$ ($J = 3$)	70413723	70439527	70436674	70432197	70085000
$2s^22p^5 3d\ {}^3D_2$	$2s_{1/2}^2 2p_{1/2}^2 2p_{3/2}^3 3d_{5/2}$ ($J = 2$)	70476350	70503186	70500497	70495416	70125800
$2s^22p^5 3d\ {}^3F_4$	$2s_{1/2}^2 2p_{1/2}^2 2p_{3/2}^3 3d_{5/2}$ ($J = 4$)	71044902	71067598	71063943	71060015	70743400
$2s^22p^5 3d\ {}^1D_2$	$2s_{1/2}^2 2p_{1/2} 2p_{1/2}^4 3d_{5/2}$ ($J = 2$)	71099136	71123937	71120524	71116222	70783500
$2s^22p^5 3d\ {}^3D_3$	$2s_{1/2}^2 2p_{1/2}^2 2p_{3/2}^3 3d_{5/2}$ ($J = 3$)	71178696	71203891	71200808	71196462	70864500
$2s^22p^5 3d\ {}^1P_1$	$2s_{1/2}^2 2p_{1/2} 2p_{1/2}^4 3d_{3/2}$ ($J = 1$)	71410851	71437566	71436721	71428864	71116200
$2s^22p^5 3d\ {}^3F_2$	$2s_{1/2}^2 2p_{1/2}^2 2p_{3/2}^3 3d_{3/2}$ ($J = 2$)	80921936	80933882	80927045	80932434	80574500

Continue Tabl.1

Level		Energy, cm^{-1}				
LS term	*jj* term	Present	GRASP [8]	GRASP [5]	FAC [8]	FAC [5]
$2s^22p^53d\ ^3D_1$	$2s_{1/2}^2 2p_{1/2}^2 2p_{3/2}^3 3d_{3/2}$ $(J=1)$	81110789	81153565	81150745	81147244	80797600
$2s^22p^53d\ ^3P_2$	$2s_{1/2}^2 2p_{1/2}^1 2p_{1/2}^4 3d_{3/2}$ $(J=2)$	81609297	81615450	81608382	81613233	81280500
$2s^22p^53d\ ^1F_3$	$2s_{1/2}^2 2p_{1/2} 2p_{1/2}^4 3d_{5/2}$ $(J=3)$	81632266	81642972	81635839	81640854	81314700

In Table 2, the wavelengths (λ), transition rates (A), line strengths (S), and lifetimes (τ) are presented for selected transitions for Ne-like Ta ($Z = 72$). The only results available in the literature with which they can be compared are those of Singh et al. [5] with GRASP for some $E1$ transitions, and of Beiersdorfer et al. [16] for a few $M1$ of Ta LXIV. It is clear that the calculated values are in general in good agreement with the GRASP calculation of Singh et al. [5] and the FAC calculations Beiersdorfer et al. [16]. For example, for the transition wavelengths, the difference between the present calculations and the theoretical wavelengths of Singh et al. [5] is less than 0.004 Å. The A values and line strengths for electric-dipole ($E1$) transitions are also in good agreement with the previous data given by Singh et al. [5]; here the differences are no more than 7.377%. The lifetime τ of a level j is defined as $1/\Sigma_i A_{ji}$, where the summation runs over the A values for all types of transitions, i.e., $E1$, $E2$, $M1$, and $M2$. Although the $E1$ transitions are the most dominant, as already stated, contributions from others not only enhance the accuracy but are very helpful for those levels. In Table 2, we present our lifetime calculations for the eight excited levels in Ne-like ions with $Z = 73$. The difference in the lifetimes of the individual multiplet levels is about 7.240%. Good agreement with the GRASP calculation of Singh et al. [5] was found for the common $E1$ transitions of Ta LXIV, for which there are small differences. This may be because the MCDF approach with the GRASP calculations of Singh et al. [5] was done with the EAL option. Rather than optimizing one orbital at a time as in GRASP2K, all the orbitals included are optimized simultaneously on the average energy of all the configurations according to some weighting scheme—in their case, they simply used the option that weights each level equally. The $M1$ wavelengths of these lines and the transition rates for $2s^22p^53s\ ^1P_1$–$2s^22p^53s\ ^3P_0$ transitions are compared with the available theoretical data in Table 2. The present result for the wavelength of the $2s^22p^53s\ ^1P_1$–$2s^22p^53s\ ^3P_0$ transition is in excellent agreement with the theoretical values of Beiersdorfer et al. [16], and the differences are no more than 0.104%. Moreover, the present $M1$ A values agree well with the calculations of Beiersdorfer et al. [16]. This comparison is very limited. Nevertheless, measurements for a few levels as well as other theoretical works will be helpful in further assessing the accuracy of our calculated results.

TABLE 2. Initial and Final State, Transition Type, Wavelengths, Transition Rates, Line Strengths, and Lifetimes of the Strongest Transitions in Ta^{63+} Ions (Ne-like). Numbers in Brackets are Powers of 10

Transition	Type	λ, Å	A_{ji}, s^{-1}	S_{ij}, au	τ	Reference
$2s^22p^6\ ^1S_0$–$2s^22p^53s\ ^1P_1$	$E1$	1.536	1.39(14)	7.54(–4)	7.19(–15)	Present
	$E1$	1.54	1.44(14)	7.74(–4)	6.93(–15)	GRASP data [5]
$2s^22p^6\ ^1S_0$–$2s^22p^53s\ ^3P_1$	$E1$	1.323	3.75(13)	1.53(–4)	2.67(14)	Present
	$E1$	1.32	3.61(13)	1.24(–4)	2.77(–14)	GRASP data [5]
$2s^22p^6\ ^1S_0$–$2s2p^63p\ ^3P_1$	$E1$	1.241	8.63(14)	2.42(–3)	1.16(–15)	Present
	$E1$	1.24	8.71(14)	2.46(–3)	1.12(–15)	GRASP data [5]
$2s^22p^6\ ^1S_0$–$2s2p^63p\ ^1P_1$	$E1$	1.198	4.29(14)	1.14(–3)	2.33(–15)	Present
	$E1$	1.20	4.22(14)	1.07(–3)	2.25(–15)	GRASP data [5]
$2s^22p^6\ ^1S_0$–$2s^22p^53d\ ^3P_1$	$E1$	1.420	7.13(13)	3.03(–4)	1.40(–14)	Present
	$E1$	1.42	7.22(13)	3.06(–4)	1.36(–14)	GRASP data [5]
$2s^22p^6\ ^1S_0$–$2s^22p^53d\ ^1P_1$	$E1$	1.400	2.60(15)	1.06(–2)	3.85(–16)	Present
	$E1$	1.40	2.63(15)	1.07(–2)	3.80(–16)	GRASP data [5]
$2s^22p^6\ ^1S_0$–$2s^22p^53d\ ^3D_1$	$E1$	1.233	1.22(15)	3.49(–3)	8.20(–16)	Present
	$E1$	1.23	1.13(15)	3.13(–3)	8.84(–16)	GRASP data [5]
$2s^22p^53s\ ^1P_1$–$2s^22p^53s\ ^3P_0$	$M1$	9.572	1.97(10)	8.55(–6)	5.08(–11)	Present
	$M1$	9.579	1.97(10)			FAC data [16]
	$M1$	9.582	1.96(10)			FAC data [16]
	$M1$	9.581	1.97(10)			FAC data [16]

Other computational results are presented in Tables 3–7, giving the levels for each ion in one table and the $E1$ and $M1$ transition energies, wavelengths, transition rates, line strengths, and lifetimes of the strongest lines in the corresponding other: for Na-like ions in Tables 3 and 4, for Mg-like ions in Tables 5 and 6, and for Al-like ions in Tables 7 and 8. Some comparisons with other calculations and measurements are made in Table 9. For the reader's convenience, we also list the dominant configuration in the *LS*-coupling scheme and the *jj*-coupling scheme, respectively.

TABLE 3. Level Energies for the Low-Lying Excited Configuration of Na-like Tantalum Ions with an Atomic Core [Ne]

LS term	*jj* term	Energy, cm^{-1}
$3s\ ^2S_{1/2}$	$3s_{1/2}\,(J = 1/2)$	0
$3p\ ^2P_{1/2}$	$3p_{1/2}\,(J = 1/2)$	1259734
$3p\ ^2P_{3/2}$	$3p_{3/2}\,(J = 3/2)$	4088878

TABLE 4. Initial and Final State, Transition Type, Wavelengths, Transition Rates, Line Strengths, and Lifetimes of the Strongest Transitions in Ta^{62+} ions (Na-like). Numbers in Brackets are Powers of 10

Transition	Type	λ, Å	A_{ji}, s^{-1}	S_{ij}, au	τ
$3s\ ^2S_{1/2}$–$3p\ ^2P_{1/2}$	$E1$	79.382	4.17(10)	2.06(–2)	2.40(–11)
$3s\ ^2S_{1/2}$–$3p\ ^2P_{3/2}$	$E1$	24.457	1.55(12)	4.46(–2)	6.45(–13)

TABLE 5. Level Energies for the Low-Lying Excited Configuration of Mg-like Ta Ions with an Atomic Core [Ne]

LS term	*jj* term	Energy, cm^{-1}
$3s^2\ ^1S_0$	$3s_{1/2}^2\ (J = 0)$	0
$3s3p\ ^3P_0$	$3s_{1/2}3p_{1/2}\,(J = 0)$	1098460
$3s3p\ ^3P_1$	$3s_{1/2}3p_{1/2}\,(J = 1)$	1222465
$3s3p\ ^3P_2$	$3s_{1/2}3p_{3/2}\,(J = 2)$	3890595
$3s3p\ ^1P_1$	$3s_{1/2}3p_{3/2}\,(J = 1)$	4187400

TABLE 6. Initial and Final State, Transition Type, Wavelengths, Transition Rates, Line Strengths, and Lifetimes of the Strongest Transitions in Ta^{61+} ions (Mg-like). Numbers in Brackets are Powers of 10

Transition	Type	λ, Å	A_{ji}, s^{-1}	S_{ij}, au	τ
$3s^2\ ^1S_0$-$3s3p\ ^3P_1$	$E1$	81.702	1.73(10)	1.41(–2)	5.78(–11)
$3s^2\ ^1S_0$-$3s3p\ ^1P_1$	$E1$	23.881	2.29(12)	4.62(–2)	4.37(–13)
$3s3p\ ^3P_1$-$3s3p\ ^3P_2$	$M1$	37.479	1.81(8)	2.35(–5)	5.52(–9)

TABLE 7. Level Energies for the Low-Lying Excited Configuration of Al-like Ta Ions with an Atomic Core [Ne]

LS term	*jj* term	Energy, cm^{-1}
$3s^23p\ ^2P_{1/2}$	$3s_{1/2}^2 3p_{1/2}\ (J = 1/2)$	0
$3s^23p\ ^2P_{3/2}$	$3s_{1/2}^2 3p_{3/2}\ (J = 3/2)$	2751453
$3s3p^2\ ^4P_{1/2}$	$3s_{1/2}3p_{1/2}^2\ (J = 1/2)$	1320794
$3s3p^2\ ^4P_{3/2}$	$3s_{1/2}3p_{1/2}3p_{3/2}\ (J = 1/2)$	3830833
$3s3p^2\ ^4P_{5/2}$	$3s_{1/2}3p_{1/2}3p_{3/2}\ (J = 1/2)$	3977001
$3s3p^2\ ^2D_{3/2}$	$3s_{1/2}3p_{3/2}^2\ (J = 1/2)$	4156541
$3s3p^2\ ^2S_{1/2}$	$3s_{1/2}3p_{3/2}^2\ (J = 1/2)$	4224831
$3s3p^2\ ^2D_{5/2}$	$3s_{1/2}3p_{3/2}^2\ (J = 1/2)$	6680842
$3s3p^2\ ^2P_{1/2}$	$3s_{1/2}3p_{1/2}3p_{3/2}\ (J = 1/2)$	6977971
$3s3p^2\ ^2P_{3/2}$	$3s_{1/2}3p_{1/2}3p_{3/2}\ (J = 1/2)$	7031672

TABLE 8. Initial and Final State, Transition Type, Wavelengths, Transition Rates, Line Strengths, and Lifetimes of the Strongest Transitions in Ta^{60+} Ions (Al-like). Numbers in Brackets are Powers of 10

Transition	Type	λ	A_{ji}, s^{-1}	S_{ij}, a.u.	τ
$3s^23p\ ^2P_{1/2}$–$3s3p^2\ ^2P_{3/2}$	$E1$	14.221	1.55(9)	8.25(–6)	2.77(–13)
$3s^23p\ ^2P_{3/2}$–$3s3p^2\ ^2P_{3/2}$	$E1$	23.362	3.61(12)	9.09(–2)	
$3s^23p\ ^2P_{1/2}$–$3s3p^2\ ^2P_{1/2}$	$E1$	14.331	7.55(9)	2.19(–5)	5.594(–13)
$3s^23p\ ^2P_{3/2}$–$3s3p^2\ ^2P_{1/2}$	$E1$	23.661	1.78(12)	2.32(–2)	
$3s^23p\ ^2P_{3/2}$–$3s3p^2\ ^2D_{5/2}$	$E1$	25.453	6.38(11)	3.11(–2)	1.567(–12)
$3s^23p\ ^2P_{1/2}$–$3s3p^2\ ^2S_{1/2}$	$E1$	23.670	2.16(12)	3.23(–2)	4.015(–13)
$3s^23p\ ^2P_{3/2}$–$3s3p^2\ ^2S_{1/2}$	$E1$	67.866	3.09(10)	9.52(–3)	
$3s^23p\ ^2P_{1/2}$–$3s3p^2\ ^2D_{3/2}$	$E1$	24.054	8.55(11)	2.35(–2)	1.144(–12)
$3s^23p\ ^2P_{3/2}$–$3s3p^2\ ^2D_{3/2}$	$E1$	71.123	2.40(10)	1.71(–2)	
$3s^23p\ ^2P_{3/2}$–$3s3p^2\ ^4P_{5/2}$	$E1$	81.625	1.37(10)	2.21(–2)	7.30(–11)
$3s^23p\ ^2P_{1/2}$–$3s3p^2\ ^4P_{3/2}$	$E1$	26.109	1.06(10)	3.72(–4)	7.91(–11)
$3s^23p\ ^2P_{3/2}$–$3s3p^2\ ^4P_{3/2}$	$E1$	92.705	2.04(9)	3.21(–3)	
$3s^23p\ ^2P_{1/2}$–$3s3p^2\ ^4P_{1/2}$	$E1$	75.727	3.59(10)	1.54(–2)	2.77(–11)
$3s^23p\ ^2P_{3/2}$–$3s3p^2\ ^4P_{1/2}$	$E1$	69.889	2.04(8)	1.38(–4)	
$3s^23p\ ^2P_{1/2}$–$3s^23p\ ^2P_{3/2}$	$M1$	36.346	1.81(8)	1.72(–5)	5.52(–9)

TABLE 9. Wavelengths, Transition Rates, and Line Strengths from Na-, Mg-, and Al-Like Ions of Ta, from the Present Calculations and Compared with the Experimental and Theoretical Results

Spectrum	Transition	λ, Å		A_{ji}, s^{-1}	S_{ij}, au
		Theory	Exp.[17]	Theory	
Ta^{62+}	$3s\ ^2S_{1/2}$–$3p\ ^2P_{1/2}$	79.382*	79.37		
		79.270[a]			
Ta^{61+}	$3s^2\ ^1S_0$–$3s3p\ ^3P_1$	81.702*	81.69		
		81.652[a]			
Ta^{60+}	$3s^23p\ ^2P_{1/2}$–$3s3p^2\ ^4P_{1/2}$	75.727*	75.70		
		75.598[a]			
	$3s^23p\ ^2P_{1/2}$–$3s3p^2\ ^2S_{1/2}$	23.670*		2.16(12)*	3.23(–2)*
		23.703[b]		2.15(12)[b]	3.23(–2)[b]
	$3s^23p\ ^2P_{3/2}$–$3s3p^2\ ^2P_{1/2}$	23.660*		1.78(12)*	2.32(–2)*
		23.697[b]		1.78(12)[b]	2.33(–2)[b]

*Present.
[a] MCDF data [17].
[b] MBPT data [18].

In Tables 9, the wavelengths, electric-dipole transition rates and line strengths are presented for transitions in Ta^{62+}, Ta^{61+}, and Ta^{60+}. We limit the table to those transitions given in [17, 18]. A comparison between the present wavelengths and the experimental values of Ralchenko et al. [17] reveals that the calculated values are consistently less than the experimental wavelengths by ~0.03 Å. Also, our calculations are also in good agreement with the MCDF results of Ralchenko et al. [17] and the relativistic many-body perturbation theory (MBPT) data from Safronova et al. [18]. The deviations from other theoretical values are less than 0.13 Å. However, a more detailed comparison of the calculated and experimental wavelengths for these transitions indicates that the transition wavelengths given by our GRASP2K calculations are in better agreement with the experimental wavelengths than the MCDF results of Ralchenko et al. [17]. Specifically, the maximum difference between the results of the experiment and our GRASPVU transition wavelengths is 0.036%, but the maximum difference for the MCDF results of Ralchenko et al. [17] and the experimental results is 0.135%. The oscillator strengths and electric dipole transition rates are also in good agreement with the previous data given by Safronova et al. [18], where the differences are no more than 0.463%. Further experimental confirmation would be very helpful in verifying the correctness of these occasionally sensitive mixing parameters.

Conclusions. Motivated by the need for accurate transition data in a variety of scientific applications, the EOL version of the MCDHF method is used to calculate the energy levels, transition rates, line strengths, and lifetimes for low-lying levels in Ne-, Na-, Mg-, and Al-like ions of tantalum. Among this, the calculated values for Ne-like to Al-like tantalum ions give excellent agreement with experimental data and theoretical results, and it is found that our results on the energy levels, wavelengths, transition rates, line strengths, and lifetimes are reliable and reasonable. Our calculations present benchmark data for many yet unmeasured properties of tantalum ions and are particularly important for the diagnostics of tantalum plasmas for a broad range of temperatures as well as for future ITER plasmas.

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