Radiative rates for E1, E2, M1, and M2 transitions in S-like to F-like tungsten ions (W LIX to W LXVI)

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Abstract

Calculations of energy levels, radiative rates and lifetimes are reported for eight ions of tungsten, i.e. S-like (W LIX) to F-like (W LXVI). A large number of levels has been considered for each ion and extensive configuration interaction has been included among a range of configurations. For the calculations, the general-purpose relativistic atomic structure package (GRASP) has been adopted, and radiative rates (as well as oscillator strengths and line strengths) are listed for all E1, E2, M1, and M2 transitions of the ions. Comparisons have been made with earlier available experimental and theoretical energies, although these are limited to only a few levels for most ions. Therefore for additional accuracy assessments, particularly for energy levels, analogous calculations have been performed with the flexible atomic code (FAC).

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1. Introduction

Tungsten (W) is one of the most important constituents of tokamak reactor walls [1]. Additionally, it radiates strongly over almost all ionisation stages. For example, the most intense emission lines of W ions [1] are from W XXII to W L in the VUV to the soft x-ray region, covering an electron temperature range from about 0.5 to 5.0 keV. Similarly, Püttcrich et al. [1] have predicted emission features from W LXI to W LXIX in the 0.1–0.15 nm, 1.8–4.0 nm and around 8 nm ranges. However, to assess radiation loss and for modelling plasmas, atomic data (including energy levels and oscillator strengths or radiative decay rates) are required for many of the W ions. Their need for atomic data for several ions, including those of W, has increased significantly due to the developing ITER project. Therefore, several groups of people are actively engaged in producing atomic data.

Early calculations for a number of W ions (W XXXVIII to W XLVIII) were performed by Fournier [2]. He adopted a relativistic atomic structure code, but reported only limited results for energy levels and oscillator strengths (f-values). A thorough critical compilation of experimental, theoretical and analytical energy levels of W ions (W III through W LXXIV) has been undertaken by Kramida and Shirai [3] and has been further reviewed by Kramida [4]. These energy levels, along with some spectral lines, are also available on the NIST (National Institute of Standards and Technology) website at http://www.nist.gov/pml/data/asd.cfm. Recently, spectra in the EUV wavelength range (4–20 nm) have been measured by Ralchenko et al. [5], for a number of W ions, namely W LV to W LXIV. Similarly, Clementson et al. [6] have discussed spectroscopy of many W ions (W XLVII to W LXXII). On the other side, calculations have been performed for several W ions, such as by Quinet [7] for W XLVIII to W LXII. Although he adopted the GRASP code for the calculations, his reported results for energy levels and radiative rates (A-values) are confined to
forbidden lines within the $3p^6$ and $3d^6$ configurations. However, for the modelling of plasmas, atomic data among a wider range of levels/transitions are preferred. Therefore, we have already reported such data for two W ions, namely W XL [8, 9] and W LVIII [10, 11]. In this paper, we extend our work to eight other W ions, S-like (W LIX) to F-like (W LXVI).

As in our earlier research [8–11] and those of others [7, 12], we have adopted the fully relativistic multi-configuration Dirac-Fock (MCDF) atomic structure code [13], better known as the general-purpose relativistic atomic structure package (GRASP) [14]. This code is based on the $jj$ coupling scheme, includes higher-order relativistic corrections arising from the Breit interaction and QED (quantum electrodynamics) effects, and is suitable for the heavy ions considered here. However, this original version [13] has undergone several revisions, such as by [14–16], and the one employed here (and by many other workers) has been revised by Dr. P. H. Norrington, and is freely available at http://web.am.qub.ac.uk/DARC/.

2. Energy levels

Extensive configuration interaction (CI) has been incorporated in GRASP, as described below for each ion, and for the optimisation of the orbitals the option of ‘extended average level’ (EAL), in which a weighted (proportional to $2j+1$) trace of the Hamiltonian matrix is minimised, has been adopted. The GRASP code has a few other choices for optimisation, such as average level (AL) and extended optimal level (EOL). However, in general, the results obtained with the AL option are comparable with those of EAL as already discussed and demonstrated by us for several other ions, such as those of Kr [17] and Xe [18]. Similarly, the EOL option may provide slightly more accurate data for a few predefined levels, but is only useful if the experimental energies are known, which is not the case for a majority of the levels of the ions studied here.

2.1. S-like W LIX

Clementson and Beiersdorfer [19] have measured wavelengths for 3 lines of W LIX. They also calculated these with two different codes, i.e. GRASP and FAC (flexible atomic code), and there is no (major) discrepancy among the results. For modelling purposes, Feldman et al. [20] calculated atomic data for many W ions, including W LIX, but did not report the data. Furthermore, they used a simple model consisting of the $3s^23p^4$, $3s3p^5$, $3s^23p^33d$, and $3p^5\ell$ configurations, generating 48 levels in total.

For our work, we have performed two sets of calculations using the GRASP code. In the first (GRASP1) we have included 2762 levels of the all possible combinations of the $n = 3$ orbitals, i.e. 18 configurations in number. The second (GRASP2) involves an additional 28 configurations, which are $3s^23p^3$, $3s^23p^23d$, $3s3p^4$, $3s3p^33d$, $3s^23p3d^2$, $3s3p^23d^2$, and $3p^5\ell$. These 46 configurations generate 12 652 levels in total. In Table A we compare the energies obtained from both models, but for only the lowest 20 levels. Differences between the two sets of energies are less than 0.025 Ryd and the inclusion of larger CI in the GRASP2 calculations has lowered the energies for most of the levels. Therefore, it is necessary to assess the effect of further CI on the energy levels. For this we have adopted the FAC code of Gu [21], which is also fully relativistic and is available from the website https://www-amdis.iaea.org/FAC/. This code is comparatively more efficient to run and generally yields results similar to those obtained with other atomic structure codes, as has already been demonstrated in several of our earlier papers – see for example Aggarwal et al. [22]. With FAC we have also performed two sets of calculations, i.e. FAC1: includes the same 2762 levels as in GRASP1, and FAC2: also includes levels of the $3s^5\ell$ configurations, generating 38 694 levels in total. Energies obtained from both these models are also listed in Table A for comparison.

Discrepancies between the GRASP1 and FAC1 energies are up to 0.15 Ryd (see level 13), in spite of including the same CI. This is because of the differences in the algorithms of the codes and also in calculating the central potentials. Additionally, the energies
obtained from FAC are generally lower for most levels. However, inclusion of additional CI in the FAC2 calculations further lowers the energies, but only up to 0.02 Ryd for some of the levels. Therefore, it may be reasonable to say that the inclusion of CI in our GRASP2 calculations is sufficient to calculate accurate results, but differences with FAC2 remain of up to 0.15 Ryd. The NIST compilation is only for a few levels of W LIX, which are mostly based on the experimental and theoretical work of Clementson et al. [6]. However, these energies are not very accurate as indicated on their website, and many levels are also missing from the compilation. Nevertheless, in Table A we have included their energies for comparison. Unfortunately, differences between their compiled energies and our (any of the) calculations are up to 0.4 Ryd for some of the levels, such as 18–20. Therefore, there may be scope to improve upon our calculated energies but the (in)accuracy cannot definitely be determined by the limited comparison shown in Table A.

Our calculated energies from GRASP2 are listed in Table 1 along with those from FAC2 for the lowest 220 levels, which belong to the $n \leq 3$ configurations. Beyond these, the levels of the $n = 4$ configurations start mixing. Discrepancies between the two sets of energies are smaller than 0.4 Ryd ($< 0.5\%$) for a majority of levels and the orderings are different only in a few instances, such as 70/71 and 151/152. We also note that some differences may be because of a mismatch between the two sets of energies, as it is not always possible to perfectly match these due to their different notations. Also note that the $LSJ$ designations of the levels listed in Table 1 are not always unambiguous, and a few of these can be (inter)changed with varying amounts of CI, codes, and authors preferences. This is inevitable in any calculation because of the strong mixing among some of the levels. As examples, we list the lowest 20 levels in Table B. For some, such as 1, 2, 10, and 12, there is a clear dominance of one vector (level) and hence there is no scope for ambiguity. However, for others, such as 3–9, several vectors (levels) dominate and therefore it is not straightforward to designate such levels. For example, the eigenvector for level 19 is dominant in 19 but is also significant in 4. However, the eigenvector for level 105 is dominant in both levels 4 and 105 (not listed in Table B). Finally, it may be noted that the degeneracy among the levels of W LIX is very large – see for example levels 3, 5, 9, 19, and 32 of $3s^23p^33d^3D^o$, which are separated by up to $\sim 30$ Ryd. For the ground state energy the Breit and QED contributions are 28.7 and 21.7 Ryd, respectively, although they amount to only $\sim 0.1\%$.

2.2. P-like W LX

For this ion we have also performed two calculations with GRASP using different levels of CI, i.e. GRASP1: includes 1313 levels of the 15 $n = 3$ configurations, which are $3s^23p^3$, $3s^23p^33d$, $3s3p^4$, $3s^23p^3d^2$, $3s3p^33d$, $3s3p^3d^2$, $3p^23d^3$, $3s3p^3d$, $3s3p^3d^3$, $3s3p^3d^4$, and $3d^5$. In the other calculation (GRASP2), a further 20 configurations of $[3s^23p^2, 3s3p^3, 3s^23p3d, 3s3p^3d, 3s3p^23d, 3s^23d^2]4\ell$ are included, generating in total 3533 levels. Similarly, two calculations with FAC are performed, i.e. FAC1 with the same CI as in GRASP2, and FAC2, which also includes all possible combinations of $3\ell^44\ell$, generating 14 608 levels in total. Energies for the lowest 220 levels from both GRASP2 and FAC2 are listed in Table 2. These levels belong to the first 8 configurations listed above. For the higher-lying levels, those of $n = 4$ intermix with $n = 3$.

In Table C we compare our energies for the lowest 25 levels of W LX from GRASP1, GRASP2, FAC1, and FAC2 with the NIST compilation. CI for W LX is not as important as for W LIX, because differences between our GRASP1 and GRASP2 energies are smaller than 0.02 Ryd. Similarly, discrepancies between the FAC1 and FAC2 energies are less than 0.03 Ryd. However, differences between the GRASP2 and FAC2 energies are up to 0.3 Ryd for some levels, for reasons already explained in section 2.1. The NIST compilation is only for the lowest 25 levels, listed in Table C, and our GRASP2 energies are (generally) lower by up to 0.3 Ryd – see for example, levels 13, 17 and 22. Similar differences remain between the NIST and FAC2 energies, and therefore are not due to
a lack of CI. However, it is worth emphasising that the compiled energies of NIST are mostly based on interpolation/extrapolation and hence are likely not very accurate. More importantly, there are differences in the designations of a few levels, particularly the ground state, which is \((3s^23p^3)^2D_{3/2}\) in our work, but \(^2P_{3/2}\) in NIST. This is a highly mixed level and the eigenvector for \(^2P_{3/2}\) dominates in both levels 1 and 25 – see Table D in which eigenvectors for the lowest 25 are listed. However, we have preferred to designate the lower (ground) level as \(^2D_{3/2}\), because the placings of \(^2D_{5/2}\) and \(^3P_{1/2}\) (levels 5 and 6) are unambiguous. There may be similar differences in designations with other calculations because of the very high mixing among some of the levels of W LX.

2.3. Si-like W LXI

As for other W ions, we have performed two calculations each with the GRASP and FAC codes to assess the effect of CI. These are GRASP1: 518 levels of 12 configurations [3s\(^2\)3p\(^2\), 3s3p\(^3\), 3s3p3d, 3s3p3d3d, 3p\(^4\), 3s3d\(^2\), 3p\(^3\)d, 3s3p3d\(^2\), 3p\(^2\)3d\(^2\), 3s3d\(^3\), 3p3d\(^3\), and 3d\(^4\)]; GRASP2: 4364 levels of 48 configurations, the additional 36 are [3s\(^2\)3p, 3s3p\(^2\), 3s3d\(^3\), 3s3p3d, 3p\(^3\), 3p\(^2\)3d, 3s3d\(^2\), 3p3d\(^2\), and 3d\(^3\)]\(\ell\); FAC1: 9798 levels of 3\(\times\)4, 3\(\times\)3 \(\times\)3, and 3\(\times\)2 \(\times\)4 \(\times\)2 configurations. Energies obtained from these calculations are compared in Table E with the NIST compilation for the lowest 21 levels of W LXI, which are the only ones in common. As for other ions, the CI is not very important for this ion, because the GRASP1 and GRASP2 energies agree within to 0.02 Ryd, and the FAC1 and FAC2 energies show no appreciable differences. Similarly, the agreement between our GRASP2 and FAC2 energies is better than 0.2 Ryd – see levels 12–15. However, as for other ions, the differences with the NIST compilation are larger, up to 0.4 Ryd – see level 9 for example. Again, the NIST energies are not very accurate and therefore such differences are not surprising. An important difference between our calculations and the NIST compilation is the designation for level 4, i.e. \((3s3p^3)^5S^0_2\) which is \(^3P^o_2\) (64) in the latter. Both these levels are highly mixed, as may be seen from the eigenvectors listed in Table F for the lowest 21 levels \(plus\) the remaining two of the 3s3p\(^3\) configuration, i.e. \(^3P^o_2\) and \(^1P^o_1\).

Our recommended energies for the lowest 215 levels of W LXI are listed in Table 3 from the GRASP2 and FAC2 calculations. These levels belong to the \(n = 3\) configurations and beyond these those of \(n = 4\) intermix. Finally, there are no major differences in the orderings of the two sets of level energies.

2.4. Al-like W LXII

For W LXII the experimental energies are also as sparse as for other W ions. However, two sets of theoretical energy levels [12, 23] are available in the literature. Safronova and Safronova [23] adopted a relativistic many-body perturbation theory (RMBPT) and reported energies for the lowest 40 levels belonging to the 3s\(^2\)3p, 3s3p\(^2\), 3s3d\(^2\), 3s3p3d, 3p\(^3\), and 3p\(^2\)3d configurations. In addition, S. Aggarwal et al. [12] have calculated energies for the lowest 148 levels of the 3s\(^2\)3p, 3s3p\(^2\), 3s3d\(^3\), 3s3p3d, 3p\(^3\), 3p\(^2\)3d, 3s3d\(^2\), 3p3d\(^2\), and 3d\(^3\) (nine) configurations, adopting the same version of the GRASP code as in the present work. The RMBPT energies [23] are closer to the NIST compilation and in general are lower than those of S. Aggarwal et al. by up to 0.4 Ryd – see Table 2 of [12].

We have performed several sets of calculations with the GRASP code but mention only three here, namely: GRASP1, which includes the basic 148 levels of the 9 configurations listed above; GRASP2, which considers an additional 776 (total 924) levels of the [3s3p, 3s3d, 3p3d, 3s\(^2\), 3p\(^3\), and 3d\(^3\)]\(\ell\) (24) configurations; and finally GRASP3 which includes a further 1079 levels (total 2003) of the 30 additional configurations, i.e. [3s3p, 3s3d, 3p3d, 3s\(^2\), 3p\(^2\), and 3d\(^2\)]\(\ell\). S. Aggarwal et al. [12] included CI among 35 configurations, which are the basic 9 of GRASP1 \(plus\) another 26, i.e. 3s3p4\(\ell\), 3s3d4\(\ell\), 3p3d4\(\ell\), 3s\(^2\)4\(\ell\), 3p\(^2\)4\(\ell\) (except 3p\(^2\)d),
3p4ℓ² (except 3p4p²), and 3d4ℓ². It is not clear why they overlooked configurations such as: 3p²4d, 3p4p², 3s4ℓ², and 3ℓ4ℓℓ′. In addition, their 35 configurations generate 1007 levels in total (see Table 1 of [24]) whereas they mention only 894, and therefore there is an anomaly of 113 levels. However, we stress that (particularly) the omission of the 3p²4d and 3p4p² configurations does not affect the energies or the corresponding lifetimes, as already discussed by one of us [24]. More importantly, levels of the 3ℓ4ℓ² configurations lie at energies well above those of our GRASP3 calculations, and hence are omitted from our work. This has been confirmed by our larger calculation with 75 configurations and 2393 levels. For the same reason we preferred not to include the 4ℓ² configurations for the calculations of energy levels for other W ions. A complete set of energies for all 148 levels (of the GRASP1 calculations) are listed in Table 4 from GRASP3 and FAC2 (see below). We note that levels from all other configurations clearly lie above these 148 and hence there is no intermixing.

As with GRASP, we have also performed several calculations with FAC, but focus on only two, i.e. FAC1: includes the same 2003 levels as in GRASP3, and FAC2: contains 12 139 levels in total, the additional ones arising from the 3*2 6*1, 3*1 4*2, 3*1 5*2 and 3*1 6*2 configurations. In Table G we compare our energies from GRASP2, GRASP3, FAC1, and FAC2 with those of NIST for the lowest 21 levels, which are in common. Also included in this table are the results of Safronova and Safronova [23] from RMBPT. The corresponding data of S. Aggarwal et al. [12] are not considered because they are similar to our GRASP2 calculations and have already been discussed previously [24]. Although a considerably large CI has been included in our calculations, it does not appear to be too important for W LXII, because the GRASP2 and GRASP3 (and FAC1 and FAC2) energies are practically identical. Therefore, the discrepancies between the GRASP and FAC energies (up to 0.4 Ryd, particularly for level 21) are not due to different levels of CI but because of the computational and theoretical dissimilarities in the codes. Nevertheless, although the NIST energies are not claimed to be very accurate, their agreements with those from FAC and RMBPT are better (within 0.1 Ryd) than with GRASP. Regarding all the 148 levels in Table 4, the differences between the GRASP and FAC energies are up to 0.4 Ryd for some (see levels 77 upwards in the table).

Finally, as for other W ions, configuration mixing is strong for W LXII also and therefore there is always a possibility of (inter)change of level designations listed in Table 4. For the 21 levels listed in Table G, their designations and orderings are the same between NIST and our calculations, but differ with those of S. Aggarwal et al. [12] for some, such as levels 10 and 68, i.e. (3p³) ²D₃/₂ and ²P₁/₂, which are reversed by them. These two levels (and many more) have strong mixing, as may be seen from Table H in which we list the eigenvectors for the lowest 21 levels plus 68, i.e. 3p³ ²P₃/₂. Similarly, there is a disagreement for most level designations between our work and NIST with those of Safronova and Safronova [23].

2.5. Mg-like W LXIII

For this ion, earlier calculations for energy levels are by Safronova and Safronova [23] using the RMBPT method for the lowest 35 levels of the 3s², 3s3p, 3p², 3s3d, 3p3d, and 3d² configurations, whereas the NIST compilation is only for 9 levels – see Table I. As for other ions we have performed several sets of calculations with GRASP and FAC and here we only state our final results. For the GRASP calculations we have considered 58 configurations, which are 3ℓ², 3s3p, 3s3d, 3p3d, 3ℓ4ℓ, 4ℓ², 4ℓℓ′, 3ℓ4ℓℓ, and 3ℓ6ℓ (except 6h), while for FAC we include 991 levels, the additional ones arising from 3ℓ7ℓ and 4ℓ5ℓ. However, levels of the 4ℓ², 4ℓℓ′ and 4ℓ5ℓ configurations mostly lie above those of 3ℓ7ℓ and can therefore be neglected. Energy levels from both calculations are listed in Table 5 for the lowest 210 levels. In Table I a comparison is shown for the lowest 35 levels with the NIST compilation and the RMBPT calculations [23]. As for W LXII, the FAC and RMBPT energies agree closely with each other as well as with NIST, but our GRASP energies are higher by up to 0.3 Ryd for many levels. Similarly, mixing for the levels is strong for a few as shown
2.6. Na-like W LXIV

For this ion we have gradually increased the number of orbitals to perform GRASP calculations for up to 1235 levels. The configurations included are $2p^6n\ell$ with $n \leq 7$ and $\ell \leq 4$, $2p^33(\ell'\ell)$, $2p^33^2\ell$, $2p^34\ell\ell'$, $2p^34\ell^2$, and $2p^33/4\ell$. However, we note that the levels of $2p^6n\ell$ lie below those of the other configurations. For this reason we only list the lowest 30 levels in Table K, all belonging to $2p^6n\ell$. However, with FAC we have performed comparatively larger calculations for up to $n = 20$ and all possible values of $\ell$, i.e. 1592 levels in total. These results are also listed in Table K along with those of NIST, which are confined to the $n \leq 5$ levels. The NIST energies differ with FAC by up to 0.26 Ryd for some levels (see Table K), but discrepancies are smaller than 0.15 Ryd with those with GRASP. Again, the differences between the GRASP and FAC energies are not because of different levels of CI, but due to methodological variations. It has not been possible to include higher $2p^6n\ell$ configurations in our GRASP calculations, but since the FAC energies have been obtained (as stated above) in Table 6 we list these for the lowest 396 levels, all belonging to $2p^6n\ell$ with $n \leq 20$. This will be helpful for future comparisons. Finally, unlike the other W ions discussed above, there is no (strong) mixing and/or ambiguity for the designation of the $2p^6n\ell$ levels listed in Tables K and 6.

Safronova et al. [25] have reported energies for 242 levels of W LXIV from three independent codes, namely RMBPT, HULLAC (Hebrew University Lawrence Livermore Atomic Code [26]) and the atomic structure code of R.D. Cowan available at http://das101.isan.troitsk.ru/cowan.htm. Although NIST energies for this ion are only available for a few levels, as already seen in Table K, their RMBPT results are closest to the measurements. Additionally, based on the comparisons made for other W ions, their RMBPT energies should be the most accurate. Nevertheless, the RMBPT energy for level 2 ($2p^53s^3P^o_2$) differs by 1.3% and 6.4% with those from HULLAC and Cowan, respectively. Corresponding differences for the remaining levels are up to 0.3% and 1%, respectively. Only the lowest 5 levels of Table K are common with their work, as the remaining 237 belong to the $2p^53\ell\ell'$ configurations. Therefore, our listed energies in Table 6 supplement their data.

2.7. Ne-like W LXV

The NIST compilation of energies for this ion is limited to only 10 levels of the $2p^53\ell$ configurations. However, Vilkas et al. [27] have reported energies for 141 levels of the $2p^6$, ($2s2p^6)3\ell$, $4\ell$, $5\ell$ (except 5g), and ($2p^5$) $3\ell$, $4\ell$, $5\ell$ (except 5g) configurations. For their calculations they adopted the relativistic multi-reference many-body Möller-Plesset (MRMP) perturbation theory, and included CI up to the $n = 5$ orbitals. We have included the same configurations for our calculations with GRASP, which generate 157 levels in total because we have also considered the 5g orbital. However, in Table 7 we list energies for only the lowest 121, because beyond this the levels of the $2s2p^66\ell$ configurations start mixing in the same way as of $2s2p^65g$ with those of $2s2p^64\ell$ – see levels 92–99 in the table. Additionally, we have performed larger calculations with FAC with up to 1147 levels, belonging to the $2*8$, $(2*7) 3*1$, $4*1$, $5*1$, $6*1$, $7*1$, and $2*6 3*2$ configurations. These results are also listed in Table 7 for comparison. Differences between the GRASP and FAC energies are up to 0.5 Ryd (0.07%) for some levels, but the level orderings are almost identical. Similarly, there is no difference in level orderings with the MRMP calculations [27] and the energies differ only by less than 0.6 Ryd (0.06%) with GRASP – see levels 63 and 77–83. Therefore, overall there is no (significant) discrepancy between the three independent calculations. However, in general the FAC energies are lower than those from GRASP for a majority of levels, whereas those of MRMP are higher.

In Table L, we compare energies with the NIST compilation for only the common levels. There is no uniform pattern for (dis)agreement between the theoretical and experimental energies. In general, the MRMP energies are closer to those of NIST.
whereas those from FAC differ the most. Unfortunately, these comparisons are not sufficient for accuracy determination, particularly when the NIST energies are not based on direct measurements. Finally, as for most W ions, for W LXV also there is a strong mixing for some levels and therefore the level designations listed in Table 7 can vary, although the MRMP calculations [27] have the same labels as in our work. Nevertheless, in Table M we list the eigenvectors for the lowest 33 levels, which include all of the NIST compilation. Note particularly the mixing for levels 24, 25 and 31.

2.8. F-like W LXVI

For this ion we have performed a series of calculations with GRASP with gradually increasing CI and our final set includes 501 levels of 38 configurations, which are: 2s2p5, 2s2p6, (2s2p4, 2s2p5, 2p6)3ℓ, 4ℓ, 5ℓ. Similarly, calculations with FAC have been performed for up to 1113 levels from the 2*7 and (2*6) 3*1, 4*1, 5*1, 6*1, 7*1 configurations. These levels span an energy range of up to 1360 Ryd. Opening the 1s shell gives rise to levels above 5000 Ryd and therefore has not been included in the calculations. Energies from both of these calculations are listed in Table 8 for the lowest 150 levels, because beyond this the levels of the \( n = 5 \) configurations start mixing. However, the listed levels include all of the \( n = 3 \) configurations. Differences between the two sets of energies are up to 0.5 Ryd for some levels, except three (145–147) for which the discrepancies are slightly larger, up to 0.7 Ryd. The level orderings are also the same for a majority of levels, but slightly differ in a few instances, such as for 93–112. NIST listings are available for only two levels, namely 2s2p5 2P1/2 and 2s2p6 2S1/2, and the energy for the latter is lower by 0.5 Ryd than the theoretical results. No other similar theoretical energies are available for this ion for comparison purposes. Finally, this ion is no exception for level mixing and examples of this are listed in Table N for the lowest 48 levels – see in particular 13, 15, 40, and 42.

3. Radiative rates

Apart from energy levels, calculations have been made for absorption oscillator strengths (\( f \)-values, dimensionless), radiative rates (\( A \)-values, \( s^{-1} \)) and line strengths (\( S \)-values, in atomic units, 1 a.u. = \( 6.460 \times 10^{-36} \) cm² esu²). However, \( f \)- and \( A \)-values for all types of transition (\( i \rightarrow j \)) are connected by the following expression:

\[
f_{ij} = \frac{mc}{8\pi^2e^2} \lambda_{ji}^2 \frac{\omega_i}{\omega_j} A_{ji} = 1.49 \times 10^{-16} \lambda_{ji}^2 \frac{\omega_i}{\omega_j} A_{ji}
\]

where \( m \) and \( e \) are the electron mass and charge, respectively, \( c \) the velocity of light, \( \lambda_{ji} \) the transition wavelength in Å, and \( \omega_i \) and \( \omega_j \) the statistical weights of the lower \( i \) and upper \( j \) levels, respectively. Similarly, \( f \)- and \( A \)-values are related to \( S \) by the standard equations given in [9].

In Tables 9–16 we present results for energies (wavelengths, \( \lambda_{ji} \) in Å), \( A \)-, \( f \)- and \( S \)-values for electric dipole (E1) transitions in W ions, which have been obtained with the GRASP code. For other types of transitions, namely magnetic dipole (M1), electric quadrupole (E2), and magnetic quadrupole (M2), only the \( A \)-values are listed, because the corresponding results for \( f \)- or \( S \)-values can be obtained using Eqs. (1-5) given in [9]. Additionally, we have also listed the ratio (R) of the velocity (Coulomb gauge) and length (Babushkin gauge) forms which often (but not necessarily) give an indication of the accuracy. The indices used to represent the lower and upper levels of a transition are defined in Tables 1–8. Furthermore, only a limited range of transitions are listed in Tables 9–16, but full tables are available online in the electronic version.

For the W ions considered here, existing \( A \)- (or \( f \)-) values are available mostly for three ions, i.e. Al-like W LXII [23], Mg-like W LXIII [23] and Na-like W LXIV [27]. Therefore, we confine our comparisons to these three ions. In Table O we compare the
$f$-values for common E1 transitions with the results of Safronova and Safronova [23]. Both sets of data agree very well for all transitions. Similarly, for a few weak transitions ($f \sim 10^{-4}$), such as 1–22, 2–3 and 14–19, the ratio R is up to 1.7 and is closer to unity for the comparatively strong transitions. Similar comparison with their results for transitions in W LXIII is shown in Table P. For the common transitions listed here, R is unity for all, and $f$-values agree closely for most with only a few exceptions, such as 20–32, 21–30 and 26–34 for which discrepancies are a factor of two. However, we note that the $f$- (or $A$-) values of [23] are only for a small number of transitions whereas our results listed in Tables 12 and 13 cover a much wider range.

Vilkas et al. [27] have listed $A$-values for some (not all) transitions of W LXV and in Table Q we compare their results with our calculations with GRASP, but only from the lowest three to higher excited levels. Additionally we have listed the $f$-values to indicate the strength of transitions. As for other W ions, R is also listed for these transitions and is within a few percent of unity, irrespective of the $f$-value. There are no appreciable differences between the two sets of $A$-values and discrepancies, if any, are (generally) within $\sim 20\%$.

The comparisons of $A$- ($f$-) values discussed above are only for a subset of transitions. Considering a wider range, for a majority of strong transitions ($f \geq 0.01$) R is often within 20% of unity, as already seen in Tables O, P and Q. However, there are (as always) some exceptions. For example, there are only six transitions of W LXIII with $f > 0.01$ for which R is up to 1.6, namely 148–166 ($f = 0.011$, $R = 1.3$), 158–173 ($f = 0.021$, $R = 1.3$), 160–174 ($f = 0.028$, $R = 1.6$), 161–175 ($f = 0.025$, $R = 1.4$), 162–176 ($f = 0.027$, $R = 1.4$), and 163–177 ($f = 0.029$, $R = 1.6$). Therefore, based on this and other comparisons already discussed, our assessment of accuracy for the $f$-values for a majority of strong transitions is $\sim 20\%$. Finally, for much weaker transitions (often with $f \leq 10^{-4}$), R can be several orders of magnitude and it is very difficult to assess the accuracy of the $f$-values because results are often much more variable with CI and/or codes. Generally, such transitions do not make an appreciable contribution to plasma modelling and their results are mostly required for completeness.

4. Lifetimes

The lifetime $\tau$ of a level $j$ is given by $1.0 / \sum A_{ji}$ and the summation includes $A$-values from all types of transitions, i.e. E1, E2, M1, and M2. Since this is a measurable quantity it helps to assess the accuracy of $A$-values, particularly when a single (type of) transition dominates. Unfortunately, to our knowledge no measurements of $\tau$ are available for the levels of the W ions considered here, but in Tables 1–8 we list our calculated results. Previous theoretical results are available for two ions, i.e. W LXII [12] and W LXV [27]. Unfortunately, the $\tau$ of S. Aggarwal et al. [12] contain large errors, by up to 14 orders of magnitude, for over 90% of the levels of W LXII and bear no relationship to the $A$-values, as already discussed [24]. For W LXV, the reported $\tau$ of Vilkas et al. [27] are included in Table 7, and there is no significant discrepancy for any level.

5. Conclusions

Energy levels and radiative rates for E1, E2, M1, and M2 transitions are reported for eight W ions (W LIX to W LXVI). A large number of levels are considered for each ion and the data sets reported here are significantly larger than available in the literature. For our calculations the GRASP code has been adopted, although FAC has also been utilised for the determination of energy levels to assess the importance of CI, larger than that considered in GRASP. It is concluded that CI beyond a certain level does not appreciably improve the level energies. Differences between the GRASP and FAC energies, and the available experimental and theoretical values, are often smaller than 0.5 Ryd, or equivalently the listed energy levels for all W ions are assessed to be accurate to
better than 1%, but scope remains for improvement. A similar assessment of accuracy for the corresponding $A$-values is not feasible, mainly because of the paucity of other comparable results. However, for strong transitions (with large $f$-values), the accuracy for $A$-values and lifetimes may be $\sim 20\%$. Lifetimes for these levels are also listed although no measurements are currently available in the literature. However, previous theoretical values are available for most levels of W LXV and there is no discrepancy with our work.

Acknowledgments

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Appendix A. Supplementary data

Owing to space limitations, only parts of Tables 9–16 are presented here, the full tables being made available as supplemental material in conjunction with the electronic publication of this work. Supplementary data associated with this article can be found, in the online version, at doi:n.nnnn/j.adt.2016.nn.nnn.

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### Table A
Comparison of threshold energies (in Ryd) for the lowest 20 levels of W LIX.

| Index | Configuration | Level | NIST | GRASP1 | GRASP2 | FAC1 | FAC2 |
|-------|---------------|-------|------|--------|--------|------|------|
| 1     | 3s3p6         | 3P1   | 0.31 | 0.32   | 0.32   | 0.31 | 0.31 |
| 2     | 3s3p5         | 3S0   | 0.01 | 0.01   | 0.01   | 0.01 | 0.01 |
| 3     | 3s3p5(3s)3d   | 3D0   | 0.17 | 0.17   | 0.17   | 0.17 | 0.17 |
| 4     | 3s3p5(3p)3d   | 3P0   | 0.17 | 0.17   | 0.17   | 0.17 | 0.17 |
| 5     | 3s3p5(3s)3d   | 3F0   | 0.17 | 0.17   | 0.17   | 0.17 | 0.17 |
| 6     | 3s3p5(3p)3d   | 3P0   | 0.17 | 0.17   | 0.17   | 0.17 | 0.17 |
| 7     | 3s3p5(3s)3d   | 3F0   | 0.17 | 0.17   | 0.17   | 0.17 | 0.17 |
| 8     | 3s3p5(3p)3d   | 3P0   | 0.17 | 0.17   | 0.17   | 0.17 | 0.17 |
| 9     | 3s3p5(3s)3d   | 3F0   | 0.17 | 0.17   | 0.17   | 0.17 | 0.17 |
| 10    | 3s3p5         | 3P1   | 0.17 | 0.17   | 0.17   | 0.17 | 0.17 |
| 11    | 3s3p5(3s)3d   | 3D0   | 0.17 | 0.17   | 0.17   | 0.17 | 0.17 |
| 12    | 3s3p5         | 3P1   | 0.17 | 0.17   | 0.17   | 0.17 | 0.17 |
| 13    | 3s3p5(3s)3d   | 3D0   | 0.17 | 0.17   | 0.17   | 0.17 | 0.17 |
| 14    | 3s3p5(3p)3d   | 3P0   | 0.17 | 0.17   | 0.17   | 0.17 | 0.17 |
| 15    | 3s3p5         | 3P1   | 0.17 | 0.17   | 0.17   | 0.17 | 0.17 |
| 16    | 3s3p5         | 3P1   | 0.17 | 0.17   | 0.17   | 0.17 | 0.17 |
| 17    | 3s3p5(3s)3d   | 3D0   | 0.17 | 0.17   | 0.17   | 0.17 | 0.17 |
| 18    | 3s3p5(3p)3d   | 3P0   | 0.17 | 0.17   | 0.17   | 0.17 | 0.17 |
| 19    | 3s3p5(3s)3d   | 3D0   | 0.17 | 0.17   | 0.17   | 0.17 | 0.17 |
| 20    | 3s3p5(3p)3d   | 3P0   | 0.17 | 0.17   | 0.17   | 0.17 | 0.17 |

NIST: http://www.nist.gov/pml/data/asd.cfm

GRASP1: Present results with the GRASP code. Numbers outside and inside a bracket correspond to EV and the level, respectively. See Table 1 for the definition of all levels.

GRASP2: Present results with the GRASP code from 64 configurations and 12 652 levels

FAC1: Present results with the FAC code from 2762 levels

FAC2: Present results with the FAC code from 38 694 levels

### Table B
Eigenvectors (EV) for the lowest 20 levels of W LIX from the GRASP code. Numbers outside and inside a bracket correspond to EV and the level, respectively. See Table 1 for the definition of all levels.

| Index | Configuration | Level | Eigenvectors |
|-------|---------------|-------|--------------|
| 1     | 3s3p5         | 3P1   | 0.67(1)+0.31(12) |
| 2     | 3s3p5         | 3P1   | 0.36(46)+0.64(2) |
| 3     | 3s3p5(3s)3d   | 3D0   | 0.16(3)+0.08(41)+0.19(18)+0.06(45)+0.10(26)+0.23(108)+0.12(132) |
| 4     | 3s3p5(3p)3d   | 3P0   | 0.26(19)+0.14(4)+0.12(37)+0.48(105) |
| 5     | 3s3p5(3s)3d   | 3D0   | 0.24(5)+0.10(14)+0.14(4)+0.18(30)+0.27(107) |
| 6     | 3s3p5(3p)3d   | 3P0   | 0.13(9)+0.12(106)+0.21(22)+0.05(44)+0.27(6)+0.06(136)+0.14(40) |
| 7     | 3s3p5(3s)3d   | 3D0   | 0.26(32)+0.14(25)+0.10(7)+0.08(130) |
| 8     | 3s3p5(3p)3d   | 3D0   | 0.10(3)+0.14(4)+0.16(8)+0.07(28)+0.04(108)+0.22(39)+0.19(132) |
| 9     | 3s3p5(3s)3d   | 3D0   | 0.14(9)+0.09(106)+0.06(22)+0.17(27)+0.30(136)+0.17(40) |
| 10    | 3s3p5         | 3P1   | 0.98(10) |
| 11    | 3s3p5(3s)3d   | 3D0   | 0.22(35)+0.14(11)+0.08(29)+0.09(30)+0.14(107)+0.24(147) |
| 12    | 3s3p5         | 3D1   | 0.31(1)+0.67(12) |
| 13    | 3s3p5(3s)3d   | 3D0   | 0.23(59)+0.06(88)+0.10(96)+0.05(285)+0.05(350)+0.08(38)+0.06(277)+0.22(13)+0.07(325) |
| 14    | 3s3p5(3p)3d   | 3P0   | 0.28(14)+0.16(85)+0.04(114)+0.21(42)+0.21(37)+0.10(342) |
| 15    | 3s3p5         | 3P2   | 0.07(28)+0.85(15) |
| 16    | 3s3p5         | 3P2   | 0.12(5)+0.05(11)+0.11(43)+0.24(86)+0.36(16) |
| 17    | 3s3p5(3s)3d   | 3F1   | 0.23(57)+0.16(221)+0.05(262)+0.08(87)+0.10(139)+0.05(282)+0.30(17) |
| 18    | 3s3p5(3p)3d   | 3P0   | 0.29(3)+0.10(41)+0.40(18)+0.13(8)+0.04(26) |
| 19    | 3s3p5(3s)3d   | 3D0   | 0.53(19)+0.21(4)+0.24(37) |
| 20    | 3s3p5(3p)3d   | 3D1   | 0.32(5)+0.05(35)+0.40(20)+0.07(11)+0.06(86)+0.05(16) |
## Table C
Comparison of threshold energies (in Ryd) for the lowest 25 levels of W Lx.

| Index | Configuration | Level          | NIST  | GRASP1 | GRASP2 | FAC1 | FAC2 |
|-------|---------------|----------------|-------|--------|--------|------|------|
| 1     | 3s²3p³        | ²D₅/₂          | 0.0000| 0.0000 | 0.0000 | 0.0000| 0.0000|
| 2     | 3s²3p³(³P)3d  | ⁴F₃/₂          | 16.6821| 16.9403| 16.9357| 16.8671| 16.8529|
| 3     | 3s²3p³(¹S)3d  | ²D₃/₂          | 23.903 | 23.8688| 23.8613| 23.8040| 23.7839|
| 4     | 3s²3p¹        | ²S₀           | 25.060 | 25.0648| 25.0619| 25.0905| 25.0865|
| 5     | 3s²3p³        | ²D₅/₂          | 25.9556| 25.9490| 25.9411| 25.9727| 25.9639|
| 6     | 3s²3p¹        | ²P₀           | 27.019 | 27.0845| 27.0831| 27.1065| 27.1049|
| 7     | 3s²3p⁴        | ⁴P₅/₂          | 37.9315| 37.9970| 38.0129| 37.9087| 37.9134|
| 8     | 3s²3p⁴        | ⁴P₃/₂          | 40.242 | 40.1880| 40.1973| 40.1132| 40.1082|
| 9     | 3s²3p⁴        | ²S₁/₂          | 40.205 | 40.3454| 40.3636| 40.2582| 40.2632|
| 10    | 3s²3p⁴(⁴P)3d  | ⁴F₅/₂          | 42.01  | 41.8139| 41.8076| 41.7643| 41.7479|
| 11    | 3s²3p⁴(⁴P)3d  | ⁴D₁/₂          | 42.16  | 42.0470| 42.0473| 41.9973| 41.9888|
| 12    | 3s²3p⁴(⁴P)3d  | ⁴G₁/₂          | 42.24  | 42.0827| 42.0820| 42.0263| 42.0159|
| 13    | 3s²3p⁴(⁴P)3d  | ⁴G₇/₂          | 42.97  | 42.7366| 42.7255| 42.6856| 42.6644|
| 14    | 3s²3p⁴(⁴P)3d  | ⁴D₇/₂          | 44.848 | 44.9721| 44.9564| 44.9235| 44.8978|
| 15    | 3s²3p⁴(⁴D)3d  | ⁴P₁/₂          | 45.51  | 45.7510| 45.7334| 45.6952| 45.6683|
| 16    | 3s²3p⁴(⁴D)3d  | ⁴D₅/₂          | 45.6572| 45.8196| 45.8091| 45.7563| 45.7341|
| 17    | 3s²3p⁴(⁴D)3d  | ⁴F₇/₂          | 47.96  | 47.7759| 47.7717| 47.7352| 47.7188|
| 18    | 3s²3p⁴(⁴P)3d  | ⁴P₃/₂          | 48.90  | 48.7073| 48.7034| 48.6656| 48.6501|
| 19    | 3s²3p⁴(⁴D)3d  | ⁴G₀/₂          | 48.98  | 48.7536| 48.7404| 48.7119| 48.6861|
| 20    | 3s²3p⁴(⁴D)3d  | ⁴F₅/₂          | 49.19  | 48.9732| 48.9665| 48.9329| 48.9141|
| 21    | 3s²3p⁴(⁴P)3d  | ⁴P₅/₂          | 50.74  | 50.5135| 50.4973| 50.4698| 50.4412|
| 22    | 3s²3p⁴(⁴D)3d  | ⁴F₇/₂          | 50.87  | 50.5992| 50.5800| 50.5583| 50.5262|
| 23    | 3s²3p⁴(³P)3d  | ⁴D₁/₂          | 51.38  | 51.2398| 51.2202| 51.1970| 51.1682|
| 24    | 3s²3p⁴(³P)3d  | ²S₁/₂          | 51.67  | 51.5331| 51.5132| 51.4871| 51.4582|
| 25    | 3s²3p⁴        | ⁴P₅/₂          | 52.18  | 52.2859| 52.2799| 52.3345| 52.3257|

NIST: [http://www.nist.gov/pml/data/asd.cfm](http://www.nist.gov/pml/data/asd.cfm)
GRASP1: Present results with the GRASP code from 15 configurations and 1313 levels
GRASP2: Present results with the GRASP code from 35 configurations and 3533 levels
FAC1: Present results with the FAC code from 1313 levels
FAC2: Present results with the FAC code from 14 608 levels
| Index | Configuration | Level     | Eigenvectors          |
|-------|---------------|-----------|-----------------------|
| 1     | 3s^2p^4      | 2^D^o_{5/2} | 0.25(4)+0.27(1)+0.48(25) |
| 2     | 3s^2p^4(3P)3d | 4^F^o_{5/2} | 0.34(2)+0.12(12)+0.10(23)+0.11(18)+0.31(60) |
| 3     | 3s^3p^1(1S)3d | 2^D^o_{5/2} | 0.17(10)+0.20(57)+0.14(21)+0.15(20)+0.30(3) |
| 4     | 3s^3p^1      | 4^S^o_{5/2} | 0.55(4)+0.45(1)       |
| 5     | 3s^3p^1      | 2^D^o_{5/2} | 1.00(5)               |
| 6     | 3s^3p^1      | 2^P^o_{1/2} | 0.98(6)               |
| 7     | 3s^3p^1      | 4^P^o_{5/2} | 0.66(7)+0.27(45)      |
| 8     | 3s^3p^1      | 2^P^o_{1/2} | 0.08(2)+0.06(58)+0.11(18)+0.06(16)+0.11(41)+0.32(8)+0.24(51) |
| 9     | 3s^3p^1      | 2^S^o_{1/2} | 0.05(59)+0.07(24)+0.24(137)+0.07(48)+0.53(9) |
| 10    | 3s^3p^1(3P)3d | 4^F^o_{5/2} | 0.46(10)+0.16(20)+0.29(74) |
| 11    | 3s^3p^1(3P)3d | 4^D^o_{5/2} | 0.79(11)+0.04(59)+0.14(70) |
| 12    | 3s^3p^1(3P)3d | 4^D^o_{5/2} | 0.32(2)+0.28(12)+0.12(18)+0.12(16)+0.05(73)+0.04(51) |
| 13    | 3s^3p^1(1D)3d | 2^D^o_{5/2} | 0.18(17)+0.14(56)+0.53(13)+0.12(22) |
| 14    | 3s^3p^1(3P)3d | 2^D^o_{5/2} | 0.10(10)+0.10(57)+0.12(21)+0.30(14)+0.24(74)+0.06(72) |
| 15    | 3s^3p^1(1D)3d | 2^P^o_{1/2} | 0.30(59)+0.35(15)+0.18(24)+0.08(9) |
| 16    | 3s^3p^1(1D)3d | 2^D^o_{5/2} | 0.22(58)+0.08(18)+0.26(16)+0.14(73)+0.13(8)+0.07(51) |
| 17    | 3s^3p^1(3P)3d | 4^E^o_{7/2} | 0.37(17)+0.48(67)+0.07(56)+0.07(22) |
| 18    | 3s^3p^1(3P)3d | 2^P^o_{1/2} | 0.16(12)+0.23(58)+0.05(23)+0.25(18)+0.06(16)+0.20(73) |
| 19    | 3s^3p^1(1D)3d | 2^G^o_{9/2} | 0.37(69)+0.62(19) |
| 20    | 3s^3p^1(3P)3d | 2^F^o_{5/2} | 0.04(10)+0.22(57)+0.07(21)+0.32(20)+0.04(74)+0.25(72) |
| 21    | 3s^3p^1(3P)3d | 4^P^o_{5/2} | 0.35(21)+0.10(20)+0.14(14)+0.08(74)+0.27(72) |
| 22    | 3s^3p^1(1D)3d | 2^P^o_{1/2} | 0.17(17)+0.05(67)+0.18(56)+0.15(13)+0.44(22) |
| 23    | 3s^3p^1(3P)3d | 2^D^o_{5/2} | 0.05(2)+0.11(12)+0.46(23)+0.14(16)+0.22(73) |
| 24    | 3s^3p^1(1D)3d | 2^S^o_{1/2} | 0.31(70)+0.23(15)+0.36(24) |
| 25    | 3s^3p^1      | 2^P^o_{1/2} | 0.19(4)+0.28(1)+0.50(25) |
Table E
Comparison of threshold energies (in Ryd) for the lowest 21 levels of W LXI.

| Index | Configuration | Level | NIST | GRASP1 | GRASP2 | FAC1 | FAC2 |
|-------|---------------|-------|------|--------|--------|------|------|
| 1     | 3s²3p²        | 1p₀   | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 |
| 2     | 3s²3p²        | 1p₁   | 25.5337 | 25.5392 | 25.5395 | 25.5650 | 25.5675 |
| 3     | 3s²3p²        | 1D₂   | 26.2946 | 26.2402 | 26.2351 | 26.2574 | 26.2587 |
| 4     | 3s³p³         | 1S₀    | 38.2094 | 38.0581 | 38.0606 | 37.9699 | 37.9709 |
| 5     | 3s³p³         | 1D₁    | 39.9800 | 40.1129 | 40.1071 | 40.0211 | 40.0210 |
| 6     | 3s²3p³d       | 1F₂    | 41.7903 | 41.7744 | 41.7215 | 41.7222 |
| 7     | 3s²3p³d       | 1F₃    | 45.1086 | 45.0826 | 45.0158 | 45.0129 |
| 8     | 3s²3p³d       | 3P₂    | 49.57   | 49.1925 | 49.1738 | 49.1246 | 49.1247 |
| 9     | 3s²3p³d       | 3P₃    | 49.65   | 49.2768 | 49.2540 | 49.2059 | 49.2052 |
| 10    | 3s³p²         | 1P₂    | 52.27   | 52.3039 | 52.2993 | 52.3463 | 52.3487 |
| 11    | 3s³p²         | 1S₀    | 53.71   | 53.8224 | 53.8202 | 53.8658 | 53.8642 |
| 12    | 3s³p²+4P₁3d   | 3F₁    | 54.6247 | 54.6092 | 54.4384 | 54.4378 |
| 13    | 3s³p²+4P₁3d   | 3P₂    | 55.1766 | 55.1588 | 54.9863 | 54.9850 |
| 14    | 3s³p²+4P₁3d   | 3P₃    | 61.6560 | 61.6353 | 61.4690 | 61.4679 |
| 15    | 3s³p²+4P₁3d   | 3F₂    | 62.7077 | 62.6817 | 62.5113 | 62.5082 |
| 16    | 3s³p³         | 1D₂    | 63.01   | 62.9640 | 62.9654 | 62.9200 | 62.9206 |
| 17    | 3s³p³         | 3D₁    | 64.46   | 64.3993 | 64.3357 | 64.2689 | 64.2712 |
| 18    | 3s³p³         | 3P₀    | 65.29   | 65.1798 | 65.1832 | 65.1238 | 65.1237 |
| 19    | 3s³p³         | 3P₁    | 66.52   | 66.2880 | 66.2870 | 66.2268 | 66.2275 |
| 20    | 3s³p³         | 1D₁    | 66.51   | 66.2776 | 66.2699 | 66.2141 | 66.2160 |
| 21    | 3s³p³         | 1S₁    | 67.24   | 67.1867 | 67.1794 | 67.1047 | 67.1036 |

NIST: http://www.nist.gov/pml/data/asp.cfm
GRASP1: Present results with the GRASP code from 12 configurations and 518 levels
GRASP2: Present results with the GRASP code from 48 configurations and 4364 levels
FAC1: Present results with the FAC code from 9798 levels
FAC2: Present results with the FAC code from 27 122 levels

Table F
Eigenvectors (EV) for the lowest 21 (plus 3P₀ and 1P₁ of 3s3p³) levels of W LXI from the GRASP code. Numbers outside and inside a bracket correspond to EV and the level, respectively. See Table 3 for the definition of all levels.

| Index | Configuration | Level | Eigenvectors |
|-------|---------------|-------|--------------|
| 1     | 3s²3p²        | 3P₀   | 0.69(1)+0.31(11) |
| 2     | 3s²3p²        | 3P₁   | 1.00(2) |
| 3     | 3s²3p²        | 1D₂   | 0.35(10)+0.64(3) |
| 4     | 3s³p³         | 5S₀   | 0.27(4)+0.16(16)+0.08(20)+0.46(64) |
| 5     | 3s³p³         | 5D₁   | 0.14(21)+0.28(5)+0.16(19)+0.24(69)+0.09(7)+0.05(29) |
| 6     | 3s²3p³d       | 3F₂   | 0.74(6)+0.19(27) |
| 7     | 3s²3p³d       | 3D₁   | 0.04(21)+0.04(5)+0.05(69)+0.44(7)+0.14(24)+0.25(29) |
| 8     | 3s³p³d        | 3P₀   | 0.34(23)+0.45(6)+0.14(27) |
| 9     | 3s³p³d        | 3F₂   | 0.50(9)+0.22(28)+0.26(22) |
| 10    | 3s³p²         | 3P₂   | 0.64(10)+0.35(3) |
| 11    | 3s³p²         | 1S₀   | 0.30(1)+0.67(11) |
| 12    | 3s³p³(8P₁)3d  | 5F₁   | 0.38(12)+0.07(32)+0.05(57)+0.08(42)+0.05(137)+0.30(110) |
| 13    | 3s³p³(8P₁)3d  | 3P₂   | 0.18(30)+0.11(105)+0.08(134)+0.12(13)+0.12(45)+0.21(113)+0.09(135) |
| 14    | 3s³p³(8P₁)3d  | 5P₃   | 0.13(33)+0.19(106)+0.15(14)+0.04(49)+0.08(60)+0.05(116)+0.30(132) |
| 15    | 3s³p³(8P₁)3d  | 3F₂   | 0.09(30)+0.05(105)+0.25(15)+0.07(134)+0.08(119)+0.07(63)+0.09(113)+0.21(135) |
| 16    | 3s³p³         | 3D₂   | 0.45(4)+0.49(16) |
| 17    | 3s³p³         | 3D₁   | 0.94(17) |
| 18    | 3s³p³         | 3P₀   | 0.86(18)+0.14(25) |
| 19    | 3s³p³         | 3P₁   | 0.18(21)+0.20(5)+0.34(19)+0.12(69)+0.04(7)+0.12(24) |
| 20    | 3s³p³         | 1D₂   | 0.08(4)+0.08(16)+0.55(20)+0.07(6)+0.12(23)+0.08(27) |
| 21    | 3s³p³         | 3S₁   | 0.32(21)+0.20(5)+0.26(19)+0.18(69) |
| 64    | 3s³p³         | 3P₁   | 0.17(4)+0.16(16)+0.14(20)+0.50(64) |
| 69    | 3s³p³         | 1P₁   | 0.23(21)+0.23(5)+0.14(19)+0.35(69) |
### Table G
Comparison of threshold energies (in Ryd) for the lowest 21 levels of W LXII.

| Index | Configuration | Level | NIST | GRASP2 | GRASP3 | FAC1 | FAC2 | RMBPT |
|-------|---------------|-------|------|--------|--------|------|------|--------|
| 1     | 3s\(^2\)3p    | \(^2\)P\(_{1/2}\) | 00.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| 2     | 3s3p\(^2\)    | \(^4\)P\(_{1/2}\) | 12.3076 | 12.4425 | 12.4422 | 12.3220 | 12.3204 | 12.3018 |
| 3     | 3s\(^2\)3p    | \(^2\)P\(_{3/2}\) | 26.7311 | 26.7061 | 26.7060 | 26.7306 | 26.7314 | 26.7056 |
| 4     | 3s3p\(^2\)    | \(^4\)P\(_{3/2}\) | 36.7742 | 36.8823 | 36.8835 | 36.7935 | 36.7959 | 36.7790 |
| 5     | 3s3p\(^2\)    | \(^2\)D\(_{5/2}\) | 38.1090 | 38.2380 | 38.2375 | 38.1447 | 38.1457 | 38.1110 |
| 6     | 3s3p\(^2\)    | \(^2\)D\(_{3/2}\) | 39.6875 | 39.7869 | 39.787 | 39.7028 | 39.7033 | 39.6637 |
| 7     | 3s3p\(^2\)    | \(^2\)P\(_{1/2}\) | 40.4238 | 40.5824 | 40.5806 | 40.4826 | 40.4819 | 40.4024 |
| 8     | 3s\(^2\)3d    | \(^2\)D\(_{5/2}\) | 43.9039 | 44.0171 | 44.0103 | 43.9482 | 43.9448 | 43.8775 |
| 9     | 3s\(^2\)3d    | \(^2\)D\(_{3/2}\) | 49.263 | 49.3268 | 49.3215 | 49.2778 | 49.2759 | 49.2626 |
| 10    | 3p\(^3\)      | \(^2\)D\(_{5/2}\) | 51.9171 | 51.9167 | 51.7504 | 51.7496 | 51.7270 | 51.7204 |
| 11    | 3s3p\(^3\)    | \(^4\)F\(_{5/2}\) | 52.9289 | 52.9278 | 52.7221 | 52.7218 | 52.6746 | 52.6739 |
| 12    | 3s3p\(^3\)    | \(^4\)F\(_{7/2}\) | 53.7715 | 53.7680 | 53.5988 | 53.5989 | 53.5817 | 53.5817 |
| 13    | 3s3p\(^3\)    | \(^4\)D\(_{5/2}\) | 55.7589 | 55.7524 | 55.5868 | 55.5849 | 55.5323 | 55.5323 |
| 14    | 3s3p\(^3\)    | \(^4\)D\(_{3/2}\) | 56.2688 | 56.2632 | 56.0908 | 56.0883 | 56.0220 | 56.0220 |
| 15    | 3s3p\(^3\)    | \(^4\)P\(_{5/2}\) | 59.7857 | 59.7835 | 59.6243 | 59.6251 | 59.6240 | 59.6240 |
| 16    | 3s3p\(^3\)    | \(^4\)P\(_{3/2}\) | 60.8471 | 60.8418 | 60.6804 | 60.6797 | 60.6611 | 60.6611 |
| 17    | 3s3p\(^3\)\(^{(1)}\)P\(^3\) | \(^2\)P\(_{1/2}\) | 61.6177 | 61.6112 | 61.4480 | 61.4457 | 61.4177 | 61.4177 |
| 18    | 3s3p\(^3\)\(^{(1)}\)P\(^3\) | \(^2\)D\(_{5/2}\) | 62.0001 | 61.9931 | 61.8237 | 61.8206 | 61.7773 | 61.7773 |
| 19    | 3s3p\(^3\)    | \(^4\)P\(_{3/2}\) | 64.372 | 64.4986 | 64.4980 | 64.4306 | 64.4321 | 64.3709 |
| 20    | 3s3p\(^3\)    | \(^2\)S\(_{1/2}\) | 67.115 | 67.2861 | 67.2849 | 67.2135 | 67.2094 | 67.1156 |
| 21    | 3p\(^3\)\(^{(1)}\)P\(^3\) | \(^4\)F\(_{5/2}\) | 67.479 | 67.8062 | 67.8002 | 67.3757 | 67.3714 | 67.4809 |

NIST: [http://www.nist.gov/pml/data/asd.cfm](http://www.nist.gov/pml/data/asd.cfm)

GRASP2: Present results with the GRASP code from 33 configurations and 928 levels

GRASP3: Present results with the GRASP code from 63 configurations and 2003 levels

FAC1: Present results with the FAC code from 2003 levels

FAC2: Present results with the FAC code from

RMBPT: Earlier results of Safronova and Safronova [23]
Table H
Eigenvectors (EV) for the lowest 21 (plus 68) levels of W LXII from the GRASP code. Numbers outside and inside a bracket correspond to EV and the level, respectively. See Table 4 for the definition of all levels.

| Index | Configuration | Level | Eigenvectors |
|-------|----------------|-------|--------------|
| 1     | 3s^3p          | 2P^o/2| 1.00( 1)     |
| 2     | 3s^3p^2        | 2P^o/2| 0.52( 2)+0.17( 7)+0.30( 20) |
| 3     | 3s^3p          | 2P^o/2| 0.98( 3)     |
| 4     | 3s^3p^2        | 4P^o/2| 0.88( 4)+0.08( 6) |
| 5     | 3s^3p^2        | 2D^o/2| 0.37(19)+0.61(5) |
| 6     | 3s^3p^2        | 2D^o/2| 0.28(22)+0.49(6)+0.18(8) |
| 7     | 3s^3p^2        | 2P^o/2| 0.29(2)+0.69(7) |
| 8     | 3s^23d         | 2D^o/2| 0.08(22)+0.12(6)+0.79(8) |
| 9     | 3s^23d         | 2D^o/2| 0.96(9)      |
| 10    | 3p^1           | 2D^o/2| 0.23(11)+0.11(18)+0.06(37)+0.12(25)+0.16(10)+0.26(68) |
| 11    | 3s3p3d         | 4P^o/2| 0.55(11)+0.10(31)+0.07(25)+0.08(10)+0.14(68) |
| 12    | 3s3p3d         | 4P^o/2| 0.42(12)+0.07(17)+0.18(35)+0.24(32) |
| 13    | 3s3p3d         | 4D^o/2| 0.58(13)+0.06(28)+0.10(39)+0.26(33) |
| 14    | 3s3p3d         | 4D^o/2| 0.32(14)+0.18(27)+0.20(37)+0.13(31)+0.05(40)+0.04(68) |
| 15    | 3s3p3d         | 4P^o/2| 0.11(12)+0.31(29)+0.38(15)+0.07(17)+0.08(35) |
| 16    | 3s3p3d         | 4P^o/2| 0.42(16)+0.23(30)+0.08(36)+0.26(38) |
| 17    | 3s3p(3P)3d     | 2P^o/2| 0.13(12)+0.12(15)+0.46(17)+0.05(32)+0.21(41) |
| 18    | 3s3p(3P)3d     | 2D^o/2| 0.11(14)+0.05(27)+0.35(18)+0.16(37)+0.20(40) |
| 19    | 3s3p^2         | 2P^o/2| 0.61(19)+0.38(5) |
| 20    | 3s3p^2         | 2S^o/2| 0.18(2)+0.14(7)+0.67(20) |
| 21    | 3p(3P)3d       | 4F^o/2| 0.06(22)+0.04(6)+0.30(21)+0.10(43)+0.08(59)+0.10(99)+0.27(93) |
| ...   |                |       |              |
| 68    | 3p^1           | 2P^o/2| 0.19(25)+0.28(10)+0.50(68) |
Table I
Comparison of threshold energies (in Ryd) for the lowest 35 levels of W LXIII.

| Index | Configuration | Level | NIST | GRASP | FAC | RMBPT |
|-------|---------------|-------|------|-------|-----|-------|
| 1     | 3s²           | 1S₀   | 00.0000 | 0.0000 | 0.0000 | 0.0000 |
| 2     | 3s3p          | 3P₀   | 10.261 | 10.3595 | 10.2414 | 10.2650 |
| 3     | 3s³           | 3P₀   | 11.4036 | 11.5247 | 11.4028 | 11.4104 |
| 4     | 3p²           | 3P₀   | 24.7520 | 24.5032 | 24.4911 | 24.4911 |
| 5     | 3s3p          | 1P₀   | 37.398 | 37.4521 | 37.3609 | 37.3922 |
| 6     | 3s³           | 3P₀   | 40.0821 | 40.2273 | 40.1296 | 40.1225 |
| 7     | 3p³           | 1D₂   | 50.6187 | 50.4140 | 50.4140 | 50.4140 |
| 8     | 3p³           | 3P₁   | 54.0418 | 54.0506 | 54.0421 | 54.0421 |
| 9     | 3s3d          | 1D₀   | 53.100 | 53.0898 | 53.0968 | 53.0968 |
| 10    | 3s3d          | 3D₁   | 60.490 | 60.4812 | 60.4926 | 60.4926 |
| 11    | 3s3d          | 3D₀   | 64.4267 | 64.1328 | 64.1616 | 64.1616 |
| 12    | 3s3d          | 3D₂   | 67.0032 | 66.7097 | 66.6958 | 66.6958 |
| 13    | 3s3d          | 3D₁   | 71.9267 | 71.6393 | 71.6688 | 71.6688 |
| 14    | 3s3d          | 3F₀   | 72.1483 | 71.8606 | 71.8875 | 71.8875 |
| 15    | 3s3d          | 3F₁   | 78.4319 | 78.2413 | 78.2584 | 78.2584 |
| 16    | 3s3d          | 3S₀   | 79.8512 | 79.6567 | 79.6637 | 79.6637 |
| 17    | 3s3d          | 3D₂   | 92.4948 | 92.2324 | 92.2537 | 92.2537 |
| 18    | 3s3d          | 3D₁   | 93.2392 | 92.9761 | 92.9927 | 92.9927 |
| 19    | 3s3d          | 3D₀   | 93.2818 | 93.0183 | 93.0311 | 93.0311 |
| 20    | 3s3d          | 3F₁   | 93.2541 | 92.9898 | 92.9946 | 92.9946 |
| 21    | 3s3d          | 3F₀   | 97.7310 | 97.4746 | 97.5357 | 97.5357 |
| 22    | 3s3d          | 3D₂   | 98.6141 | 98.3571 | 98.4030 | 98.4030 |
| 23    | 3s3d          | 3D₁   | 100.0066 | 99.7469 | 99.7687 | 99.7687 |
| 24    | 3s3d          | 3F₂   | 100.9429 | 100.6812 | 100.6989 | 100.6989 |
| 25    | 3s3d          | 3F₁   | 107.5330 | 107.1956 | 107.2079 | 107.2079 |
| 26    | 3s3d          | 3F₀   | 109.5116 | 109.1710 | 109.1870 | 109.1870 |
| 27    | 3s3d          | 3P₀   | 113.3167 | 112.9856 | 113.0263 | 113.0263 |
| 28    | 3s3d          | 3P₁   | 114.2228 | 113.8902 | 113.9201 | 113.9201 |
| 29    | 3s3d          | 3G₄   | 114.3940 | 114.0519 | 114.0755 | 114.0755 |
| 30    | 3s3d          | 3P₁   | 114.6216 | 114.2887 | 114.3189 | 114.3189 |
| 31    | 3s3d          | 3F₄   | 119.7747 | 119.4490 | 119.5071 | 119.5071 |
| 32    | 3s3d          | 3D₂   | 120.5499 | 120.2230 | 120.2754 | 120.2754 |
| 33    | 3s3d          | 3S₀   | 122.6951 | 122.3631 | 122.3938 | 122.3938 |

NIST: [http://www.nist.gov/pml/data/asd.cfm](http://www.nist.gov/pml/data/asd.cfm)

GRASP: Present results with the GRASP code from 58 configurations and 509 levels

FAC: Present results with the FAC code from 991 levels

RMBPT: Earlier results of Safronova and Safronova [23]
### Table J

Eigenvectors (EV) for the lowest 35 levels of W LXIII from the GRASP code. Numbers outside and inside a bracket correspond to EV and the level, respectively. See Table 5 for the definition of all levels.

| Index | Configuration | Level | Eigenvectors |
|-------|---------------|-------|--------------|
| 1     | 3s^2          | 1S_0  | 1.00 (1)     |
| 2     | 3s3p          | 1P_0  | 0.72 (3)+0.27 (6) |
| 3     | 3s3p          | 1P_1  | 0.69 (4)+0.30 (18) |
| 4     | 3p^2          | 1P_0  | 1.00 (5)     |
| 5     | 3s3p          | 1P_1  | 0.27 (3)+0.72 (6) |
| 6     | 3p^2          | 1D_2  | 0.28 (17)+0.56 (7)+0.05 (10)+0.12 (12) |
| 7     | 3p^2          | 1P_1  | 1.00 (8)     |
| 8     | 3s3d          | 1D_1  | 0.06 (17)+0.07 (10)+0.18 (12) |
| 9     | 3s3d          | 1D_2  | 1.00 (11)    |
| 10    | 3s3d          | 1D_3  | 0.26 (10)+0.69 (12) |
| 11    | 3s3d          | 1P_0  | 0.76 (13)+0.20 (24) |
| 12    | 3s3d          | 1D_1  | 0.35 (19)+0.48 (15)+0.14 (24) |
| 13    | 3s3d          | 1D_2  | 0.52 (16)+0.22 (25)+0.26 (22) |
| 14    | 3s3d          | 1D_3  | 0.64 (17)+0.36 (7) |
| 15    | 3p^2          | 1P_2  | 0.31 (4)+0.69 (18) |
| 16    | 3p^2          | 1D_0  | 0.19 (13)+0.52 (19)+0.04 (15)+0.25 (24) |
| 17    | 3p^2          | 1D_2  | 1.00 (20)    |
| 18    | 3p^2          | 1P_0  | 0.36 (14)+0.59 (21)+0.04 (26) |
| 19    | 3p^2          | 1P_1  | 0.48 (16)+0.18 (25)+0.35 (22) |
| 20    | 3p^2          | 1P_2  | 1.00 (23)    |
| 21    | 3p^2          | 1D_0  | 0.11 (19)+0.46 (15)+0.40 (24) |
| 22    | 3p^2          | 1D_3  | 0.61 (25)+0.38 (22) |
| 23    | 3p^2          | 1P_1  | 0.11 (14)+0.23 (21)+0.66 (26) |
| 24    | 3p^2          | 1P_2  | 0.74 (27)+0.23 (34) |
| 25    | 3p^2          | 1P_3  | 0.71 (28)+0.30 (35) |
| 26    | 3p^2          | 1P_0  | 1.00 (29)    |
| 27    | 3p^2          | 1P_1  | 0.21 (27)+0.49 (30)+0.30 (34) |
| 28    | 3p^2          | 1D_2  | 0.29 (33)+0.71 (31) |
| 29    | 3p^2          | 1D_3  | 1.00 (32)    |
| 30    | 3p^2          | 1P_0  | 0.71 (33)+0.29 (31) |
| 31    | 3p^2          | 1P_1  | 1.00 (32)    |
| 32    | 3p^2          | 1P_2  | 0.71 (33)+0.29 (31) |
| 33    | 3p^2          | 1D_2  | 0.06 (27)+0.48 (30)+0.46 (34) |
| 34    | 3p^2          | 1D_3  | 0.30 (28)+0.69 (35) |
Table K
Threshold energies (in Ryd) of the lowest 30 levels of W LXIV and their lifetimes. \((a\pm b \equiv a \times 10^{b})\).

| Index | Configuration | Level | NIST | GRASP | FAC | \(\tau\) (s) |
|-------|---------------|-------|------|-------|-----|-------------|
| 1     | 2p^63s \(^2S_{1/2}\) | 000.0 | 0.000 | 0.000 | .... |            |
| 2     | 2p^63p \(^2P_{3/2}\) | 011.7280 | 11.8989 | 11.7457 | 2.218 | 11          |
| 3     | 2p^63p \(^2P_{1/2}\) | 039.1890 | 39.3365 | 39.2218 | 5.664 | 13          |
| 4     | 2p^63d \(^2D_{3/2}\) | 052.9692 | 53.1127 | 52.9352 | 6.986 | 13          |
| 5     | 2p^63d \(^2D_{5/2}\) | 059.2105 | 59.3372 | 59.1730 | 4.987 | 12          |
| 6     | 2p^64s \(^2S_{1/2}\) | 239.12 | 239.0661 | 238.9973 | 1.501 | 14          |
| 7     | 2p^64p \(^2P_{3/2}\) | 243.92 | 243.9788 | 243.8505 | 1.267 | 14          |
| 8     | 2p^64p \(^2P_{1/2}\) | 255.18 | 255.2154 | 255.0981 | 2.010 | 14          |
| 9     | 2p^64d \(^2D_{3/2}\) | 260.37 | 260.4510 | 260.3002 | 8.821 | 15          |
| 10    | 2p^64d \(^2D_{5/2}\) | 263.09 | 263.1426 | 262.9954 | 8.466 | 15          |
| 11    | 2p^64f \(^2F_{5/2}\) | 265.94 | 265.8618 | 265.7361 | 4.087 | 15          |
| 12    | 2p^64f \(^2F_{7/2}\) | 267.12 | 267.0446 | 266.9176 | 4.198 | 15          |
| 13    | 2p^65s \(^2S_{1/2}\) | 345.593 | 345.3305 | 345.1960 | 1.888 | 14          |
| 14    | 2p^65p \(^2P_{3/2}\) | 348.0234 | 347.7664 | 347.6092 | 1.600 | 14          |
| 15    | 2p^65p \(^2P_{1/2}\) | 353.6728 | 353.4209 | 353.2701 | 2.398 | 14          |
| 16    | 2p^65d \(^2D_{3/2}\) | 356.2383 | 355.9695 | 355.7303 | 1.189 | 14          |
| 17    | 2p^65d \(^2D_{5/2}\) | 357.54 | 357.6240 | 357.3573 | 1.168 | 14          |
| 18    | 2p^65f \(^2F_{5/2}\) | 358.84 | 358.9640 | 358.7180 | 7.736 | 15          |
| 19    | 2p^65f \(^2F_{7/2}\) | 359.46 | 359.5722 | 359.3256 | 7.962 | 15          |
| 20    | 2p^65g \(^2G_{5/2}\) | 359.77 | 359.7585 | 359.5057 | 1.361 | 14          |
| 21    | 2p^65g \(^2G_{3/2}\) | 360.11 | 360.1191 | 359.8662 | 1.378 | 14          |
| 22    | 2p^66s \(^2S_{1/2}\) | 401.9007 | 401.5572 | 401.2183 | 2.653 | 14          |
| 23    | 2p^66p \(^2P_{1/2}\) | 403.3052 | 402.9603 | 402.6252 | 2.262 | 14          |
| 24    | 2p^66p \(^2P_{3/2}\) | 406.5339 | 406.2203 | 406.0029 | 3.266 | 14          |
| 25    | 2p^66d \(^2D_{5/2}\) | 407.9823 | 407.6849 | 407.4072 | 1.742 | 14          |
| 26    | 2p^66d \(^2D_{3/2}\) | 408.7585 | 408.5064 | 408.2452 | 1.735 | 14          |
| 27    | 2p^66f \(^2F_{5/2}\) | 409.5470 | 409.2872 | 409.0284 | 1.310 | 14          |
| 28    | 2p^66f \(^2F_{7/2}\) | 409.8998 | 409.6444 | 409.3902 | 1.351 | 14          |
| 29    | 2p^66g \(^2G_{7/2}\) | 410.0204 | 409.7698 | 409.4186 | 2.328 | 14          |
| 30    | 2p^66g \(^2G_{5/2}\) | 410.2293 | 409.9788 | 409.6276 | 2.357 | 14          |

NIST: http://www.nist.gov/pml/data/asd.cfm
GRASP: Present results with the GRASP code from 50 configurations and 1235 levels
FAC: Present results with the FAC code from 1592 levels

Table L
Comparison of energies (in Ryd) for the common of levels of W LXV.

| Index | Configuration | Level | NIST | GRASP | FAC | MRMP |
|-------|---------------|-------|------|-------|-----|------|
| 1     | 2s^22p^6 \(^1S_{0}\) | 610.640 | 610.2292 | 610.1423 | 610.5354 |
| 3     | 2s^22p^33s \(^1P_{1}\) | 653.859 | 653.7288 | 653.5037 | 653.7409 |
| 9     | 2s^22p^33p \(^1S_{0}\) | 661.307 | 660.9754 | 660.7169 | 661.1325 |
| 11    | 2s^22p^33d \(^3P_{1}\) | 670.246 | 670.5722 | 670.2893 | 670.6958 |
| 17    | 2s^22p^33d \(^1P_{1}\) | 711.936 | 711.7088 | 711.6628 | 712.0517 |
| 19    | 2s^22p^33s \(^3P_{0}\) | 726.088 | 725.8494 | 725.6751 | 725.9370 |
| 21    | 2s^22p^33p \(^3P_{0}\) | 758.302 | 758.6381 | 758.2086 | 758.3025 |
| 27    | 2s^22p^33p \(^3P_{1}\) | 765.027 | 764.8414 | 764.5743 | 764.9308 |
| 29    | 2s^22p^33d \(^3P_{1}\) | 786.651 | 787.2457 | 786.8073 | 786.8504 |

NIST: http://www.nist.gov/pml/data/asd.cfm
GRASP: Present results with the GRASP code from 25 configurations and 157 levels
FAC: Present results with the FAC code from 1147 levels
MRMP: Earlier calculations of Vilka et al. [27]

\(a\): See Table 7 for definition of all levels

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Table M

Eigenvectors (EV) for the lowest 33 levels of W LXV from the GRASP code. Numbers outside and inside a bracket correspond to EV and the level, respectively. See Table 7 for the definition of all levels.

| Index | Configuration | Level | Eigenvectors |
|-------|----------------|-------|--------------|
| 1     | 2s²2p⁶         | ¹S₀   | 1.00(1)      |
| 2     | 2s²2p³s        | ³P₁   | 1.00(2)      |
| 3     | 2s²2p³s        | ¹P₇   | 0.34(19)+0.66(3) |
| 4     | 2s²2p³p        | ³P₁   | 0.09(20)+0.49(4)+0.31(25)+0.10(6) |
| 5     | 2s²2p³p        | ³D₂   | 0.50(5)+0.17(8)+0.34(24) |
| 6     | 2s²2p³p        | ¹P₁   | 0.08(20)+0.36(25)+0.56(6) |
| 7     | 2s²2p³p        | ³D₃   | 1.00(7)      |
| 8     | 2s²2p³p        | ³P₃   | 0.67(8)+0.34(24) |
| 9     | 2s²2p³p        | ¹S₀   | 0.37(21)+0.62(9) |
| 10    | 2s²2p³d        | ³P₀   | 1.00(10)     |
| 11    | 2s²2p³d        | ³P₁   | 0.32(29)+0.66(11) |
| 12    | 2s²2p³d        | ³F₁   | 0.53(12)+0.07(16)+0.40(31) |
| 13    | 2s²2p³d        | ³D₂   | 0.18(28)+0.55(13)+0.10(30)+0.18(15) |
| 14    | 2s²2p³d        | ³P₂   | 1.00(14)     |
| 15    | 2s²2p³d        | ¹D₁   | 0.04(28)+0.06(13)+0.41(30)+0.49(15) |
| 16    | 2s²2p³d        | ³D₃   | 0.71(16)+0.27(31) |
| 17    | 2s²2p³d        | ¹P₇   | 0.18(29)+0.18(11)+0.62(17) |
| 18    | 2s²2p³d        | ³P₀   | 1.00(18)     |
| 19    | 2s²2p³s        | ³P₁   | 0.66(19)+0.34(3) |
| 20    | 2s²2p³s        | ³D₁   | 0.74(20)+0.23(6) |
| 21    | 2s²2p³p        | ³P₀   | 0.62(21)+0.37(9) |
| 22    | 2s²2p³s        | ³S₁   | 0.08(4)+0.86(22) |
| 23    | 2s²2p³s        | ¹S₀   | 1.00(23)     |
| 24    | 2s²2p³p        | ¹D₂   | 0.49(5)+0.17(8)+0.34(24) |
| 25    | 2s²2p³p        | ³S₁   | 0.07(20)+0.42(4)+0.26(25)+0.10(6)+0.14(22) |
| 26    | 2s²2p³p        | ³P₀   | 1.00(26)     |
| 27    | 2s²2p³p        | ³P₁   | 0.66(27)+0.31(33) |
| 28    | 2s²2p³d        | ³P₁   | 0.74(28)+0.20(15) |
| 29    | 2s²2p³d        | ³D₁   | 0.48(29)+0.15(11)+0.35(17) |
| 30    | 2s²2p³p        | ³P₁   | 0.36(13)+0.40(30)+0.14(24) |
| 31    | 2s²2p³d        | ³F₁   | 0.44(12)+0.22(16)+0.34(31) |
| 32    | 2s²2p³p        | ³P₀   | 1.00(32)     |
| 33    | 2s²2p³p        | ¹P₇   | 0.32(27)+0.67(33) |
Table N
Eigenvectors (EV) for the lowest 48 levels of W LXVI from the GRASP code. Numbers outside and inside a bracket correspond to EV and the level, respectively. See Table 8 for the definition of all levels.

| Index | Configuration | Level | Eigenvectors |
|-------|---------------|-------|--------------|
| 1     | 2s2p^4       | 2p^3   | 1.00        |
| 2     | 2s2p^3       | 2p^4   | 1.00        |
| 3     | 2p^5         | 2S      | 1.00        |
| 4     | 2s2p^4 3s    | 4p^5   | 0.69(4)+0.31(28) |
| 5     | 2s2p^3 3s    | 2p^2   | 0.12(26)+0.56(5)+0.32(29) |
| 6     | 2s2p^3 3s    | 2S^2   | 0.23(86)+0.12(27)+0.66(6) |
| 7     | 2s2p^3(P)3p  | 4p^2   | 0.07(31)+0.31(7)+0.18(92)+0.09(13)+0.16(43)+0.17(33) |
| 8     | 2s2p^3(P)3p  | 2D^2   | 0.27(38)+0.12(10)+0.29(8)+0.25(32)+0.07(45) |
| 9     | 2s2p^3(S)3p  | 2P^2   | 0.19(87)+0.04(30)+0.08(40)+0.66(9) |
| 10    | 2s2p^3(P)3p  | 4p^5   | 0.40(10)+0.27(8)+0.07(32)+0.24(45) |
| 11    | 2s2p^3(P)3p  | 2S^2   | 0.09(30)+0.18(40)+0.37(11)+0.32(46) |
| 12    | 2s2p^3(P)3p  | 2D^2   | 0.67(12)+0.32(41) |
| 13    | 2s2p^3(P)3p  | 2P^2   | 0.24(92)+0.15(39)+0.21(13)+0.13(43)+0.12(33)+0.15(14) |
| 14    | 2s2p^3(S)3p  | 2P^2   | 0.13(31)+0.12(7)+0.16(13)+0.04(43)+0.50(14) |
| 15    | 2s2p^3(D)3d  | 2P^2   | 0.32(50)+0.23(58)+0.07(62)+0.22(55)+0.08(15) |
| 16    | 2s2p^3(P)3d  | 2D^2   | 0.13(51)+0.35(16)+0.06(106)+0.10(23)+0.22(54)+0.10(60) |
| 17    | 2s2p^3(P)3d  | 4P^2   | 0.12(49)+0.50(17)+0.05(22)+0.22(63)+0.10(53) |
| 18    | 2s2p^3(P)3d  | 2P^2   | 0.28(56)+0.06(20)+0.34(18)+0.28(52) |
| 19    | 2s2p^3(S)3d  | 2D^2   | 0.17(101)+0.07(58)+0.07(62)+0.62(19) |
| 20    | 2s2p^3(P)3d  | 4D^2   | 0.06(56)+0.41(20)+0.22(18)+0.28(61) |
| 21    | 2s2p^3(P)3d  | 2P^2   | 0.67(21)+0.32(59) |
| 22    | 2s2p^3(P)3d  | 2D^2   | 0.05(49)+0.12(17)+0.50(22)+0.10(63)+0.22(53) |
| 23    | 2s2p^3(P)3d  | 2D^2   | 0.05(16)+0.22(106)+0.14(57)+0.26(23)+0.09(54)+0.21(60) |
| 24    | 2s2p^3(P)3d  | 4p^5   | 0.18(58)+0.19(62)+0.26(24)+0.10(55)+0.21(15) |
| 25    | 2s2p^3(S)3d  | 2D^2   | 0.10(51)+0.11(16)+0.04(57)+0.09(23)+0.16(25) |
| 26    | 2s2p^3(S)3d  | 4D^2   | 0.86(26)+0.12(5) |
| 27    | 2s2p^3(S)3d  | 2S^2   | 0.34(86)+0.67(27) |
| 28    | 2s2p^3(S)3d  | 2D^2   | 0.31(4)+0.67(28) |
| 29    | 2s2p^3(S)3d  | 2D^2   | 0.32(5)+0.66(29) |
| 30    | 2s2p^3(P)3p  | 4p^2   | 0.27(87)+0.52(30)+0.21(11) |
| 31    | 2s2p^3(P)3p  | 4D^2   | 0.56(31)+0.14(39)+0.13(13)+0.07(43)+0.07(33) |
| 32    | 2s2p^3(D)3p  | 2P^2   | 0.12(38)+0.05(10)+0.14(8)+0.53(32)+0.15(45) |
| 33    | 2s2p^3(D)3p  | 2P^2   | 0.12(7)+0.13(92)+0.18(13)+0.25(43)+0.29(33) |
| 34    | 2s2p^3(D)3p  | 2P^2   | 0.12(7)+0.13(92)+0.18(13)+0.25(43)+0.29(33) |
| 35    | 2s2p^3(P)3s  | 4p^2   | 0.96(34) |
| 36    | 2s2p^3(P)3s  | 2P^2   | 0.27(89)+0.67(35) |
| 37    | 2s2p^3(P)3s  | 2P^2   | 0.05(30)+0.06(11)+0.06(46)+0.10(88)+0.20(90)+0.52(36) |
| 38    | 2s2p^3(P)3s  | 4D^2   | 0.04(92)+0.16(89)+0.22(35)+0.52(37) |
| 39    | 2s2p^3(P)3p  | 4D^2   | 0.55(38)+0.28(28)+0.14(8) |
| 40    | 2s2p^3(P)3p  | 2P^2   | 0.24(7)+0.16(92)+0.46(39) |
| 41    | 2s2p^3(P)3p  | 2P^2   | 0.09(87)+0.23(30)+0.23(40)+0.19(11)+0.10(46)+0.10(36) |
| 42    | 2s2p^3(P)3p  | 2P^2   | 0.32(12)+0.67(41) |
| 43    | 2s2p^3(P)3p  | 2P^2   | 0.11(95)+0.44(130)+0.29(42)+0.13(65) |
| 44    | 2s2p^3(D)3p  | 2D^2   | 0.16(92)+0.15(13)+0.29(43)+0.27(33)+0.05(89)+0.05(37) |
| 45    | 2s2p^3(D)3p  | 2D^2   | 0.40(133)+0.17(66)+0.44(44) |
| 46    | 2s2p^3(D)3d  | 2D^2   | 0.14(10)+0.15(8)+0.04(32)+0.52(45) |
| 47    | 2s2p^3(P)3p  | 2P^2   | 0.07(87)+0.34(40)+0.05(11)+0.52(46) |
| 48    | 2s2p^3(P)3p  | 2D^2   | 0.10(91)+0.18(99)+0.08(70)+0.40(47)+0.22(135) |
| 49    | 2s2p^3(P)3p  | 2D^2   | 0.21(95)+0.05(134)+0.08(65)+0.52(48)+0.10(69) |
Table O
Comparison of oscillator strengths ($f$-values, dimensionless) for some transitions of W LXII. $a \pm b \equiv a \times 10^{b}$.
See Table 4 for definition of level indices.

| I | J | RMBPT  | GRASP  | R     |
|---|---|--------|--------|-------|
| 1 | 2 | 3.17\(\pm 2\) | 3.17\(\pm 2\) | 9.8\(\pm 1\) |
| 1 | 4 | 2.07\(\pm 3\) | 2.07\(\pm 3\) | 1.0\(\pm 0\) |
| 1 | 6 | 1.05\(\pm 1\) | 1.05\(\pm 1\) | 1.0\(\pm 0\) |
| 1 | 8 | 4.99\(\pm 1\) | 4.99\(\pm 1\) | 1.0\(\pm 0\) |
| 1 | 20 | 2.07\(\pm 4\) | 2.07\(\pm 4\) | 1.3\(\pm 0\) |
| 1 | 22 | 1.22\(\pm 4\) | 1.22\(\pm 4\) | 7.0\(\pm 1\) |
| 2 | 3 | 3.17\(\pm 4\) | 3.23\(\pm 4\) | 1.7\(\pm 0\) |
| 3 | 4 | 2.48\(\pm 3\) | 2.48\(\pm 3\) | 1.0\(\pm 0\) |
| 3 | 5 | 2.01\(\pm 2\) | 2.01\(\pm 2\) | 1.1\(\pm 0\) |
| 3 | 9 | 1.07\(\pm 2\) | 1.07\(\pm 1\) | 1.1\(\pm 0\) |
| 3 | 19 | 9.34\(\pm 2\) | 9.34\(\pm 2\) | 1.0\(\pm 0\) |
| 3 | 20 | 7.73\(\pm 2\) | 7.73\(\pm 2\) | 9.9\(\pm 1\) |
| 3 | 22 | 2.69\(\pm 1\) | 2.69\(\pm 1\) | 1.0\(\pm 0\) |
| 5 | 17 | 1.27\(\pm 2\) | 1.65\(\pm 2\) | 1.0\(\pm 0\) |
| 12 | 22 | 4.23\(\pm 3\) | 4.23\(\pm 3\) | 9.0\(\pm 1\) |
| 14 | 19 | 1.06\(\pm 4\) | 1.06\(\pm 4\) | 1.4\(\pm 0\) |
| 19 | 29 | 1.38\(\pm 4\) | 1.38\(\pm 4\) | 7.7\(\pm 1\) |
| 19 | 31 | 2.43\(\pm 4\) | 2.43\(\pm 4\) | 1.2\(\pm 0\) |
| 19 | 35 | 5.52\(\pm 2\) | 5.52\(\pm 2\) | 1.0\(\pm 0\) |
| 19 | 36 | 9.69\(\pm 2\) | 9.69\(\pm 2\) | 1.1\(\pm 0\) |
| 19 | 37 | 1.16\(\pm 2\) | 1.16\(\pm 2\) | 1.0\(\pm 0\) |
| 19 | 38 | 6.93\(\pm 2\) | 6.93\(\pm 2\) | 1.1\(\pm 0\) |
| 19 | 40 | 3.91\(\pm 3\) | 3.91\(\pm 3\) | 9.1\(\pm 1\) |
| 22 | 27 | 1.14\(\pm 4\) | 1.14\(\pm 4\) | 9.1\(\pm 1\) |
| 22 | 28 | 1.03\(\pm 3\) | 1.02\(\pm 3\) | 1.0\(\pm 0\) |
| 22 | 33 | 1.01\(\pm 3\) | 1.01\(\pm 3\) | 1.3\(\pm 0\) |
| 22 | 35 | 1.87\(\pm 3\) | 1.87\(\pm 3\) | 1.2\(\pm 0\) |
| 22 | 37 | 1.97\(\pm 2\) | 1.97\(\pm 2\) | 1.1\(\pm 0\) |
| 22 | 39 | 3.71\(\pm 3\) | 3.71\(\pm 3\) | 9.9\(\pm 1\) |
| 22 | 40 | 9.91\(\pm 3\) | 9.91\(\pm 3\) | 1.0\(\pm 0\) |

RMBPT: Earlier results of Safronova and Safronova [23]
GRASP: Present results with the GRASP code from 63 configurations and 2003 levels
R: Ratio of velocity and length forms of $f$-values
| I  | J  | RMBPT  | GRASP  | R     |
|---|---|--------|--------|-------|
| 1 | 6 | 5.97−1 | 6.08−1 | 1.0+0 |
| 2 | 8 | 2.76−1 | 2.81−1 | 1.0+0 |
| 2 | 9 | 2.23−1 | 2.27−1 | 1.0+0 |
| 3 | 4 | 3.11−2 | 3.18−2 | 1.0+0 |
| 3 | 7 | 6.43−2 | 6.45−2 | 1.0+0 |
| 3 | 8 | 5.27−2 | 5.36−2 | 1.0+0 |
| 3 | 9 | 3.61−2 | 3.67−2 | 1.0+0 |
| 3 | 10 | 3.12−1 | 3.19−1 | 1.0+0 |
| 3 | 12 | 1.85−2 | 1.85−2 | 1.0+0 |
| 4 | 14 | 4.36−1 | 4.43−1 | 1.0+0 |
| 5 | 11 | 9.10−2 | 9.27−2 | 1.1+0 |
| 5 | 17 | 1.36−1 | 1.39−1 | 1.0+0 |
| 6 | 17 | 2.63−1 | 2.67−1 | 1.0+0 |
| 6 | 18 | 9.49−2 | 9.66−2 | 1.0+0 |
| 7 | 16 | 5.51−2 | 5.63−2 | 1.1+0 |
| 7 | 19 | 1.03−1 | 1.06−1 | 1.0+0 |
| 7 | 22 | 3.45−2 | 3.44−2 | 1.1+0 |
| 8 | 15 | 9.74−2 | 9.90−2 | 1.1+0 |
| 8 | 19 | 8.62−2 | 8.76−2 | 1.0+0 |
| 8 | 20 | 3.39−2 | 3.45−2 | 1.0+0 |
| 8 | 21 | 9.14−2 | 9.31−2 | 1.0+0 |
| 9 | 19 | 1.19−1 | 1.21−1 | 1.0+0 |
| 9 | 20 | 5.15−2 | 5.24−2 | 1.0+0 |
| 9 | 21 | 1.16−1 | 1.18−1 | 1.0+0 |
| 10 | 14 | 2.57−2 | 2.19−2 | 1.1+0 |
| 10 | 19 | 2.20−2 | 2.20−2 | 1.0+0 |
| 10 | 22 | 2.97−2 | 3.04−1 | 1.0+0 |
| 11 | 23 | 1.77−1 | 1.79−1 | 1.0+0 |
| 11 | 24 | 2.50−2 | 2.53−2 | 1.0+0 |
| 11 | 25 | 7.50−2 | 7.65−2 | 1.0+0 |
| 12 | 24 | 1.17−1 | 1.19−1 | 1.0+0 |
| 12 | 25 | 7.35−2 | 7.47−2 | 1.0+0 |
| 12 | 26 | 8.57−2 | 8.71−2 | 1.0+0 |
| 13 | 27 | 1.09−1 | 1.11−1 | 1.0+0 |
| 14 | 27 | 1.05−1 | 1.07−1 | 1.0+0 |
| 14 | 28 | 7.59−2 | 7.72−2 | 1.0+0 |
| 15 | 29 | 6.22−2 | 6.33−2 | 1.0+0 |
| 15 | 30 | 8.59−2 | 8.73−2 | 1.0+0 |
| 15 | 32 | 6.76−2 | 6.87−2 | 1.0+0 |
| 16 | 29 | 6.51−2 | 6.61−2 | 1.0+0 |
| 16 | 30 | 1.87−2 | 1.90−2 | 1.0+0 |
| 16 | 31 | 1.09−1 | 1.12−1 | 1.0+0 |
| 17 | 25 | 1.66−1 | 1.69−1 | 1.1+0 |
| 18 | 26 | 1.98−1 | 2.02−1 | 1.1+0 |
| 20 | 32 | 1.95−1 | 1.06−1 | 1.1+0 |
| 21 | 30 | 3.50−2 | 6.40−2 | 1.1+0 |
| 21 | 32 | 3.31−2 | 3.35−2 | 1.1+0 |
| 22 | 31 | 1.22−1 | 9.22−2 | 1.1+0 |
| 23 | 33 | 3.03−2 | 3.11−2 | 1.1+0 |
| 24 | 34 | 8.49−2 | 8.64−2 | 1.1+0 |
| 25 | 33 | 9.07−2 | 1.24−1 | 1.1+0 |
| 26 | 34 | 3.78−2 | 5.90−2 | 1.1+0 |
| 26 | 35 | 5.39−2 | 5.39−2 | 1.1+0 |

RMBPT: Earlier results of Safronova and Safronova [23]
GRASP: Present results with the GRASP code from 58 configurations and 509 levels
R: Ratio of velocity and length forms of f-values

Table P
Comparison of oscillator strengths (f-values, dimensionless) for some transitions of W LXIII. \( a \pm b \equiv a \times 10^{−b} \).
See Table 5 for definition of level indices.
Table Q
Comparison of radiative rates ($A$-values, $s^{-1}$) for some transitions of W LXV. $a\pm b \equiv a \times 10^{b}$.
See Table 7 for definition of level indices.

| I  | J   | MRMP       | GRASP      | $f$ (GRASP) | R  |
|----|-----|------------|------------|-------------|----|
| 1  | 3   | 1.206+14   | 1.5309+14  | 1.5354−1    | 1.0−0  |
| 1  | 11  | 6.551+13   | 8.2270+13  | 7.0330−2    | 9.8−1  |
| 1  | 17  | 2.613+15   | 2.8077+15  | 2.3320+0    | 9.8−1  |
| 1  | 19  | 2.694+13   | 3.8180+13  | 2.8152−2    | 9.9−1  |
| 1  | 27  | 6.243+14   | 7.7623+14  | 5.0372−1    | 1.0−0  |
| 1  | 29  | 1.227+15   | 1.3590+15  | 8.6763−1    | 9.8−1  |
| 1  | 33  | 3.350+14   | 4.4021+14  | 2.6529−1    | 1.0−0  |
| 1  | 39  | 4.193+13   | 5.3006+13  | 2.7134−2    | 9.6−1  |
| 1  | 53  | 1.021+15   | 1.0126+15  | 4.8992−1    | 9.7−1  |
| 1  | 83  | 2.365+14   | 2.3392+14  | 9.1872−2    | 9.7−1  |
| 1  | 101 | 8.690+14   | 8.9169+14  | 3.4857−1    | 9.7−1  |
| 1  | 111 | 1.118+14   | 1.3923+14  | 5.2373−2    | 9.9−1  |
| 1  | 113 | 1.850+14   | 2.2983+14  | 8.4470−2    | 9.9−1  |
| 1  | 129 | 2.953+14   | 3.0675+14  | 9.9018−2    | 9.7−1  |
| 1  | 143 | 6.038+13   | 7.5371+13  | 2.3136−2    | 9.9−1  |
| 2  | 4   | 2.917+10   | 3.0224+10  | 3.8142−2    | 9.8−1  |
| 2  | 6   | 2.395+11   | 2.4114+11  | 1.8811−2    | 9.8−1  |
| 2  | 7   | 1.669+12   | 1.6814+12  | 1.9361−1    | 1.1−0  |
| 2  | 8   | 9.092+11   | 9.1611+11  | 7.1771−2    | 9.7−1  |
| 2  | 22  | 1.580+13   | 1.5536+13  | 6.1622−2    | 9.5−1  |
| 2  | 40  | 4.805+13   | 5.4832+13  | 6.6094−2    | 1.0−0  |
| 2  | 41  | 2.845+13   | 3.2448+13  | 6.5169−2    | 1.0−0  |
| 2  | 42  | 3.484+13   | 4.0782+13  | 1.0485−1    | 9.9−1  |
| 2  | 68  | 2.616+13   | 2.9775+13  | 1.7587−2    | 1.0−0  |
| 2  | 71  | 2.101+13   | 2.4627+13  | 3.2866−2    | 9.8−1  |
| 3  | 6   | 1.342+12   | 1.3518+12  | 1.1467−1    | 1.0−0  |
| 3  | 8   | 8.614+11   | 8.6757+11  | 1.1693−1    | 1.0−0  |
| 3  | 9   | 2.411+12   | 2.4572+12  | 5.3889−2    | 9.5−1  |
| 3  | 23  | 2.171+13   | 2.1941+13  | 4.6553−2    | 9.5−1  |
| 3  | 41  | 2.894+13   | 3.2979+13  | 1.1095−1    | 9.9−1  |
| 3  | 43  | 2.956+13   | 3.4575+13  | 6.3790−2    | 9.9−1  |
| 3  | 45  | 3.309+13   | 3.8940+13  | 2.3629−2    | 1.0−0  |
| 3  | 73  | 2.062+13   | 2.4239+13  | 7.6916−3    | 1.0−0  |

MRMP: Earlier results of Vilkas et al. [27]
GRASP: Present results with the GRASP code from 25 configurations and 157 levels
R: Ratio of velocity and length forms of $f$-values
### Explanation of Tables

#### Table 1. Energies (Ryd) for the lowest 220 levels of W LIx and their lifetimes ($\tau$, s).

| Index | Level Index |
|-------|-------------|
| Configuration | The configuration to which the level belongs |
| Level | The $LSJ$ designation of the level |
| GRASP | Present energies from the GRASP code with 12,652 level calculations |
| FAC | Present energies from the FAC code with 38,694 level calculations |
| $\tau$ (s) | Lifetime of the level in s |

#### Table 2. Energies (Ryd) for the lowest 220 levels of W LX and their lifetimes ($\tau$, s).

| Index | Level Index |
|-------|-------------|
| Configuration | The configuration to which the level belongs |
| Level | The $LSJ$ designation of the level |
| GRASP | Present energies from the GRASP code with 35,333 level calculations |
| FAC | Present energies from the FAC code with 14,608 level calculations |
| $\tau$ (s) | Lifetime of the level in s |

#### Table 3. Energies (Ryd) for the lowest 215 levels of W LXI and their lifetimes ($\tau$, s).

| Index | Level Index |
|-------|-------------|
| Configuration | The configuration to which the level belongs |
| Level | The $LSJ$ designation of the level |
| GRASP | Present energies from the GRASP code with 43,644 level calculations |
| FAC | Present energies from the FAC code with 27,122 level calculations |
| $\tau$ (s) | Lifetime of the level in s |

#### Table 4. Energies (Ryd) for the lowest 148 levels of W LXII and their lifetimes ($\tau$, s).

| Index | Level Index |
|-------|-------------|
| Configuration | The configuration to which the level belongs |
| Level | The $LSJ$ designation of the level |
| GRASP | Present energies from the GRASP code with 2003 level calculations |
| FAC | Present energies from the FAC code with 12,139 level calculations |
| $\tau$ (s) | Lifetime of the level in s |

#### Table 5. Energies (Ryd) for the lowest 210 levels of W LXIII and their lifetimes ($\tau$, s).

| Index | Level Index |
|-------|-------------|
| Configuration | The configuration to which the level belongs |
| Level | The $LSJ$ designation of the level |
| GRASP | Present energies from the GRASP code with 509 level calculations |
| FAC | Present energies from the FAC code with 991 level calculations |
| $\tau$ (s) | Lifetime of the level in s |

#### Table 6. Energies (Ryd) for the $2p^5n\ell$ ($n \leq 20$) levels of W LXIV.

| Index | Level Index |
|-------|-------------|
| Configuration | The configuration to which the level belongs |
| Level | The $LSJ$ designation of the level |
| FAC | Present energies from the FAC code with 1,592 level calculations |
Table 7. Energies (Ryd) for the lowest 121 levels of W LXV and their lifetimes ($\tau$, s).

| Index | Level Index |
|-------|-------------|
| Configuration | The configuration to which the level belongs |
| Level | The LSJ designation of the level |
| GRASP | Present energies from the GRASP code with 157 level calculations |
| FAC | Present energies from the FAC code with 1147 level calculations |
| MRMP | Earlier energies of Vilas et al. [27] |
| $\tau$ (GRASP, s) | Lifetime of the level in s from the GRASP calculations |
| $\tau$ (MRMP, s) | Lifetime of the level in s from the Vilas et al. [27] |

Table 8. Energies (Ryd) for the lowest 150 levels of W LXVI and their lifetimes ($\tau$, s).

| Index | Level Index |
|-------|-------------|
| Configuration | The configuration to which the level belongs |
| Level | The LSJ designation of the level |
| GRASP | Present energies from the GRASP code with 501 level calculations |
| FAC | Present energies from the FAC code with 1113 level calculations |
| $\tau$ (s) | Lifetime of the level in s |

Table 9. Transition wavelengths ($\lambda_{ij}$ in Å), radiative rates ($A_{ji}$ in s$^{-1}$), oscillator strengths ($f_{ji}$, dimensionless), and line strengths ($S$, in atomic units) for electric dipole (E1), and $A_{ji}$ for electric quadrupole (E2), magnetic dipole (M1), and magnetic quadrupole (M2) transitions of W LIX. The ratio R(E1) of velocity and length forms of $A$-values for E1 transitions is listed in the last column.

- $i$ and $j$ The lower ($i$) and upper ($j$) levels of a transition as defined in Table 2.
- $\lambda_{ij}$ Transition wavelength (in Å)
- $A_{E1}^{ij}$ Radiative transition probability (in s$^{-1}$) for the E1 transitions
- $f_{E1}^{ij}$ Absorption oscillator strength (dimensionless) for the E1 transitions
- $S_{E1}^{ij}$ Line strength in atomic unit (a.u.), 1 a.u. = $6.460 \times 10^{-36}$ cm$^2$ esu$^2$ for the E1 transitions
- $A_{E2}^{ij}$ Radiative transition probability (in s$^{-1}$) for the E2 transitions
- $A_{M1}^{ij}$ Radiative transition probability (in s$^{-1}$) for the M1 transitions
- $A_{M2}^{ij}$ Radiative transition probability (in s$^{-1}$) for the M2 transitions
- R(E1) Ratio of velocity and length forms of $A$- (or $f$- and $S$-) values for the E1 transitions
- $a \pm b = a \times 10^{a+b}$

Table 10. Transition wavelengths ($\lambda_{ij}$ in Å), radiative rates ($A_{ji}$ in s$^{-1}$), oscillator strengths ($f_{ji}$, dimensionless), and line strengths ($S$, in atomic units) for electric dipole (E1), and $A_{ji}$ for electric quadrupole (E2), magnetic dipole (M1), and magnetic quadrupole (M2) transitions of W LX. The ratio R(E1) of velocity and length forms of $A$-values for E1 transitions is listed in the last column.

- $i$ and $j$ The lower ($i$) and upper ($j$) levels of a transition as defined in Table 2.
- $\lambda_{ij}$ Transition wavelength (in Å)
- $A_{E1}^{ij}$ Radiative transition probability (in s$^{-1}$) for the E1 transitions
- $f_{E1}^{ij}$ Absorption oscillator strength (dimensionless) for the E1 transitions
- $S_{E1}^{ij}$ Line strength in atomic unit (a.u.), 1 a.u. = $6.460 \times 10^{-36}$ cm$^2$ esu$^2$ for the E1 transitions
- $A_{E2}^{ij}$ Radiative transition probability (in s$^{-1}$) for the E2 transitions
- $A_{M1}^{ij}$ Radiative transition probability (in s$^{-1}$) for the M1 transitions
- $A_{M2}^{ij}$ Radiative transition probability (in s$^{-1}$) for the M2 transitions
- R(E1) Ratio of velocity and length forms of $A$- (or $f$- and $S$-) values for the E1 transitions
- $a \pm b = a \times 10^{a+b}$
Table 11. Transition wavelengths ($\lambda_{ij}$ in Å), radiative rates ($A_{ji}$ in s$^{-1}$), oscillator strengths ($f_{ji}$, dimensionless), and line strengths ($S$, in atomic units) for electric dipole (E1), and $A_{ji}$ for electric quadrupole (E2), magnetic dipole (M1), and magnetic quadrupole (M2) transitions of W LXI. The ratio $R(E1)$ of velocity and length forms of $A$-values for E1 transitions is listed in the last column.

- $i$ and $j$: The lower ($i$) and upper ($j$) levels of a transition as defined in Table 3.
- $\lambda_{ij}$: Transition wavelength (in Å).
- $A_{E1}^i$: Radiative transition probability (in s$^{-1}$) for the E1 transitions.
- $f_{E1}^i$: Absorption oscillator strength (dimensionless) for the E1 transitions.
- $S_{E1}^i$: Line strength in atomic unit (a.u.), 1 a.u. = 6.460 $\times$ 10$^{-36}$ cm$^2$ esu$^2$ for the E1 transitions.
- $A_{E2}^i$: Radiative transition probability (in s$^{-1}$) for the E2 transitions.
- $A_{M1}^i$: Radiative transition probability (in s$^{-1}$) for the M1 transitions.
- $A_{M2}^i$: Radiative transition probability (in s$^{-1}$) for the M2 transitions.
- $R(E1)$: Ratio of velocity and length forms of $A$- (or $f$- and $S$-) values for the E1 transitions.
- $a \pm b$: $\equiv a \times 10^{\pm b}$.

Table 12. Transition wavelengths ($\lambda_{ij}$ in Å), radiative rates ($A_{ji}$ in s$^{-1}$), oscillator strengths ($f_{ji}$, dimensionless), and line strengths ($S$, in atomic units) for electric dipole (E1), and $A_{ji}$ for electric quadrupole (E2), magnetic dipole (M1), and magnetic quadrupole (M2) transitions of W LXII. The ratio $R(E1)$ of velocity and length forms of $A$-values for E1 transitions is listed in the last column.

- $i$ and $j$: The lower ($i$) and upper ($j$) levels of a transition as defined in Table 4.
- $\lambda_{ij}$: Transition wavelength (in Å).
- $A_{E1}^i$: Radiative transition probability (in s$^{-1}$) for the E1 transitions.
- $f_{E1}^i$: Absorption oscillator strength (dimensionless) for the E1 transitions.
- $S_{E1}^i$: Line strength in atomic unit (a.u.), 1 a.u. = 6.460 $\times$ 10$^{-36}$ cm$^2$ esu$^2$ for the E1 transitions.
- $A_{E2}^i$: Radiative transition probability (in s$^{-1}$) for the E2 transitions.
- $A_{M1}^i$: Radiative transition probability (in s$^{-1}$) for the M1 transitions.
- $A_{M2}^i$: Radiative transition probability (in s$^{-1}$) for the M2 transitions.
- $R(E1)$: Ratio of velocity and length forms of $A$- (or $f$- and $S$-) values for the E1 transitions.
- $a \pm b$: $\equiv a \times 10^{\pm b}$.

Table 13. Transition wavelengths ($\lambda_{ij}$ in Å), radiative rates ($A_{ji}$ in s$^{-1}$), oscillator strengths ($f_{ji}$, dimensionless), and line strengths ($S$, in atomic units) for electric dipole (E1), and $A_{ji}$ for electric quadrupole (E2), magnetic dipole (M1), and magnetic quadrupole (M2) transitions of W LXIII. The ratio $R(E1)$ of velocity and length forms of $A$-values for E1 transitions is listed in the last column.

- $i$ and $j$: The lower ($i$) and upper ($j$) levels of a transition as defined in Table 5.
- $\lambda_{ij}$: Transition wavelength (in Å).
- $A_{E1}^i$: Radiative transition probability (in s$^{-1}$) for the E1 transitions.
- $f_{E1}^i$: Absorption oscillator strength (dimensionless) for the E1 transitions.
- $S_{E1}^i$: Line strength in atomic unit (a.u.), 1 a.u. = 6.460 $\times$ 10$^{-36}$ cm$^2$ esu$^2$ for the E1 transitions.
- $A_{E2}^i$: Radiative transition probability (in s$^{-1}$) for the E2 transitions.
- $A_{M1}^i$: Radiative transition probability (in s$^{-1}$) for the M1 transitions.
- $A_{M2}^i$: Radiative transition probability (in s$^{-1}$) for the M2 transitions.
- $R(E1)$: Ratio of velocity and length forms of $A$- (or $f$- and $S$-) values for the E1 transitions.
- $a \pm b$: $\equiv a \times 10^{\pm b}$.

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Table 14. Transition wavelengths ($\lambda_{ij}$ in Å), radiative rates ($A_{ji}$ in s\(^{-1}\)), oscillator strengths ($f_{ji}$, dimensionless), and line strengths ($S$, in atomic units) for electric dipole (E1), and $A_{ji}$ for electric quadrupole (E2), magnetic dipole (M1), and magnetic quadrupole (M2) transitions of W LXIV. The ratio $R(E1)$ of velocity and length forms of $A$-values for E1 transitions is listed in the last column.

$$i$$  $$j$$  The lower ($i$) and upper ($j$) levels of a transition as defined in Table 6.
$$\lambda_{ij}$$  Transition wavelength (in Å)
$$A^{E1}_{ij}$$  Radiative transition probability (in s\(^{-1}\)) for the E1 transitions
$$f^{E1}_{ij}$$  Absorption oscillator strength (dimensionless) for the E1 transitions
$$S^{E1}_{ij}$$  Line strength in atomic unit (a.u.), 1 a.u. = 6.646\times10\(^{-36}\) cm\(^2\) esu\(^2\) for the E1 transitions
$$A^{E2}_{ij}$$  Radiative transition probability (in s\(^{-1}\)) for the E2 transitions
$$A^{M1}_{ij}$$  Radiative transition probability (in s\(^{-1}\)) for the M1 transitions
$$A^{M2}_{ij}$$  Radiative transition probability (in s\(^{-1}\)) for the M2 transitions
$$R(E1)$$  Ratio of velocity and length forms of $A$- (or $f$- and $S$-) values for the E1 transitions
$$a\pm b$$  $\equiv a \times 10^{i\pm b}$

Table 15. Transition wavelengths ($\lambda_{ij}$ in Å), radiative rates ($A_{ji}$ in s\(^{-1}\)), oscillator strengths ($f_{ji}$, dimensionless), and line strengths ($S$, in atomic units) for electric dipole (E1), and $A_{ji}$ for electric quadrupole (E2), magnetic dipole (M1), and magnetic quadrupole (M2) transitions of W LXV. The ratio $R(E1)$ of velocity and length forms of $A$-values for E1 transitions is listed in the last column.

$$i$$  $$j$$  The lower ($i$) and upper ($j$) levels of a transition as defined in Table 7.
$$\lambda_{ij}$$  Transition wavelength (in Å)
$$A^{E1}_{ij}$$  Radiative transition probability (in s\(^{-1}\)) for the E1 transitions
$$f^{E1}_{ij}$$  Absorption oscillator strength (dimensionless) for the E1 transitions
$$S^{E1}_{ij}$$  Line strength in atomic unit (a.u.), 1 a.u. = 6.646\times10\(^{-36}\) cm\(^2\) esu\(^2\) for the E1 transitions
$$A^{E2}_{ij}$$  Radiative transition probability (in s\(^{-1}\)) for the E2 transitions
$$A^{M1}_{ij}$$  Radiative transition probability (in s\(^{-1}\)) for the M1 transitions
$$A^{M2}_{ij}$$  Radiative transition probability (in s\(^{-1}\)) for the M2 transitions
$$R(E1)$$  Ratio of velocity and length forms of $A$- (or $f$- and $S$-) values for the E1 transitions
$$a\pm b$$  $\equiv a \times 10^{i\pm b}$

Table 16. Transition wavelengths ($\lambda_{ij}$ in Å), radiative rates ($A_{ji}$ in s\(^{-1}\)), oscillator strengths ($f_{ji}$, dimensionless), and line strengths ($S$, in atomic units) for electric dipole (E1), and $A_{ji}$ for electric quadrupole (E2), magnetic dipole (M1), and magnetic quadrupole (M2) transitions of W LXVI. The ratio $R(E1)$ of velocity and length forms of $A$-values for E1 transitions is listed in the last column.

$$i$$  $$j$$  The lower ($i$) and upper ($j$) levels of a transition as defined in Table 8.
$$\lambda_{ij}$$  Transition wavelength (in Å)
$$A^{E1}_{ij}$$  Radiative transition probability (in s\(^{-1}\)) for the E1 transitions
$$f^{E1}_{ij}$$  Absorption oscillator strength (dimensionless) for the E1 transitions
$$S^{E1}_{ij}$$  Line strength in atomic unit (a.u.), 1 a.u. = 6.646\times10\(^{-36}\) cm\(^2\) esu\(^2\) for the E1 transitions
$$A^{E2}_{ij}$$  Radiative transition probability (in s\(^{-1}\)) for the E2 transitions
$$A^{M1}_{ij}$$  Radiative transition probability (in s\(^{-1}\)) for the M1 transitions
$$A^{M2}_{ij}$$  Radiative transition probability (in s\(^{-1}\)) for the M2 transitions
$$R(E1)$$  Ratio of velocity and length forms of $A$- (or $f$- and $S$-) values for the E1 transitions
$$a\pm b$$  $\equiv a \times 10^{i\pm b}$

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