



Radiative Recombination of Pm-like Tungsten (W XIV): A Theoretical Benchmark for Kilonova Modelling [†]

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Abstract

Recombination processes heavily influence the ionization balance and level populations of Non-Local Thermodynamic Equilibrium (Non-LTE) plasmas. This is especially relevant for kilonovae, whose ejecta rapidly evolves into a Non-LTE regime. Collisional-radiative models become necessary, but are limited by the scarcity of data for heavy *r*-process elements. In this work, we present radiative recombination (RR) rate coefficients for Pm-like tungsten (W XIV) using the Flexible Atomic Code (FAC). W XIV makes a reliable benchmark for two primary reasons: tungsten is one of the heavy elements best characterized across its ionization sequence, providing a wealth of available data for comparison, and this charge state shares the complicated open *f*-shell structure of key *r*-process elements, consequently presenting similar challenges that emerge when executing this type of calculation. Validating our approach here provides the foundation for extending this methodology to the lanthanide sequence. The calculations performed in this work show good agreement with previous relevant works. Additionally, an RR calculation with a set of configurations that captured the low-lying energy structure of the recombined ion was performed. The results remain within the same order of magnitude as the standard method across the 10³ to 10⁹ K temperature range.

Keywords: radiative recombination; Pm-like tungsten; atomic data; lanthanides; astrophysical plasmas; kilonovae

1. Introduction

Following the recent detection of the events GW170817 and GRB230307A, neutron star mergers are now considered possible prime sites for *r*-process nucleosynthesis, creating heavy nuclei such as lanthanides and actinides [1–6]. Validating this hypothesis relies on analyzing their electromagnetic transients, so called kilonovae. These spectra had an exceptionally rapid spectral evolution across all observed epochs, unlike any other observed astrophysical transients [7].

Modelling these observed kilonova spectra rests on an accurate and highly comprehensive description in terms of atomic data [8–10]. Small errors in predicted wavelengths can invalidate the correspondence between theoretical spectral features and observed



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lines, with discrepancies sometimes exceeding 50% between theoretical and experimental values [11,12].

Especially in Non-LTE regimes, where ionization balance and level populations are no longer described by Maxwell–Boltzmann distributions, explicit collisional-radiative models become necessary. As the ejecta expands and cools, the density and ionization conditions vary drastically across the different ejecta layers and timescales. Here the LTE approximation starts to break down, giving way to a far more heterogeneous and time-dependent environment. Processes such as radiative recombination (RR) emerge as principal contributors to the overall cooling influencing the spectrum shape, highlighting the need for a broad and complete range of atomic parameters [13,14].

Although these observations have strongly accelerated research in this area, the volume of atomic data produced to date remains insufficient, as the research pathways are numerous, spanning multiple ionization stages, elements, physical processes, and derived quantities.

For recombination processes, the scarcity of data for key *r*-process elements is particularly concerning. Often, models rely on extrapolations from lighter elements or simplified approximations, leading to discrepancies reaching an order of magnitude [15]. The dense-energy-level structures of heavy elements impose substantial computational costs. Simultaneously, experimental measurements of RR rates for low-charged heavy ions such as lanthanides remain highly challenging due to difficulties in ion source generation and high background noise [15].

In this context, the choice of tungsten as the subject of this work is well motivated. Structurally, tungsten ions in low charge states have an open *f*-shell, giving rise to a dense and complex energy level structure. This enhances the difficulty of the calculations, as demonstrated by Krantz et al. [16], which we expect to encounter equally in lanthanide ions given their structural similarity. Simultaneously, tungsten is among the most thoroughly studied heavy elements across its ionization sequence, given its importance as a plasma-facing material in tokamak devices such as ITER, where it acts as an impurity whose properties must be precisely known for plasma diagnostics [17]. Because of these factors, tungsten is a solid starting point for this work: by first benchmarking our approach against existing data, we can then apply the same methodology to lanthanide ions with greater confidence.

2. Methods

2.1. Atomic Structure

All calculations in this work were performed with the fully relativistic Distorted Wave (DW) method within the Flexible Atomic Code (FAC) [18]. The atomic structure is based on the diagonalization of the Dirac–Coulomb Hamiltonian:

$$H_{\text{DC}} = \sum_{i=1}^N \left(c\boldsymbol{\alpha}_i \cdot \mathbf{p}_i + (\beta_i - 1)c^2 + V_i \right) + \sum_{i<j}^N \frac{1}{r_{ij}}, \quad (1)$$

where $\boldsymbol{\alpha}_i$ and β_i are the 4×4 Dirac matrices and V_i accounts for the nuclear potential. Higher-order QED corrections, including self-energy and vacuum polarization, are incorporated within the screened hydrogenic approximation, and the Breit interaction is included in the zero-frequency limit.

The electron–electron repulsion is treated under the central field approximation, simplifying the many-body problem into *N* independent one-electron equations. Each is solved in a mean field representing the averaged charge distribution of the remaining electrons. This central potential is obtained through a self-consistent Dirac–Hartree–Fock–Slater (DHFS) method, optimized for the ground-state configuration of the recombined ion

(W XIII, [Pd] $4f^{14}5s^2$), as is standard practice using this code in RR [19], and from which the radial orbitals are derived.

The Atomic State Function (ASF) is represented, in the Relativistic Configuration Interaction (RCI) approach, as a linear combination of configuration state functions (CSFs), each of which is an antisymmetrized linear combination of products of single-electron Dirac orbitals. By solving the eigenvalue problems, energy levels and wavefunctions can be obtained and used as the input for the RR calculations.

2.2. Radiative Recombination

Electron-ion recombination can be divided into two distinct channels. The radiative recombination is a direct and continuous process in which a continuum electron with kinetic energy ϵ and angular momentum κ is captured with simultaneous photon emission. The other channel is dielectronic recombination (DR), which occurs through autoionizing resonances producing sharp features in the capture cross-sections. In this work, we restrict ourselves to the RR channel. Particularly, for the RR of W XIV (or W^{13+}):

$$e^-(\epsilon, \kappa) + [W^{13+}]_i \rightarrow [W^{12+}]_f + h\nu. \quad (2)$$

Since RR is the time-reversed process of photoionization (PI), the RR cross-section (RRCS) follows from the PI cross-section via the Milne relation [20]:

$$\sigma^{RR} = \frac{\alpha^2}{2} \frac{g_f}{g_i} \frac{\omega^2}{\epsilon(1 + \alpha^2\epsilon/2)} \sigma^{PI}, \quad (3)$$

where α is the fine-structure constant, g_i and g_f are the statistical weights of the initial and final states, and ω is the photon energy in atomic units. Similarly, the PI cross-section can be defined as [18]

$$\sigma^{PI} = 2\pi\alpha \frac{\omega(\alpha\omega)^{2L-2}}{(2L+1)g_f} S_{fi}, \quad (4)$$

where L is the rank of the multipole inducing the transition and S_{fi} is the line strength of the process

$$S_{fi} = \sum_{\kappa J_T} \left| \langle \psi_f, \kappa; J_T | O^L | \psi_i \rangle \right|^2. \quad (5)$$

Here, O^L denotes the multipole operator of rank L that mediates the interaction, with J_T being the coupled total angular momentum of the recombined ion and the free electron. The full treatment decomposes the matrix element into angular and radial parts via the Wigner-Eckart theorem [18].

The state-resolved RR rate coefficients are obtained through a weighted integral of the cross-sections over the Maxwell-Boltzmann electron velocity distribution for a given electron temperature T_e [21,22]:

$$R_i(T_e) = \sqrt{\frac{2}{\pi}} \left(\frac{m_e}{k_B T_e} \right)^{3/2} \int_0^\infty v_e^3 \sigma_i^{RR}(v_e) \exp\left(-\frac{m_e v_e^2}{2k_B T_e}\right) dv_e. \quad (6)$$

where m_e is the electron mass and k_B is the Boltzmann constant. The total RR rate coefficient is obtained by summing over all bound levels i , such that

$$\alpha_{\text{total}}^{RR} = \sum_i R_i. \quad (7)$$

Following the convention adopted in plasma and astrophysical contexts [21], the resulting rate coefficients are expressed in $\text{cm}^3 \text{s}^{-1}$.

We stress that for spectral modelling, the relevant quantity is the total recombination rate coefficient $\alpha_{\text{total}}(T) = \alpha_{\text{RR}}(T) + \alpha_{\text{DR}}(T)$ [23], since DR can dominate the radiative counterpart by orders of magnitude at low-to-moderate temperatures [23,24]. Within the DW approximation as implemented in FAC, RR and DR are treated as separate and independent processes, in contrast to codes employing the R-matrix formalism, where the complex resonant structures are included through channel couplings and both contributions are obtained in a unified manner [23]. The DR calculation for this charge state is considerably more demanding and is currently in progress; the corresponding results will be published elsewhere.

2.3. Calculation Description

Following standard practices to produce RR rate coefficients [24–29], the present rates were calculated from the RRCSs of the ground state of the recombining ion under the electric-dipole (E1) approximation. Typically, the states considered for the recombined ion consist of the ground state of the recombining ion coupled with an electron in an nl orbital. Using this approach, the RR rate coefficients of Preval et al. [24] for this particular charge state were reproduced using FAC. It included configurations that were formed by the free electron being captured into the ground-state level of the recombining ion forming the set, as listed in Table 1.

Table 1. Configuration set for W^{12+} used to reproduce Preval et al [24].

Ground Config.	Single Excitations
$4f^{14}5s^2$	$4f^{13}5s^2nl$ ($n = 5, l = p, d, f, g$) $4f^{13}5s^2nl$ ($n = 6 \text{ to } 10, l = \text{all}$) $4f^{13}5s^2nl$ ($n = 11 \text{ to } 25, l \leq 10$)

Additionally, this work explores an alternative approach by focusing on the explicit inclusion of the lowest-energy configurations of the recombined ion, giving priority to low-lying states over the systematic expansion of shells with high n and l . The configuration set for W XIII tested, listed in Table 2, was obtained by previously optimized atomic structure calculations, with explicit shells up to $n = 7$ and $l = 4$.

Table 2. Configuration set for W^{12+} used for the low-lying state calculation.

Ground Config.	Single Excitations	Double Excitations
$4f^{14}5s^2$	$4f^{14}5snl$ ($n = 5, l = p, d, f, g$) $4f^{14}5snl$ ($n = 6, l = s, p, d, f$) $4f^{14}5snl$ ($n = 7, l = s, p, d, f$) $4f^{13}5s^2nl$ ($nl = 5p, 5d$) $4f^{13}5s^2nl$ ($n = 6, l = s, p, d, f$) $4f^{13}5s^2nl$ ($n = 7, l = s, p, d, f$)	$4f^{14}nl^2$ ($n = 5 - 7, l = p, d, f$) $4f^{14}5pnl$ ($nl = 5d, 5f, 5g$) $4f^{14}6s^2, 6p^2, 6d^2, 6f^2$ $4f^{14}7s^2, 7p^2, 7d^2, 7f^2$ $4f^{13}5snl^2$ ($n = 5, l = p, d, f$) $4f^{13}5snl^2$ ($n = 6, l = s, p, d, f$) $4f^{13}5s5pnl$ ($nl = 5d, 6s, 6p, 6d, 6f$) $4f^{13}5s5dnl$ ($nl = 6s, 6p, 6d, 6f$) $4f^{13}5s6snl$ ($nl = 6p, 6d, 6f$) $4f^{13}5s6pnl$ ($nl = 6d, 6f$) $4f^{13}5s6d6f$ $4f^{12}5s^25p^2, 4f^{12}5s^25p5d$

Note that in the work of Preval et al. [24], the Rydberg nl electron states were taken into account sequentially up to $n = 25$, and then quasi-logarithmically up to $n = 999$. In our reproduction of the Preval et al. results, these high- n contributions were not explicitly calculated, but rather recovered through a hydrogenic approximation using the Kramers

formula. This analytical extrapolation was applied sequentially from $n = 26$ up to $n = 1000$, and for the low-lying states calculation, from $n = 8$ up to $n = 1000$.

3. Results and Discussion

3.1. Energy Levels

The calculated energy levels relative to the structural calculation of the low-energy states shown in Table 2 are in good agreement with the literature. The relative deviation with respect to the comparison sources [30,31] is presented in Figure 1. Over the full energy comparison range, a mean relative deviation of 3.0% with respect to Lu et al. (FAC) [31] and 4.6% with respect to Henderson et al. (Cowan) [30] is obtained. For the lowest-lying levels ($E < 30$ eV), where the ratio metric is disproportionately sensitive to small differences, the mean absolute deviation provides a more representative measure of the accuracy of the calculation. It holds 0.1 ± 0.3 eV with respect to Lu et al. and 0.6 ± 0.2 eV with respect to Henderson et al. These values are consistent with the expected accuracy of relativistic FAC calculations for this type of highly correlated system.

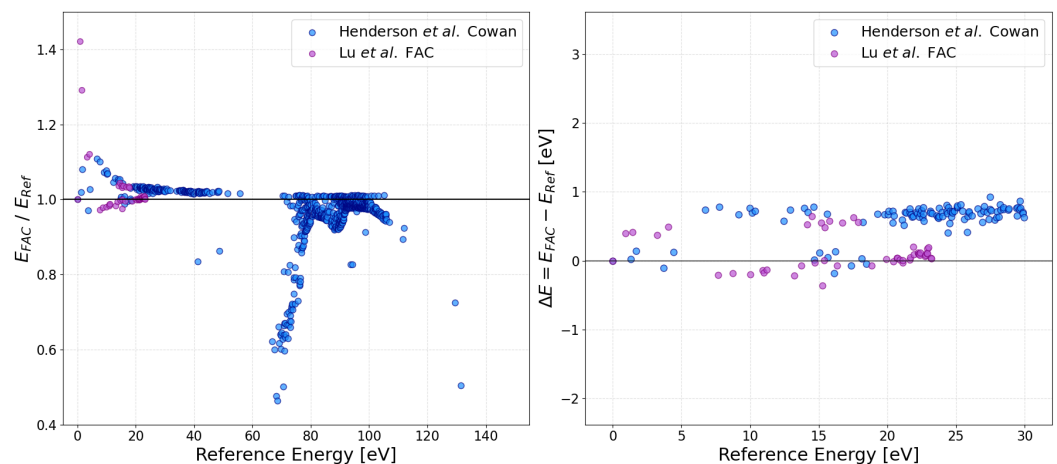


Figure 1. Comparison of the excitation energies from the present FAC calculations with those of Stuart Henderson et al. [30] (blue circles) and Lu et al. [31] (purple circles) for W XIII. On the left, the ratio $E_{\text{FAC}}/E_{\text{Ref}}$ is shown over the full energy range, illustrating the global agreement between calculations. On the right, the absolute energy difference is employed for levels below 30 eV.

3.2. Radiative Recombination Rates

The results of the FAC reproduction of Preval et al. and the low-lying states calculation are presented in Figure 2.

For the Preval et al. comparison, the results show good agreement, with a mean relative error of $\approx 6\%$. Both FAC and AUTOSTRUCTURE used in [24] by Preval et al. treat the electron–electron interaction through a local central potential. Moreover, both codes use the DW approximation and include the configuration interaction methodology, making the two approaches reasonably comparable in this regard. A direct comparison with other relevant works, such as Trzhaskovskaya et al. [25], that employ the full Dirac–Fock (DF) method, may not be meaningful. The DF method treats the electron exchange interaction exactly, in contrast to the Dirac–Hartree–Fock–Slater approach used in FAC. As noted by Trzhaskovskaya et al., cross-sections obtained by these two methods may diverge by several times at electron energies $E_k \lesssim 100$ eV ($\approx 1.16 \times 10^6$ K), making a faithful replication unfeasible within the scope of this work. With these methodological differences kept in mind, the data from Trzhaskovskaya et al. [25] are nonetheless shown for comparison.

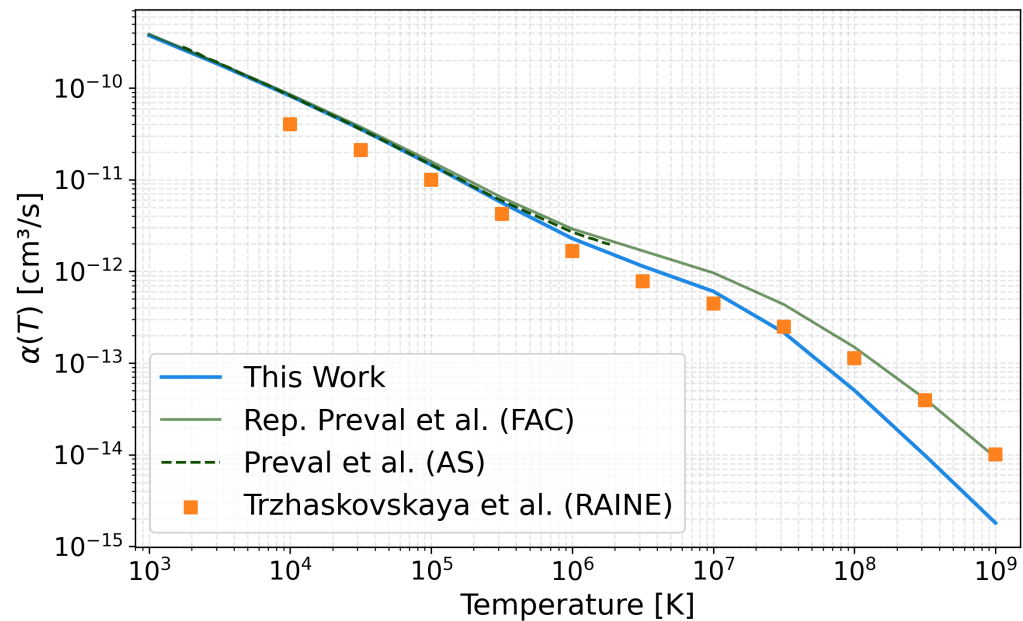


Figure 2. RR rate coefficients for W XIV as a function of temperature. The green dashed line is the original data from Preval et al. [24] (AUTOSTRUCTURE), with the solid green line being our FAC reproduction. The blue line shows the rates obtained in this work from the low-lying states calculation, including hydrogenic extrapolation up to $n = 1000$. The orange squares denote the data from Trzhaskovskaya et al. [25] (RAINE).

The calculation of low-lying states, enhanced by the contribution of nl Rydberg states which were hydrogenically approximated, successfully reproduces the rate coefficients from [24] up to $10^{5.5}$ K. Within this temperature range, the results fall slightly below the other values, being on average 4% lower than the original data from Preval et al. and 6% lower than our reproduction of their work. For $T \gtrsim 10^{5.5}$ K, the curve remains within the same order of magnitude as the reproduced Preval et al. calculation, dropping on average to approximately half of those values in this regime. It is worth noting that at these higher temperatures, the slopes of the radiative recombination (RR) rate coefficients can increase significantly due to electron capture into low-energy levels, which are not as effectively screened from the nucleus as higher levels [28,29]. The present RR rate coefficients are available in Table 3.

Table 3. FAC RR rate coefficients for W XIV from the Rep. Preval et al. calculation and the low-lying states calculation with the hydrogenic extrapolation up to $n = 1000$ (this work).

T [K]	$\alpha_{\text{Rep. Preval}} [\text{cm}^3 \text{s}^{-1}]$	$\alpha_{\text{This Work}} [\text{cm}^3 \text{s}^{-1}]$
$10^{3.0}$	3.87×10^{-10}	3.74×10^{-10}
$10^{3.5}$	1.84×10^{-10}	1.79×10^{-10}
$10^{4.0}$	8.50×10^{-11}	8.20×10^{-11}
$10^{4.5}$	3.76×10^{-11}	3.56×10^{-11}
$10^{5.0}$	1.58×10^{-11}	1.45×10^{-11}
$10^{5.5}$	6.40×10^{-12}	5.61×10^{-12}
$10^{6.0}$	2.91×10^{-12}	2.28×10^{-12}
$10^{6.5}$	1.67×10^{-12}	1.14×10^{-12}
$10^{7.0}$	9.63×10^{-13}	6.05×10^{-13}
$10^{7.5}$	4.35×10^{-13}	2.15×10^{-13}
$10^{8.0}$	1.49×10^{-13}	5.03×10^{-14}
$10^{8.5}$	4.07×10^{-14}	9.84×10^{-15}
$10^{9.0}$	9.33×10^{-15}	1.80×10^{-15}

4. Conclusions and Future Work

In this work, we present RR rate coefficients calculated using the fully relativistic FAC under the DW approximation. Our results show good agreement with previous studies that utilize a similar method. Regarding the effect of the lowest-energy states on the RR rate coefficients, the explicit calculation of the low-lying energy levels results in values comparable to the standard approach, where the captured electron is coupled with the ground state of the recombining ion in an nl orbital. The agreement at temperatures between 10^3 and 10^6 K is particularly notable, where the application of the hydrogenic extrapolation further improves the alignment with the standard method. This work establishes our methodological baseline for calculating RR coefficients, using W XIV as a benchmark since it shares a similar atomic structure with an open f -shell with lanthanides. Unlike lanthanides, tungsten has a wealth of data for comparison, allowing us to proceed with greater confidence to the lanthanide series, which is one of the main focuses in kilonova modelling.

In the future, it will be highly relevant to deepen the analysis of radiative processes, namely by investigating the influence of triple excitations, which are not commonly considered in these calculations, and by extending the present methodology to include DR, whose results will be published in another work.

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References

1. Abbott, B.P.; Abbott, R.; Abbott, T.D.; Acernese, F.; Ackley, K.; Adams, C.; Adams, T.; Addesso, P.; Adhikari, R.X.; Adya, V.B.; et al. Properties of the Binary Neutron Star Merger GW170817. *Phys. Rev. X* **2019**, *9*, 011001. [\[CrossRef\]](#)
2. Abbott, B.P.; Abbott, R.; Abbott, T.D.; Acernese, F.; Ackley, K.; Adams, C.; Adams, T.; Addesso, P.; Adhikari, R.X.; Adya, V.B.; et al. GW170817: Observation of gravitational waves from a binary neutron star inspiral. *Phys. Rev. Lett.* **2017**, *119*, 161101. [\[CrossRef\]](#) [\[PubMed\]](#)
3. Abbott, B.P.; Abbott, R.; Abbott, T.D.; Acernese, F.; Ackley, K.; Adams, C.; Adams, T.; Addesso, P.; Adhikari, R.X.; Adya, V.B.; et al. Multi-messenger Observations of a Binary Neutron Star Merger. *Astrophys. J. Lett.* **2017**, *848*, L12. [\[CrossRef\]](#)
4. Abbott, B.P.; Abbott, R.; Abbott, T.D.; Acernese, F.; Ackley, K.; Adams, C.; Adams, T.; Addesso, P.; Adhikari, R.X.; Adya, V.B.; et al. Gravitational waves and gamma-rays from a binary neutron star merger: GW170817 and GRB 170817A. *Astrophys. J. Lett.* **2017**, *848*, L13. [\[CrossRef\]](#)
5. Smartt, S.J.; Chen, T.-W.; Jerkstrand, A.; Coughlin, M.; Kankare, E.; Sim, S.A.; Fraser, M.; Innes, C.; Maguire, K.; Chambers, K.C.; et al. A kilonova as the electromagnetic counterpart to a gravitational-wave source. *Nature* **2017**, *551*, 75–79. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Metzger, B.D. Kilonovae. *Living Rev. Relativ.* **2019**, *23*, 1. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Snopce, A.; Watson, D.; Damgaard, R.; Heintz, K.E.; Vieira, N.; Väisänen, P.; Mahoro, A. Emergence hour-by-hour of r-process features in the kilonova AT2017gfo. *Astron. Astrophys.* **2024**, *690*, A398. [\[CrossRef\]](#)

8. Gillanders, J.H.; Smartt, S.J.; Sim, S.A.; Bauswein, A.; Goriely, S. Modelling the spectra of the kilonova AT2017gfo – I. The photospheric epochs. *Mon. Not. R. Astron. Soc.* **2022**, *515*, 631–651. [\[CrossRef\]](#)
9. Gillanders, J.H.; Sim, S.A.; Smartt, S.J.; Goriely, S.; Bauswein, A. Modelling the spectra of the kilonova AT2017gfo – II. Beyond the photospheric epochs. *Mon. Not. R. Astron. Soc.* **2023**, *529*, 2918–2945. [\[CrossRef\]](#)
10. Gillanders, J.H.; Flors, A.; da Silva, R.F. Improved lanthanide constraints for the kilonova AT 2017gfo. *arXiv* **2025**, arXiv:2512.24257. [\[CrossRef\]](#)
11. Shingles, L.J.; Collins, C.E.; Vijayan, V.; Flörs, A.; Just, O.; Leck, G.; Xiong, Z.; Bauswein, A.; Martínez-Pinedo, G.; Sim, S.A. Self-consistent 3D Radiative Transfer for Kilonovae: Directional Spectra from Merger Simulations. *Astrophys. J. Lett.* **2023**, *954*, L41. [\[CrossRef\]](#)
12. Flörs, A.; Silva, R.F.; Deprince, J.; Carvajal Gallego, H.; Leck, G.; Shingles, L.J.; Martínez-Pinedo, G.; Sampaio, J.M.; Amaro, P.; Marques, J.P.; et al. Opacities of singly and doubly ionized neodymium and uranium for kilonova emission modeling. *Mon. Not. R. Astron. Soc.* **2023**, *524*, 3083–3101. [\[CrossRef\]](#)
13. Pognan, Q.; Jerkstrand, A.; Grumer, J. On the validity of steady-state for nebular phase kilonovae. *Mon. Not. R. Astron. Soc.* **2022**, *510*, 3806–3837. [\[CrossRef\]](#)
14. McCann, M.; Mulholland, L.P.; Xiong, Z.; Ramsbottom, C.A.; Ballance, C.P.; Just, O.; Bauswein, A.; Martínez-Pinedo, G.; McNeill, F.; Sim, S.A. Luminosity predictions for the first three ionisation stages of W, Pt and Au to probe potential sources of emission in kilonova. *arXiv* **2024**, arXiv:2411.16476. [\[CrossRef\]](#)
15. Singh, S.; Harman, Z.; Keitel, C.H. Dielectronic recombination studies of ions relevant to kilonovae and non-LTE plasma. *Astron. Astrophys.* **2025**, *700*, A110. [\[CrossRef\]](#)
16. Krantz, C.; Badnell, N.R.; Müller, A.; Schippers, S.; Wolf, A. Recombination of open-*f*-shell tungsten ions. *J. Phys. B At. Mol. Opt. Phys.* **2017**, *50*, 052001. [\[CrossRef\]](#)
17. Trzhaskovskaya, M.B.; Nikulin, V.K.; Clark, R.E.H. Radiative recombination and photoionization cross sections for heavy element impurities in plasmas. *At. Data Nucl. Data Tables* **2008**, *94*, 71–139. [\[CrossRef\]](#)
18. Gu, M.F. The flexible atomic code. *Can. J. Phys.* **2008**, *86*, 675–689. [\[CrossRef\]](#)
19. Gu, M.F. *FAC 1.1.5 Manual*; 2024. Available online: <https://github.com/flexible-atomic-code/fac/blob/master/doc/manual.tex> (accessed on 1 June 2026).
20. Fritzsche, S.; Maiorova, A.V.; Wu, Z. Radiative Recombination Plasma Rate Coefficients for Multiply Charged Ions. *Atoms* **2023**, *11*, 50. [\[CrossRef\]](#)
21. Mao, J.; Kaastra, J. Parameterization of the level-resolved radiative recombination rate coefficients for the SPEX code. *Astron. Astrophys.* **2016**, *587*, A84. [\[CrossRef\]](#)
22. Mao, J. Astrophysical Plasma Modeling of the Hot Universe. Ph.D. Thesis, Utrecht University, Utrecht, The Netherlands, 2018.
23. Nahar, S.N.; Pradhan, A.K. Unified treatment of electron-ion recombination in the close-coupling approximation. *Phys. Rev. A* **1994**, *49*, 1816–1835. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Preval, S.P.; Badnell, N.R.; O'Mullane, M.G. Dielectronic recombination of lanthanide and low ionization state tungsten ions: W^{13+} to W^{1+} . *J. Phys. B At. Mol. Opt. Phys.* **2019**, *52*, 025201. [\[CrossRef\]](#)
25. Trzhaskovskaya, M.B.; Nikulin, V.K.; Tsarev, Y.N. Radiative recombination data for low-charged tungsten ions: IV. W^{3+} to W^{13+} . *At. Data Nucl. Data Tables* **2021**, *139*, 101389. [\[CrossRef\]](#)
26. Verner, D.A.; Ferland, G.J. Atomic data for astrophysics. I. Radiative recombination rates for H-like, He-like, Li-like and Na-like ions over a broad range of temperature. *Astrophys. J. Suppl. Ser.* **1996**, *103*, 467–473. [\[CrossRef\]](#) [\[PubMed\]](#)
27. Trzhaskovskaya, M.B.; Nikulin, V.K. Radiative Recombination and Photoionization Data for Tungsten Ions. *Electron Structure of Ions in Plasmas. Atoms* **2015**, *3*, 86–119. [\[CrossRef\]](#)
28. Badnell, N.R. Radiative Recombination Data for Modeling Dynamic Finite-Density Plasmas. *Astrophys. J. Suppl. Ser.* **2006**, *167*, 334–342. [\[CrossRef\]](#)
29. Sterling, N.C. Atomic data for neutron-capture elements. II. Photoionization and recombination properties of low-charge krypton ions. *Astron. Astrophys.* **2011**, *533*, A62. [\[CrossRef\]](#)
30. ADAS Consortium. Open-ADAS Dataset: Adf04/copssh74/ssh41_cs_icw12.dat. 2017. Available online: <https://open.adas.ac.uk> (accessed on 10 March 2026).
31. Lu, Q.; Fu, N.; Yan, C.; Qu, F.; Yang, Y.; Wang, K.; Chen, C.; Zou, Y.; Xiao, J. Experimental and theoretical investigations of visible spectra of W^{12+} . *J. Quant. Spectrosc. Radiat. Transf.* **2022**, *279*, 108064. [\[CrossRef\]](#)
32. *Spectral Analysis and Radiative Data for Elemental Kilonovae Identification (SPARKLE)*; FCT: Lisbon, Portugal, 2025. [\[CrossRef\]](#)

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