

Systematic Opacity Calculations for Kilonovae

MASAOMI TANAKA,¹ DAIJI KATO,^{2,3} GEDIMINAS GAIGALAS,⁴ AND KYOHEI KAWAGUCHI⁵

¹*Astronomical Institute, Tohoku University, Aoba, Sendai 980-8578, Japan*

²*National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan*

³*Department of Advanced Energy Engineering Science, Kyushu University, Kasuga, Fukuoka 816-8580, Japan*

⁴*Institute of Theoretical Physics and Astronomy, Vilnius University, Saulėtekio Ave. 3, Vilnius, Lithuania*

⁵*Institute for Cosmic Ray Research, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8582, Japan*

ABSTRACT

Coalescence of neutron stars gives rise to kilonova, thermal emission powered by radioactive decays of newly synthesized *r*-process nuclei. Although observational properties are largely affected by atomic opacities of *r*-process elements, available atomic data have been limited. In this paper, we perform the first systematic atomic structure calculations for all the *r*-process elements. We find that the distributions of energy levels tend to be higher as electron occupation increases for each electron shell. As a result, at typical temperature of kilonovae ($T \sim 5,000$ K), elements with a fewer number of electrons in the outermost shells give largest contributions to the bound-bound opacities since these elements have larger number of low-lying energy levels. The average opacities of mixture of *r*-process elements are found to be $\kappa \sim 20 - 30 \text{ cm}^2 \text{ g}^{-1}$ for $Y_e \leq 0.20$, $\kappa \sim 3 - 5 \text{ cm}^2 \text{ g}^{-1}$ for $Y_e = 0.25 - 0.35$, and $\kappa \sim 1 \text{ cm}^2 \text{ g}^{-1}$ for $Y_e = 0.40$ at $T = 5,000 - 10,000$ K, and they steeply decrease at lower temperature. We perform radiative transfer simulations with the new opacity data. We find that a model with high electron fraction ($Y_e = 0.30 - 0.40$, with no lanthanide) reproduces early, blue emission found in GW170817/AT2017gfo while a model with intermediate electron fraction ($Y_e = 0.20 - 0.30$, lanthanide fraction of $\sim 5 \times 10^{-3}$) reproduces long-lasting near-infrared emission.

Keywords: radiative transfer — opacity — stars: neutron

1. INTRODUCTION

Coalescence of neutron stars (NSs) is a phenomenon of interest in a wide area in astrophysics: it is one of the primary targets of gravitational wave (GW) observations, a candidate progenitor of short gamma-ray bursts (GRBs), and a possible origin of the *r*-process elements in the Universe. In fact, the detection of gravitational waves from a NS merger has been achieved for the first time in 2017 (GW170817, Abbott et al. 2017a). Subsequent electromagnetic (EM) observations over a wide wavelength range (Abbott et al. 2017b) identified the counterpart AT2017gfo, and provided rich information including the link between NS mergers and GRBs (Abbott et al. 2017c) and *r*-process nucleosynthesis by the NS merger.

In particular, intensive observations have been performed for AT2017gfo in the ultraviolet, optical,

and infrared wavelengths (e.g., Andreoni et al. 2017; Arcavi et al. 2017; Chornock et al. 2017; Coulter et al. 2017; Cowperthwaite et al. 2017; Díaz et al. 2017; Drout et al. 2017; Evans et al. 2017; Kasliwal et al. 2017; Kilpatrick et al. 2017; Lipunov et al. 2017; McCully et al. 2017; Nicholl et al. 2017; Pian et al. 2017; Shappee et al. 2017; Siebert et al. 2017; Smartt et al. 2017; Soares-Santos et al. 2017; Tanvir et al. 2017; Tominaga et al. 2018; Troja et al. 2017; Utsumi et al. 2017; Valenti et al. 2017). The observed properties are broadly consistent with kilonova (Kasen et al. 2017; Tanaka et al. 2017; Rosswog et al. 2017), thermal emission powered by radioactive decays of newly synthesized *r*-process elements (Li & Paczyński 1998; Kulkarni 2005; Metzger et al. 2010, see Rosswog 2015; Tanaka 2016; Fernández & Metzger 2016; Metzger 2017 for reviews). The presence of the “red” (near-infrared, NIR) component implies that the ejecta are composed of lanthanide elements (Kasen et al. 2013; Tanaka & Hotokezaka 2013). On the other hand, the “blue” (optical) component suggests that lighter *r*-process elements are also synthesized (Metzger & Fernández

Corresponding author: Masaomi Tanaka
 masaomi.tanaka@astr.tohoku.ac.jp

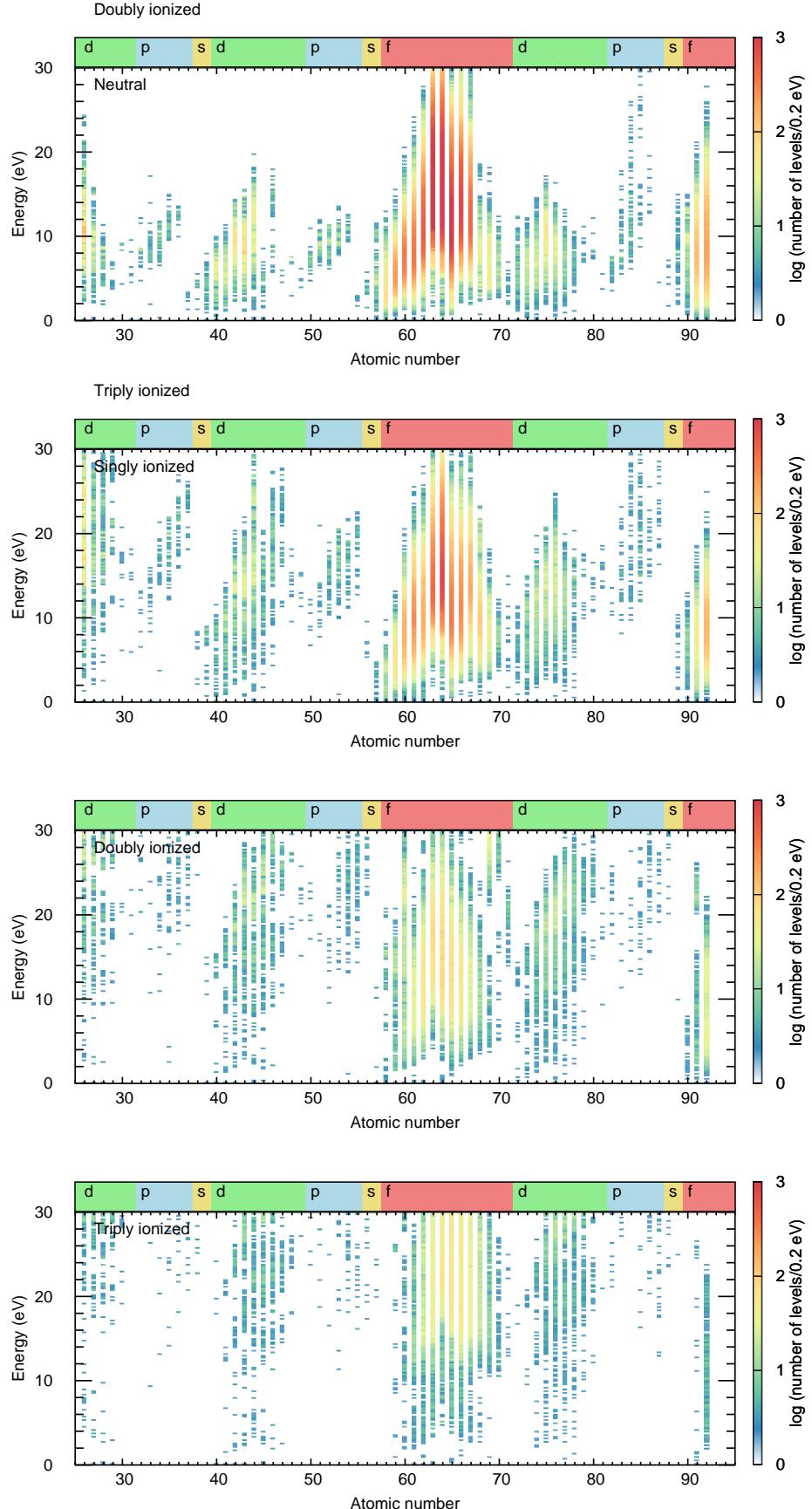


Figure 1. Distribution of energy levels of all the elements (neutral to triply ionized ion from top to bottom panels). The color scale represents the number of energy levels in 0.2 eV energy bin.

2014; Kasen et al. 2015; Tanaka et al. 2018). These multiple ejecta components are naturally expected in numerical simulations (see e.g., Shibata et al. 2017; Perego et al. 2017; Kawaguchi et al. 2018).

Although r -process nucleosynthesis is confirmed in GW170817/AT2017gfo, the exact abundance pattern synthesized by the NS merger is not yet clear. The most straightforward ways are identifying elements in the observed spectra and measuring their abundances. However, due to the large Doppler shift and blend of many absorption lines, conclusive identification is not yet done (see e.g., Kasen et al. 2017; Smartt et al. 2017). Another method is modelling the light curves. In fact, many attempts of light curve modelling have been performed by assuming simple, constant opacities (e.g., Cowperthwaite et al. 2017; Villar et al. 2017). But the opacities in NS merger ejecta depend on the abundances and they evolve with time. Therefore, to connect the abundance pattern in the ejecta with the observed properties, we need to consider detailed atomic opacities of r -process elements

In fact, our knowledge on atomic opacities of r -process elements in kilonova has grown in the past several years. Kasen et al. (2013) first performed atomic structure calculations for selected lanthanide elements while Tanaka & Hotokezaka (2013) compiled available data for r -process elements. They found high opacities of lanthanide elements. Then, atomic structure calculations for selected lanthanide elements and lighter r -process elements have been performed by Fontes et al. (2017), Wollaeger et al. (2018), and Tanaka et al. (2018). More recently, Kasen et al. (2017) and Fontes et al. (2019) provided systematic calculations of lanthanide elements. However, available calculations and data are still limited and do not cover all the r -process elements that NS mergers synthesize.

In this paper, we perform the first systematic opacity calculations of all the r -process elements. In Section 2, we show results of atomic structure calculations. We present the opacities of these elements in Section 3. Then, we apply the opacity data for radiative transfer simulations in Section 4. Finally we give a summary in Section 5. Throughout of the paper, magnitudes are given in AB magnitude system.

2. ATOMIC CALCULATIONS

2.1. Methods

We perform systematic atomic calculations for the elements from Fe ($Z = 26$) to U ($Z = 92$). To cover typical temperature range of kilonovae ($T \lesssim 20,000\text{K}$) at $t \gtrsim 1$ day after the merger (hereafter t denotes time after the merger), we calculate atomic energy levels and radiative

transitions for neutral atom and singly to triply ionized ions (I - IV) using HULLAC (Hebrew University Lawrence Livermore Atomic Code, Bar-Shalom et al. 2001).

Since the calculation methods are same as in Tanaka et al. (2018), we give only a brief overview of the calculations. In the HULLAC code, the orbital functions are derived by solving the single electron Dirac equation with a central-field potential which includes both a nuclear field and a spherically averaged potential due to electron-electron interactions. Then, N -electron configuration state functions are constructed by coupled anti-symmetric products of the orbital functions. The total Hamiltonian is diagonalized with multi configuration state functions and atomic energy levels are obtained as eigenvalues of the total Hamiltonian. Electric-dipole transition probabilities are calculated in length (Babushkin) gauge.

We summarize configurations used in the calculations in Table 2. Since the calculations involves the assumption of the central-field potential, the calculated results are compared with the energy levels in the NIST Atomic Spectra Database (ASD, Kramida et al. 2018). The potential is optimized so that the first-order configuration average energies of the ground state and low-lying excited states are minimized. The configurations used for the energy minimization are shown in bold in Table 2. To perform systematic calculations, we normally choose only the ground configuration for the energy minimization. However, we also include other configurations when the lowest energy for each configuration significantly deviates from that in the NIST ASD.

2.2. Energy levels

Figure 1 summarizes the calculated energy levels for all the elements from $Z = 26$ to $Z = 92$. The color scale represents the distribution of energy levels, i.e., the number of energy levels in every 0.2 eV energy bin. As expected from complexity measure (Kasen et al. 2013), f -shell elements have a larger number of energy levels than the other elements and then d -shell and p -shell elements follow.

The trend of the energy levels is determined by the combination of two effects as follows. (1) Within a certain electron shell, the distribution of the energy levels tend to be shifted toward higher energy as more electrons occupy the shell (e.g., see $Z = 40$ to $Z = 48$ for the case of $4d$ shell). Since orbital radii become smaller with Z , values of Coulomb and spin-orbit integrals increases for larger Z . Therefore, the energy spacing, i.e., the energy difference to the neighboring level, also increases with Z (Cowan 1981). As a result, the distri-

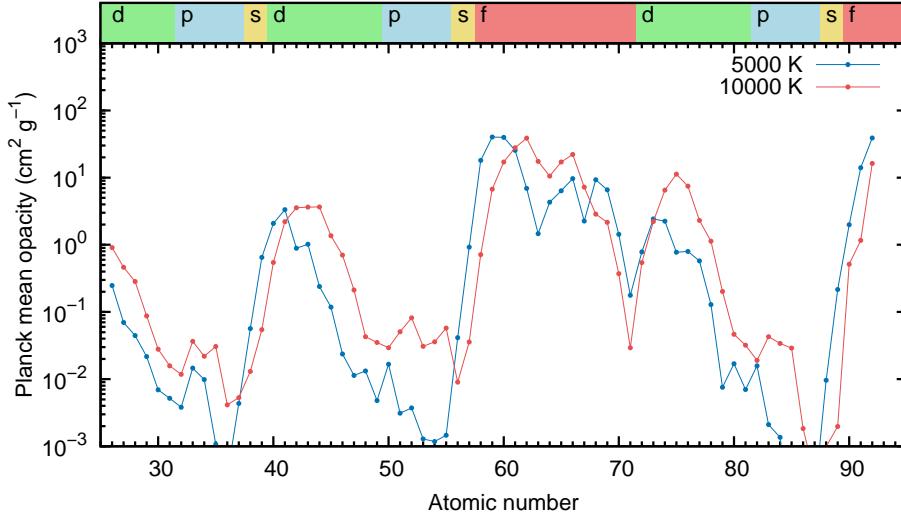


Figure 2. Planck mean opacities for all the elements. The opacities are calculated by assuming $\rho = 1 \times 10^{-13} \text{ g cm}^{-3}$, and $t = 1$ day after the merger. Blue and red lines present the opacities for $T = 5,000$ and $10,000$ K, respectively.

bution of the energy levels becomes wider for higher Z in a given shell. (2) At the same time, the number of states is the largest for the half-closed shell since it gives the highest complexity, i.e., the number of combinations formed from different quantum numbers is the largest.

For the case of lanthanides ($Z = 57 - 71$), the total number of levels is the largest for Eu or Gd which have half closed $4f$ -shells, depending on the ionization states. But the distribution of the energy levels is pushed up as Z increases, and thus, the number of low-lying levels is not necessarily higher than that of other lanthanide elements. This is the reason why the opacities of these complex elements are not always higher than those of the other lanthanides (Section 3).

3. OPACITY

In a typical timescale of kilonova emission ($t \gtrsim 1$ day), bound-bound transitions play the dominant role for the opacities in near ultraviolet, optical, and infrared wavelengths (Kasen et al. 2013; Barnes & Kasen 2013; Tanaka & Hotokezaka 2013). To evaluate the bound-bound opacities in rapidly expanding medium, such as supernova or neutron star merger ejecta, expansion opacities are commonly used (Karp et al. 1977; Eastman & Pinto 1993; Kasen et al. 2006). In the homologous expansion, the expansion opacity is expressed by

$$\kappa_{\text{exp}}(\lambda) = \frac{1}{ct\rho} \sum_l \frac{\lambda_l}{\Delta\lambda} (1 - e^{-\tau_l}), \quad (1)$$

where summation is taken over all the transitions within the wavelength bin $\Delta\lambda$ in radiative transfer simulations. Here τ_l is the Sobolev optical depth for each bound-

bound transition;

$$\tau_l = \frac{\pi e^2}{m_e c} f_{\text{int}} \lambda_l, \quad (2)$$

where n is the number density in a lower level of the transition and f_l and λ_l are the oscillator strength and transition wavelength, respectively. Whenever not explicitly mentioned, the expansion opacities shown in this paper are evaluated at $t = 1$ day after the merger by assuming density of $\rho = 1 \times 10^{-13} \text{ g cm}^{-3}$, which is typical for the ejecta mass of $M_{\text{ej}} \sim 10^{-2} M_{\odot}$ and the ejecta velocity of $v \sim 0.1c$.

Our simulations assume local thermodynamic equilibrium (LTE), and ionization states are calculated by solving Saha equation. Population of excited states follow the Boltzmann distribution. By the exponential dependence of the population of excited states ($n \propto e^{-E/kT}$), bound-bound transitions from lower energy levels have much higher contributions to the total opacities.

Figure 2 shows the overview of the opacity as a function of atomic number: the Plank mean opacities are shown for $T = 5,000$ and $10,000$ K for all the elements. In the following sections, properties of the opacities are discussed for each open shell of the elements.

3.1. *f*-shell elements

Open *f*-shell elements, lanthanides and actinides, have larger opacities than the elements with other open shells (Kasen et al. 2013; Tanaka & Hotokezaka 2013; Fontes et al. 2017; Tanaka et al. 2018; Wollaeger et al. 2018; Fontes et al. 2019). Due to the large number of energy levels with small energy spacing, the opacities

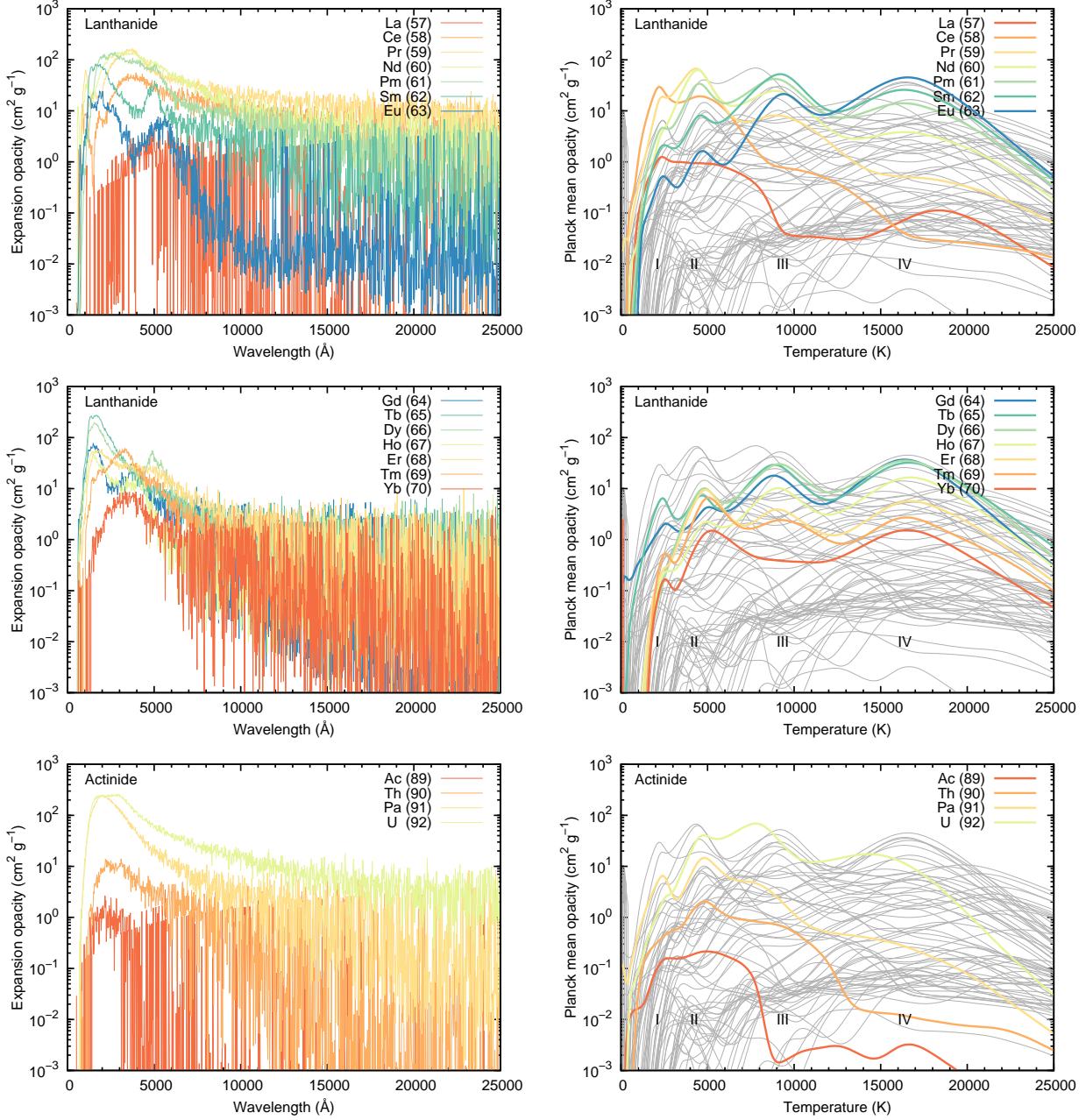


Figure 3. Left: Expansion opacity for f -shell (lanthanide and actinide) elements at $T = 5,000$ K. Right: Planck mean opacities as a function of temperature (color). Gray lines show the Planck mean opacities of all the other elements. The labels (I, II, III, and IV) show typical temperature ranges for each ionization state.

remain high to the NIR wavelengths (left panels of Figure 3). Depending on the elements and temperature, the Planck mean opacities are $\kappa \sim 0.1 - 50$ cm² g⁻¹ (right panels).

For $T = 5,000$ K, Planck mean opacities of Pr, Nd, and Pm ($Z = 59, 60$, and 61) are the highest among lanthanide elements (Figure 4). The opacities gradually decrease as more electrons occupy $4f$ -shell. This is because the number of low-lying energy levels decreases as

f -shell has more electrons (i.e., Z increases). Although the total number of energy levels is the largest for nearly half-closed f -shell elements (Eu or Gd), their opacities are not necessarily highest, as also found by Kasen et al. (2017) and Fontes et al. (2019). This is understood by the relatively high energy level distributions of Eu and Gd (Figure 1).

For $T > 10,000$ K, the Planck mean opacities are the highest for nearly half-closed elements (Figure 4). This

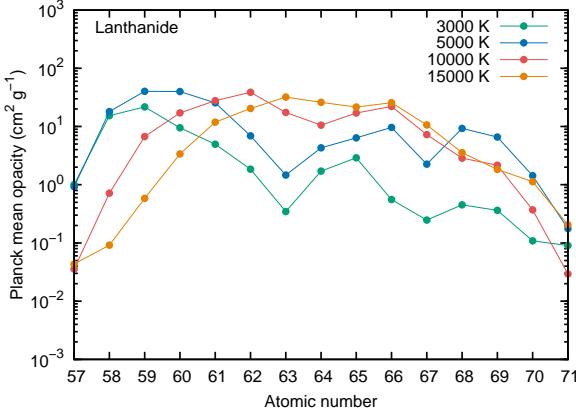


Figure 4. Planck mean opacities of lanthanide elements as a function of atomic number. For lower temperature ($T < 5,000$ K), the opacity tends to decrease for higher atomic numbers. For higher temperature ($T > 10,000$ K), the opacities are highest around half-closed elements.

is because relatively high energy levels of Eu or Gd start to contribute to the opacities. Also, at this temperature, the lanthanides are doubly ionized and low- Z lanthanide elements such as Pr and Nd have smaller contributions to the opacities.

Temperature dependence is different for low and high electron occupations in f -shell (Figure 4). This dependence is more clearly visible in the right panels of Figure 3. Low- Z lanthanide elements such as Ce, Pr, Nd ($Z = 58, 59$, and 60) show decreasing Planck mean opacities as a function of temperature because they have smaller number of electrons in $4f$ -shell. On the other hand, elements with more f -shell electrons such as Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, and Yb ($Z = 62 - 70$) show increasing opacities with temperature since they become closer to half-closed shell as temperature increases.

As shown in the right panels of Figure 3, our opacity data for f -shell elements are applicable only at $T \lesssim 20,000$ K since our atomic calculations include only up to triply ionized ions. This temperature corresponds to about 0.5–1 day after the merger although this epoch depends on the ejecta parameters such as mass, velocity, and opacity. We need atomic calculations for highly ionized ions to correctly understand the emission at earlier epochs.

3.2. d -shell elements

Open d -shell elements have the second largest contributions to the opacities after open f -shell elements. Compared with the f -shell elements, the opacities of the d -shell elements have a stronger wavelength dependence, i.e., the opacities are more concentrated to the shorter wavelengths around 1,000–3,000 Å (left panels of Figure 5).

The Planck mean opacities are within the range of $\kappa \sim 0.01 - 10 \text{ cm}^2 \text{ g}^{-1}$ (right panels).

For relatively low temperature ($T < 5,000$ K), the elements with a smaller number of d -shell electrons tend to have larger opacities (Figure 6). This is due to the lower energy level distributions and larger number of active strong transitions for the elements with the smaller number of d -shell electrons (Figure 1). For a higher temperature, the contributions to the opacities from the elements with 1 or 2 electrons in neutral atoms (Zr and Nb for $4d$, Hf and Ta for $5d$) becomes smaller (right panels in Figure 5) since these elements do not have d -shell electrons when doubly ionized. This is the reason why the Planck mean opacities have a peak around groups 7 and 8 at $T = 10,000$ K.

As in the case of f -shell elements, opacities are underestimated at a high temperature ($T \gtrsim 20,000$ K) due to the lack of atomic data of higher ionization states. The applicable temperature range for d -shell elements is wider than that of f -shell elements because of the higher ionization potential of d -shell elements.

3.3. p -shell elements

Open p -shell elements have smaller contributions to the opacities compared with open d -shell and f -shell elements (Kasen et al. 2013; Tanaka et al. 2018; Wollaeger et al. 2018). The opacities are highest at ultraviolet wavelengths (left panels of Figure 7). For the optical and near-infrared wavelengths, the Planck mean opacities increase as a function of temperature but they are at most $\kappa \sim 1 \text{ cm}^2 \text{ g}^{-1}$ for $T < 20,000$ K (right panels).

As in the cases for open d -shell elements, the opacities of p -shell elements are smaller for more p -shell electrons (Figure 2) since the distribution of energy levels is shifted toward higher energy. This trend is more significant because the average energy levels of p -shell elements are higher than those of d -shell elements (Figure 1).

3.4. s -shell elements

The opacities of open s -shell elements are almost negligible to the total opacities. Since there are fewer number of transitions, they do not form quasi-continuum opacities (left panel of Figure 8). For the typical temperature of kilonovae, the Planck mean opacities are $\kappa \lesssim 0.1 \text{ cm}^2 \text{ g}^{-1}$ (right panel).

It does not mean, however, that they do not contribute to the outcome of kilonova emission. In fact, open s -shell elements such as Mg and Ca often show strong absorption lines in stellar spectra, and thus, s -shell elements may contribute to absorption lines in the spectra. Unfortunately, since the calculations presented in this paper

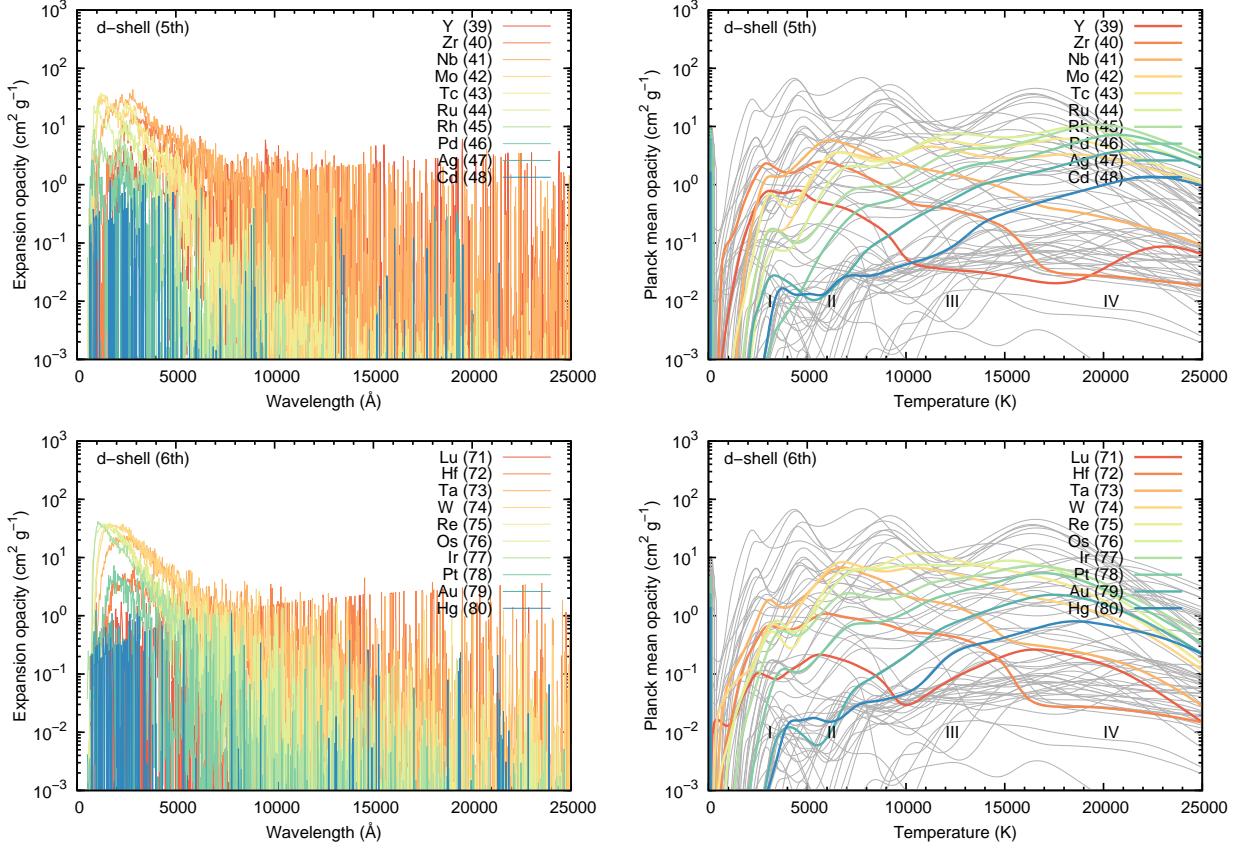


Figure 5. Same as Figure 3 but for *d*-shell elements.

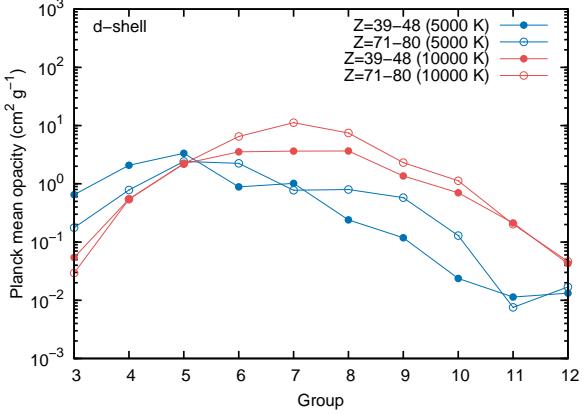


Figure 6. Planck mean opacities of *d*-shell elements ($Z = 39 - 48$ in the 4th period and $Z = 71 - 80$ in the 5th period) as a function group in the periodic table (the group number is approximately the number of electrons in the *d*-shell for the case of neutral atoms).

are not accurate enough to predict the exact wavelengths of each transition, the usefulness of our opacity data for open *s*-shell elements is limited.

4. APPLICATIONS TO KILONOVAE

4.1. Opacities of element mixture

Ejecta from NS mergers consist of mixture of *r*-process elements. Abundance distribution is mainly determined by electron fraction Y_e . The first dynamical ejecta have a wide Y_e distribution down to $Y_e \sim 0.1$ (Wanajo et al. 2014; Sekiguchi et al. 2015, 2016; Goriely et al. 2015; Radice et al. 2016; Foucart et al. 2016) while subsequent post-merger ejecta can have higher Y_e due to the neutrino absorption if a massive neutron star remains for a certain period (Fernández & Metzger 2013; Fujibayashi et al. 2018; Fernández et al. 2019). Lanthanide elements are efficiently produced with $Y_e \lesssim 0.25$ (e.g., Lippuner & Roberts 2015; Kasen et al. 2015). Therefore, if the ejecta consists of material with $Y_e > 0.25$, a short-lived, bright and blue emission is expected due to the absence of high opacity lanthanide (Metzger & Fernández 2014; Kasen et al. 2015; Tanaka et al. 2018).

We are now able to quantitatively connect the opacities to Y_e thanks to the systematic atomic data. For the mixture of elements, we construct a line list from Kurucz's line list (Kurucz & Bell 1995) for $Z = 1 - 28$, the VALD database (Piskunov et al. 1995; Ryabchikova et al. 1997; Kupka et al. 1999, 2000) for

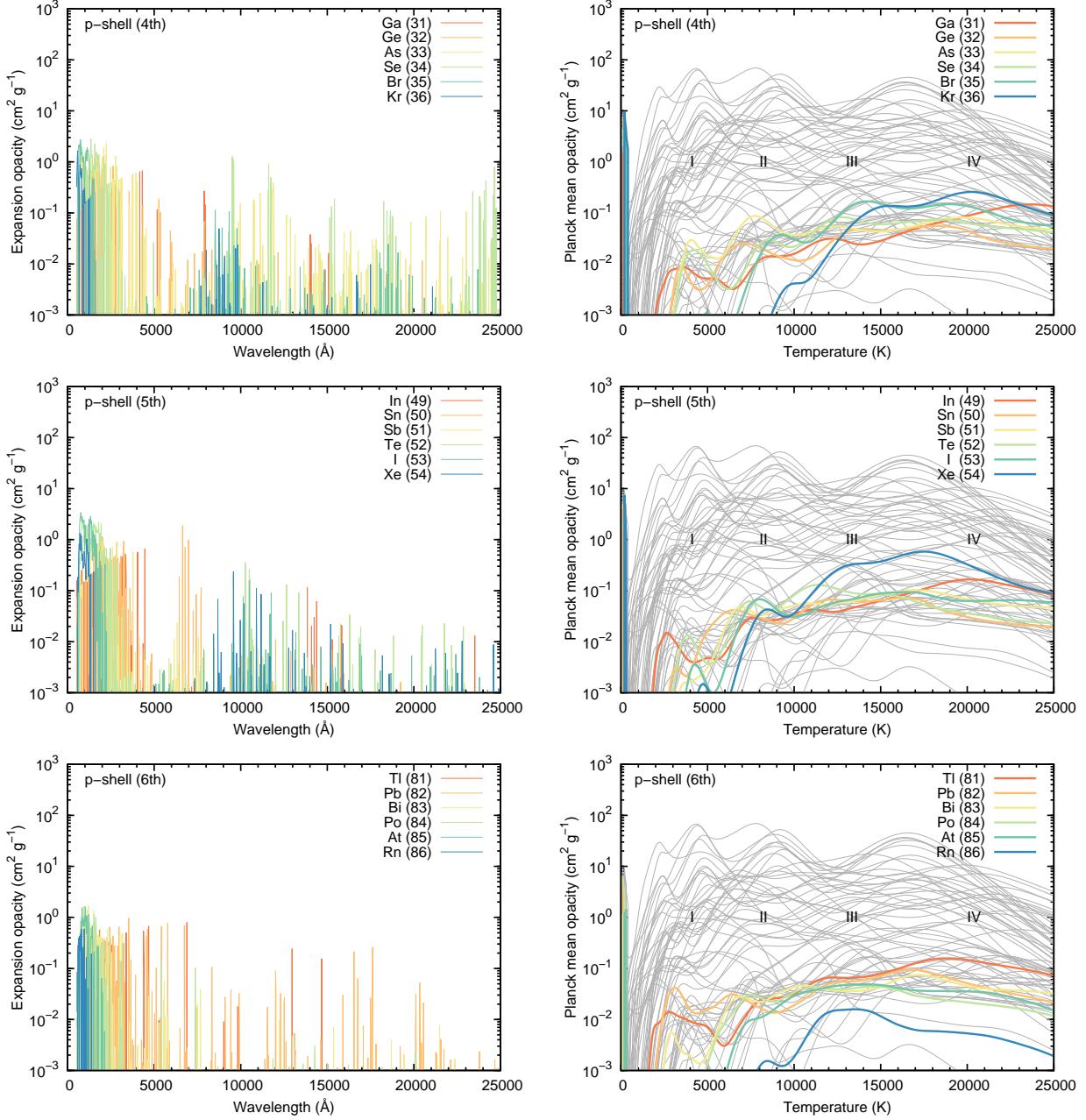


Figure 7. Same as Figure 3 but for *p*-shell elements.

$Z = 29$ and 30 , and the results of our new atomic calculations for $Z = 31 - 92$.

Figure 9 shows expansion opacities for different Y_e . At $Y_e \leq 0.20$, the opacities do not strongly depend on Y_e . The Planck mean opacities stays around $\kappa \sim 20 - 30 \text{ cm}^2 \text{ g}^{-1}$ at $T > 5,000 \text{ K}$. The temperature dependence at $T > 5,000 \text{ K}$ is weaker than in individual elements because of the mixture of elements with different peaks positions as a function of temperature.

The opacities are smaller for higher Y_e . For $Y_e = 0.25 - 0.35$, the Planck mean opacities are in the range

of $\kappa = 1 - 10 \text{ cm}^2 \text{ g}^{-1}$ at $T > 5,000 \text{ K}$. The opacities slightly increase with temperature due to the contribution of latter half of *d*-shell elements (group 8-11, see Figure 6). For $Y_e = 0.4$, the contributions from *d*-shell elements decrease and the opacities are even lower, i.e., $\kappa = 0.1 - 1 \text{ cm}^2 \text{ g}^{-1}$ at $T > 5,000 \text{ K}$.

At a high temperature ($T \gtrsim 20,000 \text{ K}$), the opacity of the low Y_e case decreases more rapidly than that of the high Y_e case. This is due to the limitation of ionization states in our atomic data (see Sections 3.1 and 3.2), i.e., our opacity data are not applicable for high tempera-

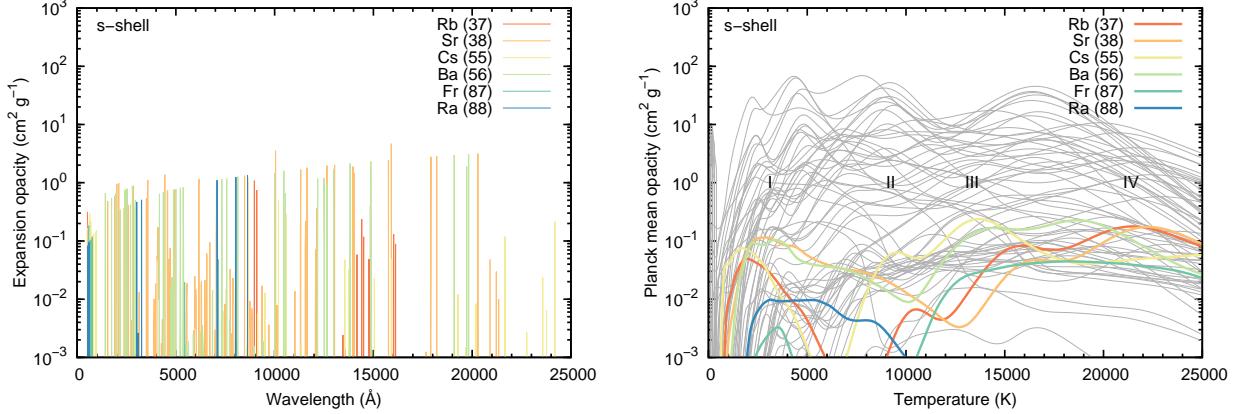


Figure 8. Same as Figure 3 but for *s*-shell elements.

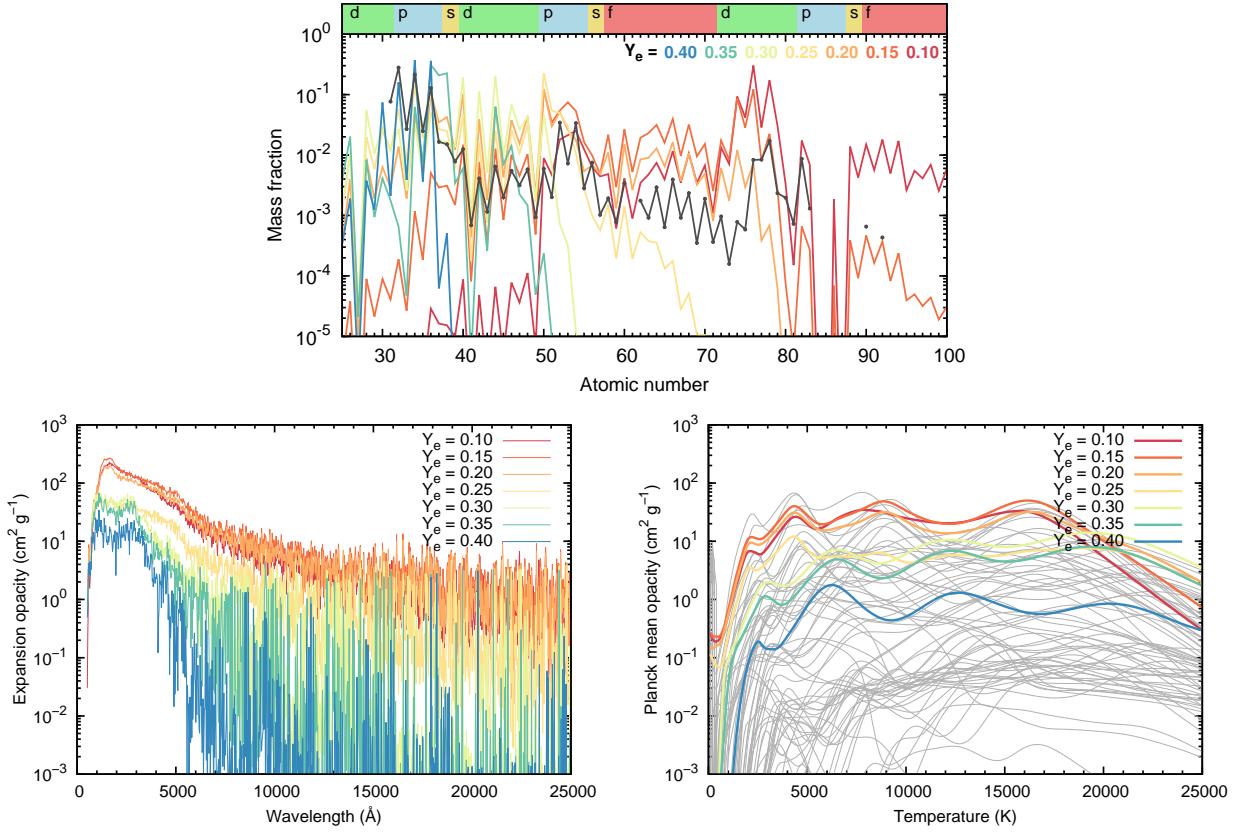


Figure 9. Top: Abundance distribution for different Y_e (Wanajo et al. 2014). Bottom left: Expansion opacity as a function of wavelength for each Y_e . Bottom right: Planck mean opacity as a function of temperature for each Y_e .

ture. Since the ionization potentials of *d*-shell elements are generally higher than those of *f*-shell elements, the applicable temperature range is wider for high Y_e cases, where *d*-shell elements dominate the opacities.

Note that the opacity of $\kappa = 0.1 - 0.5 \text{ cm}^2 \text{ g}^{-1}$ is often used for blue kilonovae because it gives a good approximation for Type Ia supernova. However, the opacities of

mixture of *r*-process elements are almost always higher than $\kappa = 0.1 - 0.5 \text{ cm}^2 \text{ g}^{-1}$ even for high Y_e , except for a low temperature ($T < 2,000 \text{ K}$). This is because Fe is not necessarily representative of *d*-shell elements and the contribution of Fe-like elements (Ru and Os) is low compared with other *d*-shell elements at $T < 10,000 \text{ K}$ (Figure 5).

Table 1. Planck mean opacity for element mixture

Y_e	$X(\text{La})^a$	$X(\text{La+Ac})^b$	κ^c $\text{cm}^2 \text{ g}^{-1}$
0.10	7.1×10^{-2}	$1.7 \times 10^{-1}^d$	27.0
0.15	2.6×10^{-1}	2.6×10^{-1}	32.9
0.20	1.1×10^{-1}	1.1×10^{-1}	22.3
0.25	5.5×10^{-3}	5.5×10^{-3}	5.60
0.30	3.4×10^{-7}	3.4×10^{-7}	5.36
0.35	0.0	0.0	3.30
0.40	0.0	0.0	0.96

NOTE— ^a Mass fraction of lanthanide elements.

^b Mass fraction of lanthanide and actinide elements.

^c Average Planck mean opacity for $T = 5,000 - 10,000 \text{ K}$ ($\rho = 1 \times 10^{-13} \text{ g cm}^{-3}$ and $t = 1 \text{ day}$ after the merger).

^d 1.1×10^{-1} excluding elements with $Z \geq 93$, for which no atomic data are available.

For the ease of applications in analytical models, we give average values of the Planck mean opacities in Table 1. However, it is emphasized that the average opacities are derived only at $T = 5,000 - 10,000 \text{ K}$ and there is a strong temperature dependence at $T < 5,000 \text{ K}$. Furthermore, the expansion opacities also depend on the density (and thus, the position in the ejecta) as well as the time after the merger. Therefore, we need full numerical calculations to quantitatively connect observational properties with abundance distributions.

4.2. Light curves

In this section, we apply our new opacity data to radiative transfer simulations of kilonovae. We use a Monte-Carlo radiative transfer code developed by Tanaka & Hotokezaka (2013); Tanaka et al. (2014) and further updated by Kawaguchi et al. (2018) to include special-relativistic effects. We adopt a simple one-dimensional ejecta model with a power-law density structure $\rho \propto r^{-3}$ from $v = 0.05c$ to $v = 0.2c$ (Metzger et al. 2010; Metzger 2017), which gives an average velocity of $\langle v \rangle = 0.1c$. The total mass is set to be $M_{\text{ej}} = 0.03M_{\odot}$.

To see the effects of opacities, we perform simulations by changing the abundances of *r*-process elements. We show three cases with different Y_e ranges: high Y_e ($Y_e = 0.30 - 0.40$, no lanthanide), intermediate Y_e ($Y_e = 0.20 - 0.30$, lanthanide fraction of $\sim 5 \times 10^{-3}$), and

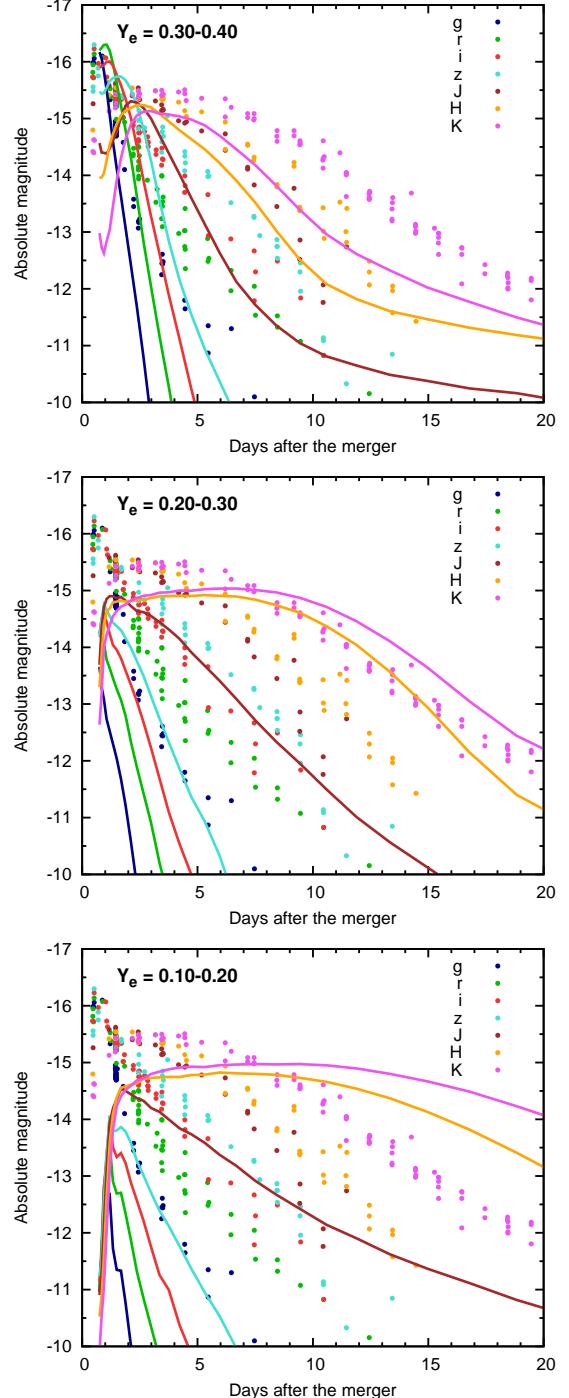


Figure 10. Multi-color light curves in optical (*griz*) and NIR (*JHK*) filters for the models with high Y_e ($Y_e = 0.30 - 0.40$, top), intermediate Y_e ($Y_e = 0.20 - 0.30$, middle), and low Y_e ($Y_e = 0.10 - 0.20$, bottom) compared with the observed light curves of GW170817/AT2017gfo (compiled by Villar et al. 2017).

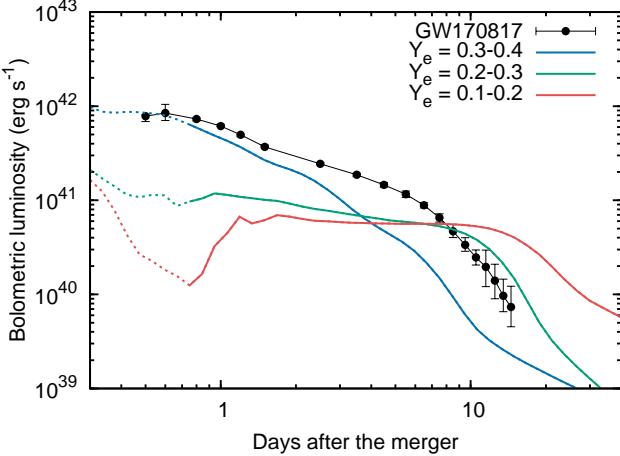


Figure 11. Bolometric light curves of the models with high Y_e ($Y_e = 0.30 - 0.40$, blue), intermediate Y_e ($Y_e = 0.20 - 0.30$, green), and low Y_e ($Y_e = 0.10 - 0.20$, red) compared with the bolometric light curve of GW170817/AT2017gfo constructed by Waxman et al. (2018). Dotted lines show the epoch in which our calculations are not reliable since the ejecta temperature is too high for our opacity data (only up to triply ionized ions, see Section 3).

low Y_e ($Y_e = 0.10 - 0.20$, lanthanide fraction of ~ 0.1). The abundances are averaged over the Y_e range above by using single- Y_e nucleosynthesis calculations with a step of $\Delta Y_e = 0.01$ by Wanajo et al. (2014). The nuclear heating rates for corresponding Y_e ranges are also taken from Wanajo et al. (2014). The thermalization efficiencies of γ -rays, α particles, β particles, and fission are separately taken into account by analytically estimating characteristic timescales (Barnes et al. 2016).

The overall light curve behaviors are not significantly different from our previous calculations (Tanaka et al. 2018) using only Se (p -shell), Ru (d -shell), Te (p -shell), Nd (f -shell), and Er (f -shell) as representative elements. However, the light curves with new opacity data are more smooth both in time and wavelength. In particular, the use of representative elements can often exaggerate emission in certain wavelengths. At later time ($t \gtrsim 10$ days), only transitions from low-lying energy levels contribute the opacities. And thus, the use of small number of elements artificially enhances contributions from transitions of these elements. These effects are smeared out by properly including all the elements, which results in smooth spectra.

The differences in the abundances are clearly imprinted in the multi-color light curves (Figure 10). For lower Y_e , the light curves become redder, i.e., optical brightness is suppressed and NIR brightness is enhanced. Due to the large opacities in the intermediate and low Y_e models, the evolutions of the NIR light curves

are slow. A blue emission dominated in the optical wavelengths is realized only for the high Y_e model at $t < 3$ days after the merger.

Compared with the observed properties of AT2017gfo associated with GW170817, the early optical light curves are most similar to the high Y_e model while the NIR light curves are most similar to the intermediate Y_e model. The same agreement is also found in the bolometric light curve (Figure 11). The early part ($t \sim 1 - 2$ days) best matches with the high Y_e model while the later part matches with the intermediate Y_e model. Note that our models are very simple, and ejecta parameters such as mass and velocity are not tuned to reproduce the properties of AT2017gfo. Nevertheless, these qualitative agreements confirm the presence of multi-component ejecta with different abundances.

The low Y_e model overproduces the total luminosity and gives too red color, which suggests that such a low Y_e component with a lanthanide fraction of $X(\text{La}) \sim 0.1$ is not dominant ($M_{\text{ej}} \ll 0.03 M_{\odot}$). This is consistent with a relatively low lanthanide fraction $X(\text{La}) \lesssim 0.01$ estimated by the spectral and light curve modelling (Chornock et al. 2017; Kasen et al. 2017; Kilpatrick et al. 2017; Tanaka et al. 2017; Tanvir et al. 2017).

4.3. Spectra

The spectral features in our models are of interest because this is the first calculations with the atomic data of all the r -process elements. Figure 12 compares the model spectra with the observed spectra of GW170817/AT2017gfo with VLT/X-Shooter (Pian et al. 2017; Smartt et al. 2017). The models capture overall spectral shape and its evolution: the high Y_e model gives a similar shape of the optical spectra at early phases while intermediate Y_e model gives a similar NIR flux level at later phases.

However, detailed spectral features are not necessarily consistent between the observations and models. This is not surprising because our atomic data do not have a good accuracy for each transition wavelength. To identify the spectral features, we need to use either well-calibrated (but not complete) atomic data as done by Tanaka & Hotokezaka (2013) or very accurate atomic calculations as done by Gaigalas et al. (2019).

There are two potentially important drawbacks in our models. One is too narrow spectral features in the early spectra. This is due to the assumption of $\langle v \rangle = 0.1c$ in our model. The observed broader features indicate that the line-forming region of the blue component should have $v > 0.1c$. In fact, such high velocities of the blue component have been sug-

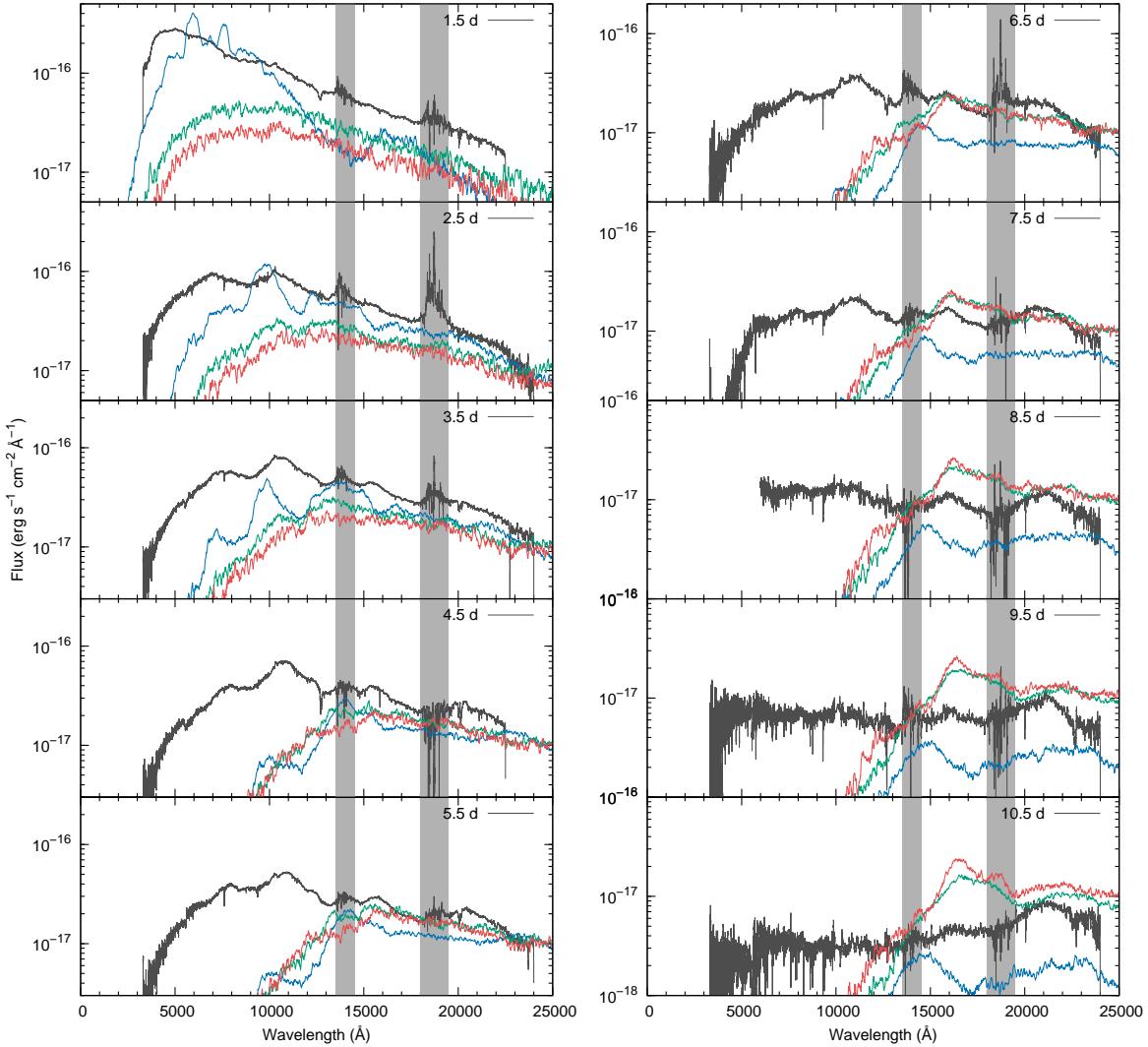


Figure 12. Spectral evolution of the models with high Y_e ($Y_e = 0.30 - 0.40$, blue), intermediate Y_e ($Y_e = 0.20 - 0.30$, green), and low Y_e ($Y_e = 0.10 - 0.20$, red) compared with the spectra of GW170817/AT2017gfo taken with VLT/X-Shooter (Pian et al. 2017; Smartt et al. 2017, taken through the WISeREP, Yaron & Gal-Yam 2012). The shaded areas show the wavelength ranges heavily affected by the atmospheric absorption.

gested (e.g., Kilpatrick et al. 2017; McCully et al. 2017; Nicholl et al. 2017; Shappee et al. 2017). However, it was based on comparison with previous models, which could exaggerate the spectral features by the incompleteness in the atomic data. The comparison with our new model with the complete opacity data securely confirms the necessity of the high velocity for the blue component.

The other is the deficit of the optical flux at $t \gtrsim 5$ days after the merger. This is also seen in the light curves (Figure 10). It is difficult to keep the optical flux at $t \gtrsim 5$ days because the optical flux in the high Y_e model declines too quickly and those in the intermediate and

low Y_e models are suppressed too much. This difficulty remains even by changing ejecta mass and velocity. We may need multi-dimensional simulations by taking into account the interplay between multiple ejecta components (Kawaguchi et al. 2018). Alternatively, this difficulty may point out the necessity of more advanced radiative transfer calculation by taking into account non-local thermodynamic equilibrium or fluorescence of numerous transitions, which are known to be important in supernovae (e.g., Baron et al. 1995; Pinto & Eastman 2000; Mazzali 2000; Dessart & Hillier 2005).

5. SUMMARY

We perform the first systematic atomic structure calculations for neutral atoms and singly, doubly, and triply ionized ions of the elements from Fe ($Z = 26$) to U ($Z = 92$). Using the results, we calculated the opacities of all the r -process elements which can be applied for kilonovae.

We find that the distributions of energy levels tend to be shifted to higher energy for increasing number of electrons in each shell. Also, the total number of excited levels is the highest for the half-closed, most complex elements. The combination of these two effects determines degree of contributions to the opacities. For typical temperature of kilonova ($T \sim 5,000$ K), elements with lower number of electrons have bigger contributions to the opacity thanks to the relatively low-lying energy levels. By this reason, Fe is not a good representative for the opacity of lanthanide-free ejecta. For a higher temperature ($T \gtrsim 10,000$ K), elements with more electrons start to contribute because more transitions from excited levels become active.

The average opacities of mixture of r -process elements are $\kappa \sim 20 - 30 \text{ cm}^2 \text{ g}^{-1}$ for $Y_e \leq 0.20$, $\kappa \sim 3 - 5 \text{ cm}^2 \text{ g}^{-1}$ for $Y_e = 0.25 - 0.35$, and $\kappa \sim 1 \text{ cm}^2 \text{ g}^{-1}$ for $Y_e = 0.40$ at $T = 5,000 - 10,000$ K. But since the opacities depend strongly on temperature at $T < 5,000$ K and they also

evolve with density and time, we need detailed radiative transfer calculations to properly extract information from observations.

Radiative transfer simulations with the new opacity data confirm that multi-component ejecta are necessary to reproduce the observed properties of GW170817/AT2017gfo. The early blue part is best explained by the model with high Y_e ($Y_e = 0.30 - 0.40$, no lanthanide) while the late NIR part is more similar to the model with intermediate Y_e ($Y_e = 0.20 - 0.30$, lanthanide fraction of $\sim 5 \times 10^{-3}$). The model with low Y_e ($Y_e = 0.10 - 0.20$, lanthanide fraction of ~ 0.1) overproduces the NIR light curves, which suggests that such a low Y_e component is not dominant ($M_{\text{ej}} \ll 0.03M_{\odot}$).

Although our calculations include all the r -process elements, the detailed spectral features in the model cannot be compared with the observed spectra because our atomic data only focus on statistical properties and do not have enough accuracies in the transition wavelengths. To identify spectral features, combined use of accurate, well-calibrated (though not complete) atomic data will be important.

Table 2. Summary of HULLAC calculations

Ion	Configurations	Levels	Lines	Lines ^a
Fe I	3d⁶4s², 3d⁸ , 3d ⁷ 4s ¹ , 3d ⁶ 4s ¹ 4p ¹ , 3d ⁷ 4p ¹ , 3d ⁵ 4s ² 4p ¹ , 3d ⁶ 4s ¹ 5s ¹ , 3d ⁷ 5s ¹ , 3d ⁶ 4s ¹ 5p ¹ , 3d ⁶ 4s ¹ 4d ¹ , 3d ⁷ 5p ¹ , 3d ⁷ 4d ¹ , 3d ⁶ 4s ¹ 6s ¹ , 3d ⁷ 6s ¹ , 3d ⁶ 4s ¹ 6p ¹ , 3d ⁶ 4s ¹ 5d ¹	3195	1130295	26490
Fe II	3d⁶4s¹, 3d⁷ , 3d ⁵ 4s ² , 3d ⁶ 4p ¹ , 3d ⁵ 4s ¹ 4p ¹ , 3d ⁶ 5s ¹ , 3d ⁶ 4d ¹ , 3d ⁶ 5p ¹ , 3d ⁶ 6s ¹ , 3d ⁶ 4f ¹ , 3d ⁵ 4s ¹ 5s ¹ , 3d ⁶ 5d ¹ , 3d ⁶ 6p ¹ , 3d ⁵ 4p ² , 3d ⁵ 4s ¹ 4d ¹ , 3d ⁶ 7s ¹	3467	1253693	73267
Fe III	3d⁶ , 3d ⁵ 4s ¹ , 3d ⁵ 4p ¹ , 3d ⁵ 4d ¹ , 3d ⁵ 5s ¹ , 3d ⁵ 5p ¹ , 3d ⁵ 4f ¹ , 3d ⁴ 4s ¹ 4p ¹ , 3d ⁵ 5d ¹ , 3d ⁵ 6s ¹ , 3d ⁵ 6p ¹	2338	560985	120376
Fe IV	3d⁵ , 3d ⁴ 4s ¹ , 3d ⁴ 4p ¹ , 3d ³ 4s ¹ 4p ¹ , 3d ⁴ 5s ¹ , 3d ⁴ 5p ¹	736	45182	38785
Co I	3p⁶3d⁷4s², 3p⁶3d⁸4s¹, 3p⁶3d⁹ , 3p ⁶ 3d ⁷ 4s ¹ 4p ¹ , 3p ⁶ 3d ⁸ 4p ¹ , 3p ⁶ 3d ⁸ 5s ¹ , 3p ⁶ 3d ⁷ 4s ¹ 5s ¹ , 3p ⁶ 3d ⁸ 4d ¹ , 3p ⁶ 3d ⁷ 4s ¹ 4d ¹	778	64798	7619
Co II	3d⁸ , 3d ⁷ 4s ¹ , 3d ⁶ 4s ² , 3d ⁷ 4p ¹ , 3d ⁶ 4s ¹ 4p ¹ , 3d ⁷ 5s ¹ , 3d ⁷ 4d ¹ , 3d ⁷ 5p ¹ , 3d ⁷ 6s ¹	905	87188	13324

Table 2 continued

Table 2 (*continued*)

Ion	Configurations	Levels	Lines	Lines ^a
Co III	3d⁷ , 3d ⁶ 4s ¹ , 3d ⁶ 4p ¹ , 3d ⁶ 4d ¹ , 3d ⁶ 5s ¹ ,	601	35051	32983
Co IV	3d⁶ , 3d ⁵ 4s ¹ , 3d ⁵ 4p ¹ , 3d ⁴ 4s ¹ 4p ¹ , 3d ⁵ 4d ¹ , 3d ⁵ 5s ¹	1088	130730	57610
Ni I	3d⁸4s² , 3d⁹4s¹ , 3d⁹4p¹ , 3d ¹⁰ , 3d ⁸ 4s ¹ 4p ¹ , 3d ⁹ 5s ¹ , 3d ⁸ 4s ¹ 5s ¹ , 3d ⁹ 5p ¹ , 3d ⁹ 4d ¹ , 3d ⁹ 6s ¹ , 3d ⁹ 6p ¹ , 3d ⁹ 5d ¹ , 3d ⁹ 4f ¹	236	7042	1233
Ni II	3p⁶3d⁹ , 3p ⁶ 3d ⁸ 4s ¹ , 3p ⁶ 3d ⁷ 4s ² , 3p ⁶ 3d ⁸ 4p ¹ , 3p ⁶ 3d ⁷ 4s ¹ 4p ¹ , 3p ⁶ 3d ⁸ 5s ¹ , 3p ⁶ 3d ⁸ 4d ¹ , 3p ⁶ 3d ⁸ 5p ¹ , 3p ⁶ 3d ⁸ 6s ¹ , 3p ⁶ 3d ⁸ 4f ¹ , 3p ⁶ 3d ⁸ 5d ¹	587	38893	8360
Ni III	3p⁶3d⁸ , 3p ⁶ 3d ⁷ 4s ¹ , 3p ⁶ 3d ⁷ 4p ¹ , 3p ⁶ 3d ⁶ 4s ² , 3p ⁶ 3d ⁷ 4d ¹ , 3p ⁶ 3d ⁷ 5s ¹ , 3p ⁶ 3d ⁷ 5p ¹ , 3p ⁶ 3d ⁶ 4s ¹ 4p ¹	867	76483	28070
Ni IV	3p⁶3d⁷ , 3p ⁶ 3d ⁶ 4s ¹ , 3p ⁶ 3d ⁶ 4p ¹ , 3p ⁶ 3d ⁵ 4s ² , 3p ⁶ 3d ⁶ 4d ¹ , 3p ⁶ 3d ⁶ 5s ¹ , 3p ⁶ 3d ⁶ 5p ¹	818	76592	75409
Cu I	3d¹⁰4s¹ , 3d⁹4s² , 3d¹⁰4p¹ , 3d ⁹ 4s ¹ 4p ¹ , 3d ¹⁰ 5s ¹ , 3d ¹⁰ 5p ¹ , 3d ¹⁰ 4d ¹ , 3d ¹⁰ 6s ¹ , 3d ¹⁰ 6p ¹ , 3d ¹⁰ 5d ¹ , 3d¹⁰ , 3d ⁹ 4s ¹ , 3d ⁹ 4p ¹ , 3d ⁸ 4s ² , 3d ⁸ 4s ¹ 4p ¹ ,	38	186	186
Cu II	3d ⁹ 5s ¹ , 3d ⁹ 4d ¹ , 3d ⁹ 5p ¹ , 3d ⁹ 6s ¹ , 3d ⁹ 4f ¹ , 3d ⁹ 5d ¹ , 3d ⁹ 6p ¹	204	4559	390
Cu III	3p⁶3d⁹ , 3p ⁶ 3d ⁸ 4s ¹ , 3p ⁶ 3d ⁸ 4p ¹ , 3p ⁶ 3d ⁷ 4s ² , 3p ⁶ 3d ⁸ 5s ¹ , 3p ⁶ 3d ⁸ 4d ¹ , 3p ⁶ 3d ⁸ 5p ¹ , 3p ⁶ 3d ⁷ 4s ¹ 4p ¹ , 3p ⁶ 3d ⁸ 4f ¹ , 3p ⁶ 3d ⁸ 6s ¹ , 3p ⁶ 3d ⁸ 5d ¹	587	38893	17666
Cu IV	3p⁶3d⁸ , 3p ⁶ 3d ⁷ 4s ¹ , 3p ⁶ 3d ⁷ 4p ¹ , 3p ⁶ 3d ⁷ 4d ¹ , 3p ⁶ 3d ⁶ 4s ² , 3p ⁶ 3d ⁷ 5s ¹	397	14803	14595
Zn I	3d¹⁰4s² , 3d ¹⁰ 4s ¹ 4p ¹ , 3d ¹⁰ 4s ¹ 5s ¹ , 3d ¹⁰ 4s ¹ 5p ¹ , 3d ¹⁰ 4s ¹ 4d ¹ , 3d ¹⁰ 4s ¹ 6s ¹ , 3d ¹⁰ 4s ¹ 6p ¹ , 3d ¹⁰ 4s ¹ 5d ¹ , 3d ¹⁰ 4s ¹ 4f ¹	29	130	130
Zn II	3d¹⁰4s¹ , 3d ¹⁰ 4p ¹ , 3d ⁹ 4s ² , 3d ¹⁰ 5s ¹ , 3d ¹⁰ 4d ¹ , 3d ¹⁰ 5p ¹ , 3d ⁹ 4s ¹ 4p ¹ , 3d ¹⁰ 6s ¹ , 3d ¹⁰ 4f ¹ , 3d ¹⁰ 5d ¹ , 3d ¹⁰ 6p ¹	40	195	156
Zn III	3d¹⁰ , 3d ⁹ 4s ¹ , 3d ⁹ 4p ¹ , 3d ⁸ 4s ² , 3d ⁹ 4d ¹ , 3d ⁹ 5s ¹ , 3d ⁹ 5p ¹ , 3d ⁸ 4s ¹ 4p ¹	150	2206	510
Zn IV	3p⁶3d⁹ , 3p ⁶ 3d ⁸ 4s ¹ , 3p ⁶ 3d ⁸ 4p ¹ , 3p ⁶ 3d ⁸ 4d ¹ , 3p ⁶ 3d ⁸ 5p ¹ , 3p ⁶ 3d ⁸ 4f ¹ , 3p ⁶ 3d ⁸ 6p ¹ , 3p ⁶ 3d ⁸ 5f ¹	382	12353	12168
Ga I	4s²4p¹ , 4s ² 5s ¹ , 4s ² 5p ¹ , 4s ² 4d ¹ , 4s ² 6s ¹ , 4s ¹ 4p ² , 4s ² 6p ¹ , 4s ² 5d ¹ , 4s ² 4f ¹	22	85	36
Ga II	4s² , 4s ¹ 4p ¹ , 4s ¹ 5s ¹ , 4p ² , 4s ¹ 4d ¹ , 4s ¹ 5p ¹ , 4s ¹ 6s ¹ , 4s ¹ 5d ¹	26	100	100
Ga III	3d¹⁰4s¹ , 3d ¹⁰ 4p ¹ , 3d ⁹ 4s ² , 3d ¹⁰ 5s ¹ , 3d ¹⁰ 4d ¹ , 3d ¹⁰ 5p ¹ , 3d ¹⁰ 4f ¹	12	26	26
Ga IV	3d¹⁰ , 3d ⁹ 4s ¹ , 3d ⁹ 4p ¹ , 3d ⁹ 4d ¹ , 3d ⁹ 5s ¹ , 3d ⁹ 5p ¹	51	396	396
Ge I	4s²4p² , 4s¹4p³ , 4s ² 4p ¹ 5s ¹ , 4s ² 4p ¹ 5p ¹ , 4s ² 4p ¹ 4d ¹ , 4s ² 4p ¹ 6s ¹ , 4s ² 4p ¹ 6p ¹ , 4s ² 4p ¹ 5d ¹ , 4s ² 4p ¹ 4f ¹	79	966	106

Table 2 continued

Table 2 (*continued*)

Ion	Configurations	Levels	Lines	Lines ^a
Ge II	4s²4p¹ , 4s ¹ 4p ² , 4s ² 5s ¹ , 4s ² 5p ¹ , 4s ² 4d ¹ , 4s ² 6s ¹ , 4s ² 5d ¹ , 4s ² 4f ¹ , 4s ² 6p ¹	22	85	85
Ge III	3d¹⁰4s² , 3d ¹⁰ 4s ¹ 4p ¹ , 3d ¹⁰ 4p ² , 3d ¹⁰ 4s ¹ 5s ¹ , 3d ¹⁰ 4s ¹ 4d ¹ , 3d ¹⁰ 4s ¹ 5p ¹ , 3d ¹⁰ 4s ¹ 4f ¹ , 3d ¹⁰ 4s ¹ 6s ¹ , 3d ¹⁰ 4s ¹ 5d ¹ , 3d ¹⁰ 4s ¹ 7s ¹ ,	32	144	144
Ge IV	3d¹⁰4s¹ , 3d ¹⁰ 4p ¹ , 3d ¹⁰ 4d ¹ , 3d ¹⁰ 5s ¹ , 3d ¹⁰ 5p ¹ , 3d ¹⁰ 4f ¹ , 3d ⁹ 4s ² , 3d ¹⁰ 5d ¹ , 3d ¹⁰ 6s ¹	15	39	39
As I	4s²4p³ , 4s ² 4p ² 5s ¹ , 4s ¹ 4p ⁴ , 4s ² 4p ² 5p ¹ , 4s ² 4p ² 4d ¹ , 4s ² 4p ² 6s ¹ , 4s ² 4p ² 6p ¹	99	1738	1096
As II	4s²4p² , 4s ¹ 4p ³ , 4s ² 4p ¹ 5s ¹ , 4s ² 4p ¹ 4d ¹ , 4s ² 4p ¹ 5p ¹ , 4s ² 4p ¹ 6s ¹ , 4s ² 4p ¹ 5d ¹ , 4s ² 4p ¹ 6p ¹	67	707	684
As III	4s²4p¹ , 4s ¹ 4p ² , 4s ² 5s ¹ , 4s ² 4d ¹ , 4s ² 5p ¹ , 4p ³ , 4s ² 6s ¹ , 4s ² 4f ¹ , 4s ² 5d ¹	25	122	122
As IV	3d¹⁰4s² , 3d ¹⁰ 4s ¹ 4p ¹ , 3d ¹⁰ 4s ¹ 4d ¹ , 3d ¹⁰ 4p ² , 3d ¹⁰ 4s ¹ 5s ¹ , 3d ¹⁰ 4s ¹ 5p ¹ , 3d ¹⁰ 4s ¹ 4f ¹ , 3d ¹⁰ 4s ¹ 5d ¹ , 3d ¹⁰ 4s ¹ 6s ¹	30	131	131
Se I	4s²4p⁴ , 4s ² 4p ³ 5s ¹ , 4s ² 4p ³ 5p ¹ , 4s ² 4p ³ 4d ¹ , 4s ² 4p ³ 6s ¹ , 4s ² 4p ³ 6p ¹ , 4s ² 4p ³ 5d ¹	157	3600	971
Se II	4s²4p³ , 4s ¹ 4p ⁴ , 4s ² 4p ² 5s ¹ , 4s ² 4p ² 5p ¹ , 4s ² 4p ² 6s ¹ , 4s ² 4p ² 5d ¹	78	970	927
Se III	4s²4p² , 4s ¹ 4p ³ , 4s ² 4p ¹ 4d ¹ , 4s ² 4p ¹ 5s ¹ , 4s ² 4p ¹ 5p ¹ , 4s ² 4p ¹ 6s ¹ , 4s ² 4p ¹ 5d ¹	57	419	419
Se IV	4s²4p¹ , 4s ¹ 4p ² , 4s ² 4d ¹ , 4s ² 5s ¹ , 4p ³ , 4s ² 5p ¹	20	86	86
Br I	4s²4p⁵ , 4s ² 4p ⁴ 5s ¹ , 4s ² 4p ⁴ 5p ¹ , 4s ² 4p ⁴ 4d ¹ , 4s ² 4p ⁴ 6s ¹ , 4s ¹ 4p ⁶ , 4s ² 4p ⁴ 6p ¹ , 4s ² 4p ⁴ 5d ¹	117	2166	1102
Br II	4s²4p⁴ , 4s ² 4p ³ 5s ¹ , 4s ¹ 4p ⁵ , 4s ² 4p ³ 4d ¹ , 4s ² 4p ³ 5p ¹ , 4s ² 4p ³ 6s ¹ , 4s ² 4p ³ 5d ¹ , 4s ² 4p ³ 4f ¹	173	4023	3490
Br III	4s²4p³ , 4s ¹ 4p ⁴ , 4s ² 4p ² 4d ¹ , 4s ² 4p ² 5s ¹ , 4s ² 4p ² 5p ¹ , 4s ² 4p ² 5d ¹ , 4s ² 4p ² 6s ¹	106	1448	1448
Br IV	4s²4p² , 4s ¹ 4p ³ , 4s ² 4p ¹ 4d ¹ , 4s ² 4p ¹ 5s ¹ , 4s ² 4p ¹ 5p ¹ , 4s ² 4p ¹ 6s ¹	45	309	309
Kr I	4s²4p⁶ , 4s ² 4p ⁵ 5s ¹ , 4s ² 4p ⁵ 5p ¹ , 4s ² 4p ⁵ 4d ¹ , 4s ² 4p ⁵ 6s ¹ , 4s ² 4p ⁵ 6p ¹ , 4s ² 4p ⁵ 5d ¹	53	434	434
Kr II	4s²4p⁵ , 4s ¹ 4p ⁶ , 4s ² 4p ⁴ 5s ¹ , 4s ² 4p ⁴ 4d ¹ , 4s ² 4p ⁴ 5p ¹ , 4s ² 4p ⁴ 6s ¹ , 4s ² 4p ⁴ 5d ¹ , 4s ² 4p ⁴ 6p ¹ , 4s ² 4p ⁴ 4f ¹	147	3305	2903
Kr III	4s²4p⁴ , 4s ¹ 4p ⁵ , 4s ² 4p ³ 4d ¹ , 4s ² 4p ³ 5s ¹ , 4s ² 4p ³ 5p ¹ , 4s ² 4p ³ 6s ¹ , 4s ² 4p ³ 5d ¹ , 4s ² 4p ³ 6d ¹ , 4p ⁶	172	2786	2749
Kr IV	4s²4p³ , 4s ¹ 4p ⁴ , 4s ² 4p ² 4d ¹ , 4s ² 4p ² 5s ¹ , 4s ² 4p ² 5p ¹ , 4s ² 4p ² 5d ¹ , 4s ² 4p ² 6s ¹	106	1448	1448
Rb I	4p⁶5s¹ , 4p ⁶ 5p ¹ , 4p ⁶ 4d ¹ , 4p ⁶ 6s ¹ , 4p ⁶ 6p ¹ , 4p ⁶ 5d ¹ , 4p ⁶ 7s ¹ , 4p ⁶ 4f ¹ , 4p ⁶ 7p ¹ , 4p ⁶ 6d ¹ ,	17	54	54

Table 2 continued

Table 2 (*continued*)

Ion	Configurations	Levels	Lines	Lines ^a
Rb II	4p⁶ , 4p ⁵ 5s ¹ , 4p ⁵ 4d ¹ , 4p ⁵ 5p ¹ , 4p ⁵ 6s ¹ , 4p ⁵ 5d ¹ , 4p ⁵ 6p ¹ , 4p ⁵ 4f ¹ , 4p ⁵ 7s ¹ , 4p ⁵ 6d ¹ , 4p ⁵ 5f ¹	93	1251	1251
Rb III	4s²4p⁵ , 4s ¹ 4p ⁶ , 4s ² 4p ⁴ 4d ¹ , 4s ² 4p ⁴ 5s ¹ , 4s ² 4p ⁴ 5p ¹ , 4s ² 4p ⁴ 6s ¹ , 4s ² 4p ⁴ 5d ¹	96	1132	1132
Rb IV	4s²4p⁴ , 4s ¹ 4p ⁵ , 4s ² 4p ³ 4d ¹ , 4s ² 4p ³ 5s ¹ , 4s ² 4p ³ 5p ¹ , 4s ² 4p ³ 5d ¹ , 4s ² 4p ³ 6s ¹	133	2022	2022
Sr I	5s² , 5s ¹ 5p ¹ , 5s ¹ 4d ¹ , 5s ¹ 6s ¹ , 4d ¹ 5p ¹ , 5s ¹ 6p ¹ , 5s ¹ 5d ¹ , 5p ² , 5s ¹ 7s ¹ , 5s ¹ 4f ¹ , 5s ¹ 7p ¹ , 5s ¹ 6d ¹	50	392	365
Sr II	4p⁶5s¹ , 4p ⁶ 4d ¹ , 4p ⁶ 5p ¹ , 4p ⁶ 6s ¹ , 4p ⁶ 5d ¹ , 4p ⁶ 6p ¹ , 4p ⁶ 4f ¹ , 4p ⁶ 7s ¹ , 4p ⁶ 6d ¹ , 4p ⁶ 7p ¹ , 4p ⁶ 5f ¹ , 4p ⁶ 5g ¹	21	69	69
Sr III	4p⁶ , 4p ⁵ 4d ¹ , 4p ⁵ 5s ¹ , 4p ⁵ 5p ¹ , 4p ⁵ 5d ¹ , 4p ⁵ 6s ¹ , 4p ⁵ 4f ¹ , 4p ⁵ 6p ¹	65	634	634
Sr IV	4s²4p⁵ , 4s ¹ 4p ⁶ , 4s ² 4p ⁴ 4d ¹ , 4s ² 4p ⁴ 5s ¹ , 4s ² 4p ⁴ 5p ¹ , 4s ² 4p ⁴ 5d ¹ , 4s ² 4p ⁴ 4f ¹	118	2020	2020
Y I	4d¹5s² , 5s ² 5p ¹ , 4d ² 5s ¹ , 4d ¹ 5s ¹ 5p ¹ , 4d ² 5p ¹ , 4d ³ , 5s ² 6s ¹ , 4d ¹ 5s ¹ 6s ¹ , 5p ² 5s ¹ , 5s ² 5d ¹ , 5s ² 6p ¹	128	2385	1958
Y II	5s² , 4d ¹ 5s ¹ , 4d ² , 5s ¹ 5p ¹ , 4d ¹ 5p ¹ , 4d ¹ 6s ¹ , 5s ¹ 6s ¹ , 4d ¹ 5d ¹ , 5p ² , 4d ¹ 6p ¹ , 5s ¹ 5d ¹ , 5s ¹ 6p ¹ , 4d ¹ 4f ¹	99	1324	1324
Y III	4p⁶4d¹ , 4p ⁶ 5s ¹ , 4p ⁶ 5p ¹ , 4p ⁶ 6s ¹ , 4p ⁶ 5d ¹ , 4p ⁶ 6p ¹ , 4p ⁶ 4f ¹ , 4p ⁶ 7s ¹ , 4p ⁶ 6d ¹ , 4p ⁶ 5f ¹ ,	17	48	48
Y IV	4p⁶ , 4p ⁵ 4d ¹ , 4p ⁵ 5s ¹ , 4p ⁵ 5p ¹ , 4p ⁵ 5d ¹ , 4p ⁵ 4f ¹ , 4p ⁵ 6s ¹ , 4p ⁵ 6p ¹	65	634	634
Zr I	4d²5s² , 4d ³ 5s ¹ , 4d ² 5s ¹ 5p ¹ , 4d ¹ 5s ² 5p ¹ , 4d ⁴ , 4d ³ 5p ¹ , 4d ² 5s ¹ 6s ¹ , 4d ² 5s ¹ 6p ¹ , 4d ² 5s ¹ 5d ¹ , 4d ³ 6s ¹ , 4d ² 5p ² , 4d ² 5s ¹ 7p ¹	788	76953	42680
Zr II	4d²5s¹ , 4d ³ , 4d ¹ 5s ² , 4d ² 5p ¹ , 4d ¹ 5s ¹ 5p ¹ , 4d ² 6s ¹ , 4d ² 5d ¹	188	4452	4452
Zr III	4d² , 4d ¹ 5s ¹ , 5s ² , 4d ¹ 5p ¹ , 5s ¹ 5p ¹ , 4d ¹ 5d ¹ , 4d ¹ 6s ¹ , 4d ¹ 6p ¹ , 4d ¹ 4f ¹	84	933	933
Zr IV	4p⁶4d¹ , 4p ⁶ 5s ¹ , 4p ⁶ 5p ¹ , 4p ⁶ 5d ¹ , 4p ⁶ 6s ¹ , 4p ⁶ 4f ¹ , 4p ⁶ 6p ¹ , 4p ⁶ 6d ¹	14	35	35
Nb I	4d⁴5s¹ , 4d³5s² , 4d⁵ , 4d ³ 5s ¹ 5p ¹ , 4d ⁴ 5p ¹ , 4d ⁴ 6s ¹ , 4d ³ 5s ¹ 6s ¹	649	49341	20961
Nb II	4d⁴ , 4d³5s¹ , 4d²5s² , 4d ³ 5p ¹ , 4d ² 5s ¹ 5p ¹ , 4d ³ 6s ¹ , 4d ³ 5d ¹	487	27199	27162
Nb III	4d³ , 4d ² 5s ¹ , 4d ² 5p ¹ , 4d ¹ 5s ² , 4d ¹ 5s ¹ 5p ¹ , 4d ² 5d ¹ , 4d ² 6s ¹	188	4452	4452

Table 2 continued

Table 2 (*continued*)

Ion	Configurations	Levels	Lines	Lines ^a
Nb IV	4d² , 4d ¹ 5s ¹ , 4d ¹ 5p ¹ , 5s ² , 5s ¹ 5p ¹ , 4d ¹ 5d ¹ , 4d ¹ 6s ¹	52	336	336
Mo I	4d⁵5s¹ , 4d ⁴ 5s ² , 4d ⁶ , 4d ⁵ 5p ¹ , 4d ⁴ 5s ¹ 5p ¹ , 4d ⁵ 6s ¹ , 4d ⁵ 5d ¹ , 4d ⁵ 7s ¹ , 4d ⁴ 5s ¹ 6s ¹ , 4d ⁵ 6d ¹ ,	1654	275258	9747
Mo II	4d⁵ , 4d ⁴ 5s ¹ , 4d ⁴ 5p ¹ , 4d ³ 5s ² , 4d ³ 5s ¹ 5p ¹ , 4d ⁴ 6s ¹ , 4d ⁴ 5d ¹	851	84312	66668
Mo III	4d⁴ , 4d ³ 5s ¹ , 4d ³ 5p ¹ , 4d ² 5s ² , 4d ² 5s ¹ 5p ¹ , 4d ³ 6s ¹ , 4d ³ 5d ¹	487	27199	27199
Mo IV	4d³ , 4d ² 5s ¹ , 4d ² 5p ¹ , 4d ¹ 5s ² , 4d ¹ 5s ¹ 5p ¹ , 4d ² 6s ¹ , 4d ² 5d ¹	188	4452	4452
Tc I	4d⁵5s² , 4d ⁶ 5s ¹ , 4d ⁷ , 4d ⁵ 5s ¹ 5p ¹ , 4d ⁶ 5p ¹ , 4d ⁵ 5s ¹ 6s ¹ , 4d ⁶ 6s ¹ , 4d ⁵ 5s ¹ 5d ¹ , 4d ⁶ 5d ¹ , 4d ⁶ 6p ¹ ,	2026	440047	27092
Tc II	4d⁵5s¹ , 4d⁶ , 4d ⁵ 5p ¹ , 4d ⁴ 5s ² , 4d ⁴ 5s ¹ 5p ¹ , 4d ⁵ 6s ¹ , 4d ⁵ 5d ¹	1122	138447	72563
Tc III	4d⁵ , 4d ⁴ 5s ¹ , 4d ⁴ 5p ¹ , 4d ³ 5s ² , 4d ³ 5s ¹ 5p ¹ , 4d ⁴ 6s ¹ , 4d ⁴ 5d ¹	851	84312	82338
Tc IV	4d⁴ , 4d ³ 5s ¹ , 4d ³ 5p ¹ , 4d ² 5s ² , 4d ² 5s ¹ 5p ¹ , 4d ³ 6s ¹ , 4d ³ 5d ¹	487	27199	27199
Ru I	4d⁷5s¹ , 4d⁶5s² , 4d⁸ , 4d ⁶ 5s ¹ 5p ¹ , 4d ⁷ 5p ¹ , 4d ⁷ 6s ¹ , 4d ⁷ 6p ¹ , 4d ⁷ 5d ¹ , 4d ⁶ 5s ¹ 6s ¹ , 4d ⁶ 5s ¹ 5d ¹ ,	1545	250476	6823
Ru II	4d⁷ , 4d ⁶ 5s ¹ , 4d ⁵ 5s ² , 4d ⁶ 5p ¹ , 4d ⁵ 5s ¹ 5p ¹ , 4d ⁶ 6s ¹ , 4d ⁶ 5d ¹ , 4d ⁵ 5s ¹ 6p ¹	1472	213952	58450
Ru III	4d⁶ , 4d ⁵ 5s ¹ , 4d ⁵ 5p ¹ , 4d ⁵ 5d ¹ , 4d ⁵ 6s ¹ ,	728	49066	48911
Ru IV	4d⁵ , 4d ⁴ 5s ¹ , 4d ⁴ 5p ¹ , 4d ³ 5s ² , 4d ³ 5s ¹ 5p ¹ , 4d ⁴ 6s ¹ , 4d ⁴ 5d ¹	851	84312	84312
Rh I	4d⁸5s¹ , 4d⁹ , 4d⁸5p¹ , 4d ⁷ 5s ² , 4d ⁸ 6s ¹ ,	98	1321	1190
Rh II	4d⁸ , 4d ⁷ 5s ¹ , 4d ⁷ 5p ¹ , 4d ⁶ 5s ² , 4d ⁷ 6s ¹ , 4d ⁷ 6p ¹	339	12696	10992
Rh III	4d⁷ , 4d ⁶ 5s ¹ , 4d ⁶ 5p ¹ , 4d ⁵ 5s ² , 4d ⁶ 5d ¹ , 4d ⁶ 6s ¹ , 4d ⁶ 6p ¹	818	76592	74318
Rh IV	4d⁶ , 4d ⁵ 5s ¹ , 4d ⁵ 5p ¹ , 4d ⁴ 5s ² , 4d ⁵ 5d ¹ , 4d ⁵ 6s ¹ , 4d ⁵ 6p ¹	976	104622	104622
Pd I	4d¹⁰ , 4d ⁹ 5s ¹ , 4d ⁸ 5s ² , 4d ⁹ 5p ¹ , 4d ⁹ 6s ¹ , 4d ⁸ 5s ¹ 5p ¹ , 4d ⁹ 6p ¹ , 4d ⁹ 5d ¹	150	2206	206
Pd II	4d⁹ , 4d ⁸ 5s ¹ , 4d ⁸ 5p ¹ , 4d ⁷ 5s ² , 4d ⁷ 5s ¹ 5p ¹ , 4d ⁸ 6s ¹ , 4d ⁸ 5d ¹ , 4d ⁸ 6p ¹	423	18636	8018
Pd III	4d⁸ , 4d ⁷ 5s ¹ , 4d ⁷ 5p ¹ , 4d ⁷ 6s ¹ , 4d ⁶ 5s ¹ 5p ¹ ,	555	19157	15929
Pd IV	4d⁷ , 4d ⁶ 5s ¹ , 4d ⁶ 5p ¹ , 4d ⁶ 5d ¹ , 4d ⁶ 6s ¹ , 4d ⁶ 6p ¹	781	70102	70102
Ag I	4d¹⁰5s¹ , 4d¹⁰5p¹ , 4d⁹5s² , 4d ¹⁰ 6s ¹ , 4d ¹⁰ 6p ¹ , 4d ¹⁰ 5d ¹ , 4d ¹⁰ 7s ¹ , 4d ¹⁰ 7p ¹ , 4d ¹⁰ 6d ¹ , 4d ¹⁰ 4f ¹ , 4d ¹⁰ 8s ¹	18	60	60

Table 2 continued

Table 2 (*continued*)

Ion	Configurations	Levels	Lines	Lines ^a
Ag II	4d¹⁰ , 4d ⁹ 5s ¹ , 4d ⁹ 5p ¹ , 4d ⁸ 5s ² , 4d ⁹ 6s ¹ , 4d ⁹ 5d ¹ , 4d ⁸ 5s ¹ 5p ¹ , 4d ⁹ 6p ¹	150	2206	642
Ag III	4d⁹ , 4d ⁸ 5s ¹ , 4d ⁸ 5p ¹ , 4d ⁷ 5s ² , 4d ⁸ 6s ¹ , 4d ⁸ 5d ¹ , 4d ⁸ 6p ¹	210	5764	5764
Ag IV	4d⁸ , 4d ⁷ 5s ¹ , 4d ⁷ 5p ¹ , 4d ⁶ 5s ² , 4d ⁷ 6s ¹ , 4d ⁷ 5d ¹ , 4d ⁷ 6p ¹	507	29606	29606
Cd I	4d¹⁰5s² , 4d ¹⁰ 5s ¹ 5p ¹ , 4d ¹⁰ 5s ¹ 6s ¹ , 4d ¹⁰ 5s ¹ 6p ¹ , 4d ¹⁰ 5s ¹ 5d ¹ , 4d ¹⁰ 5s ¹ 7s ¹ , 4d ¹⁰ 5s ¹ 7p ¹ , 4d ¹⁰ 5s ¹ 6d ¹ , 4d ¹⁰ 5s ¹ 4f ¹	29	130	130
Cd II	4d¹⁰5s¹ , 4d ¹⁰ 5p ¹ , 4d ⁹ 5s ² , 4d ¹⁰ 6s ¹ , 4d ¹⁰ 5d ¹ , 4d ¹⁰ 6p ¹ , 4d ⁹ 5s ¹ 5p ¹ , 4d ¹⁰ 7s ¹ , 4d ¹⁰ 4f ¹ , 4d ¹⁰ 6d ¹ , 4d ¹⁰ 7p ¹	40	195	156
Cd III	4d¹⁰ , 4d ⁹ 5s ¹ , 4d ⁹ 5p ¹ , 4d ⁸ 5s ² , 4d ⁹ 5d ¹ , 4d ⁹ 6s ¹	48	258	258
Cd IV	4d⁹ , 4d ⁸ 5s ¹ , 4d ⁸ 5p ¹ , 4d ⁷ 5s ² , 4d ⁸ 5d ¹ , 4d ⁸ 6s ¹	165	2882	2882
In I	5s²5p¹ , 5s ² 6s ¹ , 5s ² 6p ¹ , 5s ² 5d ¹ , 5s ¹ 5p ² , 5s ² 7s ¹ , 5s ² 7p ¹ , 5s ² 6d ¹ , 5s ² 4f ¹	22	85	54
In II	5s² , 5s ¹ 5p ¹ , 5s ¹ 6s ¹ , 5s ¹ 5d ¹ , 5p ² , 5s ¹ 6p ¹ , 5s ¹ 7s ¹ , 5s ¹ 4f ¹ , 5s ¹ 6d ¹ , 5s ¹ 7p ¹ ,	34	181	181
In III	4d¹⁰5s¹ , 4d ¹⁰ 5p ¹ , 4d ⁹ 5s ² , 4d ¹⁰ 6s ¹ , 4d ¹⁰ 5d ¹ , 4d ¹⁰ 6p ¹ , 4d ⁹ 5s ¹ 5p ¹ , 4d ¹⁰ 4f ¹	35	120	120
In IV	4d¹⁰ , 4d ⁹ 5s ¹ , 4d ⁹ 5p ¹ , 4d ⁸ 5s ² , 4d ⁹ 5d ¹ , 4d ⁹ 6s ¹	48	258	258
Sn I	5s²5p² , 5s ² 5p ¹ 6s ¹ , 5s ¹ 5p ³ , 5s ² 5p ¹ 6p ¹ , 5s ² 5p ¹ 5d ¹ , 5s ² 5p ¹ 7s ¹ , 5s ² 5p ¹ 7p ¹ , 5s ² 5p ¹ 6d ¹ , 5s ² 5p ¹ 4f ¹ , 5s ² 5p ¹ 8s ¹ , 5s ² 5p ¹ 7d ¹	95	1326	464
Sn II	5s²5p¹ , 5s ¹ 5p ² , 5s ² 6s ¹ , 5s ² 5d ¹ , 5s ² 6p ¹ , 5s ² 7s ¹ , 5s ² 4f ¹ , 5s ² 6d ¹ , 5s ² 7p ¹ , 5s ² 8s ¹ , 5s ² 5f ¹	25	104	104
Sn III	4d¹⁰5s² , 4d ¹⁰ 5s ¹ 5p ¹ , 4d ¹⁰ 5p ² , 4d ¹⁰ 5s ¹ 6s ¹ , 4d ¹⁰ 5s ¹ 5d ¹ , 4d ¹⁰ 5s ¹ 6p ¹ , 4d ¹⁰ 4f ¹ 5s ¹ , 4d ¹⁰ 5s ¹ 7s ¹ , 4d ¹⁰ 5s ¹ 6d ¹ , 4d ¹⁰ 5s ¹ 7p ¹ ,	34	181	181
Sn IV	4d¹⁰5s¹ , 4d ¹⁰ 5p ¹ , 4d ¹⁰ 5d ¹ , 4d ⁹ 5s ² , 4d ¹⁰ 6s ¹ , 4d ¹⁰ 6p ¹ , 4d ¹⁰ 4f ¹ , 4d ¹⁰ 6d ¹ , 4d ¹⁰ 7s ¹ , 4d ¹⁰ 5g ¹ , 4d ⁹ 5s ¹ 5p ¹	40	198	198
Sb I	5p³ , 5p ² 6s ¹ , 5p ² 6p ¹ , 5p ² 5d ¹ , 5p ² 7s ¹ , 5p ² 6d ¹ , 5p ² 7p ¹ , 5p ² 4f ¹ , 5p ² 8s ¹ , 5p ² 8p ¹ , 5p ² 7d ¹	206	6684	794
Sb II	5s²5p² , 5s ¹ 5p ³ , 5s ² 5p ¹ 6s ¹ , 5s ² 5p ¹ 5d ¹ , 5s ² 5p ¹ 6p ¹ , 5s ² 5p ¹ 7s ¹ , 5s ² 5p ¹ 6d ¹ , 5s ² 5p ¹ 4f ¹ , 5p ⁴	74	809	678
Sb III	5s²5p¹ , 5s ¹ 5p ² , 5s ² 6s ¹ , 5s ² 5d ¹ , 5s ² 6p ¹ , 5s ² 4f ¹ , 5s ² 7s ¹ , 5s ² 6d ¹ , 5s ² 8s ¹	21	65	65

Table 2 continued

Table 2 (*continued*)

Ion	Configurations	Levels	Lines	Lines ^a
Sb IV	5s² , 5s ¹ 5p ¹ , 5p ² , 5s ¹ 5d ¹ , 5s ¹ 6s ¹ , 5s ¹ 6p ¹ , 5s ¹ 4f ¹ , 5s ¹ 6d ¹ , 5s ¹ 7s ¹	30	131	131
Te I	5p⁴ , 5p ³ 6s ¹ , 5p ³ 6p ¹ , 5p ³ 5d ¹ , 5p ³ 7s ¹ , 5p ³ 7p ¹ , 5p ³ 6d ¹ , 5p ³ 4f ¹ , 5p ³ 8s ¹ , 5p ³ 7d ¹ ,	245	8313	1546
Te II	5s²5p³ , 5s ¹ 5p ⁴ , 5s ² 5p ² 6s ¹ , 5s ² 5p ² 5d ¹ , 5s ² 5p ² 6p ¹ , 5s ² 5p ² 7s ¹ , 5s ² 5p ² 6d ¹ , 5s ² 5p ² 4f ¹ , 5s ² 5p ² 7p ¹ , 5s ² 5p ² 8s ¹ ,	165	4238	3870
Te III	5s²5p² , 5s ¹ 5p ³ , 5s ² 5p ¹ 5d ¹ , 5s ² 5p ¹ 6s ¹ , 5s ² 5p ¹ 6p ¹ , 5s ² 5p ¹ 6d ¹ , 5s ² 5p ¹ 7s ¹	57	419	419
Te IV	5s²5p¹ , 5s ¹ 5p ² , 5s ² 5d ¹ , 5s ² 6s ¹ , 5s ² 6p ¹ , 5s ² 6d ¹ , 5s ² 7s ¹	18	48	48
I I	5s²5p⁵ , 5s ² 5p ⁴ 6s ¹ , 5s ² 5p ⁴ 6p ¹ , 5s ² 5p ⁴ 5d ¹ , 5s ² 5p ⁴ 7s ¹ , 5s ² 5p ⁴ 7p ¹ , 5s ² 5p ⁴ 6d ¹ , 5s ² 5p ⁴ 4f ¹ , 5s ² 5p ⁴ 8s ¹ , 5s ² 5p ⁴ 8p ¹ , 5s ² 5p ⁴ 7d ¹	203	6432	3000
I II	5s²5p⁴ , 5s ² 5p ³ 6s ¹ , 5s ¹ 5p ⁵ , 5s ² 5p ³ 5d ¹ , 5s ² 5p ³ 6p ¹ , 5s ² 5p ³ 7s ¹ , 5s ² 5p ³ 6d ¹ , 5s ² 5p ³ 4f ¹ , 5s ² 5p ³ 7p ¹ , 5s ² 5p ³ 8s ¹ , 5s ² 5p ³ 7d ¹ , 5s ² 5p ³ 5f ¹	289	11510	8251
I III	5s²5p³ , 5s ¹ 5p ⁴ , 5s ² 5p ² 5d ¹ , 5s ² 5p ² 6s ¹ , 5s ² 5p ² 7s ¹ , 5s ² 5p ² 6d ¹ , 5s ² 5p ² 8s ¹ , 5s ² 5p ² 7d ¹	121	431	431
I IV	5s²5p² , 5s ¹ 5p ³ , 5s ² 5p ¹ 5d ¹ , 5s ² 5p ¹ 6s ¹ , 5s ² 5p ¹ 6d ¹ , 5s ² 5p ¹ 7s ¹ , 5s ² 5p ¹ 7d ¹ , 5s ² 5p ¹ 8s ¹	63	179	179
Xe I	5p⁶ , 5p ⁵ 6s ¹ , 5p ⁵ 6p ¹ , 5p ⁵ 5d ¹ , 5p ⁵ 7s ¹ , 5p ⁵ 7p ¹ , 5p ⁵ 6d ¹ , 5p ⁵ 8s ¹ , 5p ⁵ 4f ¹ , 5p ⁵ 7d ¹	81	951	715
Xe II	5s²5p⁵ , 5s ¹ 5p ⁶ , 5s ² 5p ⁴ 6s ¹ , 5s ² 5p ⁴ 5d ¹ , 5s ² 5p ⁴ 6p ¹ , 5s ² 5p ⁴ 7s ¹ , 5s ² 5p ⁴ 6d ¹ , 5s ² 5p ⁴ 4f ¹ , 5s ² 5p ⁴ 7p ¹ , 5s ² 5p ⁴ 8s ¹ ,	155	3685	3393
Xe III	5s²5p⁴ , 5s ¹ 5p ⁵ , 5s ² 5p ³ 5d ¹ , 5s ² 5p ³ 6s ¹ , 5s ² 5p ³ 6p ¹ , 5s ² 5p ³ 4f ¹ , 5s ² 5p ³ 6d ¹ , 5s ² 5p ³ 7s ¹ , 5s ² 5p ³ 5f ¹ , 5p ⁶ ,	214	6052	6024
Xe IV	5s²5p³ , 5s ¹ 5p ⁴ , 5s ² 5p ² 5d ¹ , 5s ² 5p ² 6s ¹ , 5s ² 5p ² 4f ¹ , 5s ² 5p ² 6p ¹	100	1480	1480
Cs I	5p⁶6s¹ , 5p ⁶ 6p ¹ , 5p ⁶ 5d ¹ , 5p ⁶ 7s ¹ , 5p ⁶ 7p ¹ , 5p ⁶ 6d ¹ , 5p ⁶ 8s ¹ , 5p ⁶ 4f ¹ , 5p ⁶ 8p ¹ , 5p ⁶ 7d ¹ , 5p⁶ , 5p ⁵ 6s ¹ , 5p ⁵ 5d ¹ , 5p ⁵ 6p ¹ , 5p ⁵ 7s ¹	17	54	54
Cs II	5p ⁵ 6d ¹ , 5p ⁵ 4f ¹ , 5p ⁵ 7p ¹ , 5p ⁵ 8s ¹ , 5p ⁵ 5f ¹ , 5p ⁵ 7d ¹ , 5p ⁵ 8p ¹	103	1569	1569
Cs III	5s²5p⁵ , 5s ¹ 5p ⁶ , 5s ² 5p ⁴ 5d ¹ , 5s ² 5p ⁴ 6s ¹ , 5s ² 5p ⁴ 6p ¹ , 5s ² 5p ⁴ 4f ¹ , 5s ² 5p ⁴ 6d ¹ , 5s ² 5p ⁴ 7s ¹ , 5s ² 5p ⁴ 7p ¹ , 5s ² 5p ⁴ 5f ¹ , 5s ² 5p ⁴ 8s ¹	185	4932	4932
Cs IV	5s²5p⁴ , 5s ¹ 5p ⁵ , 5s ² 5p ³ 5d ¹ , 5s ² 5p ³ 6s ¹ , 5s ² 5p ³ 6d ¹ , 5s ² 5p ³ 7s ¹ , 5s ² 5p ³ 7d ¹ , 5s ² 5p ³ 8s ¹	153	410	410
Ba I	6s² , 6s ¹ 5d ¹ , 6s ¹ 6p ¹ , 5d ² , 5d ¹ 6p ¹ , 6s ¹ 7s ¹ , 6s ¹ 6d ¹ , 6s ¹ 7p ¹ , 5d ¹ 7s ¹ , 6s ¹ 8s ¹ , 6p ² , 6s ¹ 4f ¹ , 6s ¹ 7d ¹	59	516	394

Table 2 continued

Table 2 (*continued*)

Ion	Configurations	Levels	Lines	Lines ^a
Ba II	5p⁶6s¹ , 5p ⁶ 5d ¹ , 5p ⁶ 6p ¹ , 5p ⁶ 7s ¹ , 5p ⁶ 6d ¹ , 5p ⁶ 4f ¹ , 5p ⁶ 7p ¹ , 5p ⁶ 5f ¹ , 5p ⁶ 8s ¹ , 5p ⁶ 7d ¹ , 5p ⁶ 8p ¹	19	63	63
Ba III	5p⁶ , 5p ⁵ 5d ¹ , 5p ⁵ 6s ¹ , 5p ⁵ 4f ¹ , 5p ⁵ 6p ¹ , 5p ⁵ 6d ¹ , 5p ⁵ 7s ¹ , 5p ⁵ 5f ¹ , 5p ⁵ 7p ¹ , 5p ⁵ 7d ¹ , 5p ⁵ 8s ¹	93	1251	1251
Ba IV	5s²5p⁵ , 5s ¹ 5p ⁶ , 5s ² 5p ⁴ 5d ¹ , 5s ² 5p ⁴ 6s ¹ , 5s ² 5p ⁴ 6p ¹ , 5d²6s¹ , 5d ¹ 6s ² , 5d ³ , 5d ¹ 6s ¹ 6p ¹ , 4f ¹ 6s ² ,	60	574	574
La I	6s ² 6p ¹ , 5d ² 6p ¹ , 4f ¹ 5d ¹ 6s ¹ , 4f ¹ 6s ¹ 6p ¹ , 5d ² 7s ¹ , 5d ¹ 6s ¹ 7s ¹ , 5d ² 6d ¹ , 5d ² 7p ¹ , 4f ¹ 5d ² , 5d ¹ 6s ¹ 7p ¹ , 6s ² 8p ¹	414	20274	8229
La II	5d² , 4f¹6s¹ , 4f¹5d¹ , 5d ¹ 6s ¹ , 6s ² , 5d ¹ 6p ¹ , 6s ¹ 6p ¹ , 4f ¹ 6p ¹	66	553	553
La III	5p⁶5d¹ , 5p⁶4f¹ , 5p ⁶ 6s ¹ , 5p ⁶ 6p ¹ , 5p ⁶ 7s ¹ , 5p ⁶ 6d ¹ , 5p ⁶ 5f ¹ , 5p ⁶ 7p ¹ , 5p ⁶ 8s ¹	15	36	36
La IV	5p⁶ , 5p ⁵ 4f ¹ , 5p ⁵ 5d ¹ , 5p ⁵ 6s ¹ , 5p ⁵ 6p ¹ , 5p ⁵ 6d ¹ , 5p ⁵ 7s ¹	55	422	422
Ce I	4f²6s² , 4f ¹ 5d ¹ 6s ² , 4f ¹ 5d ² 6s ¹ , 4f ² 5d ¹ 6s ¹ , 4f ¹ 5d ¹ 6s ¹ 6p ¹ , 4f ¹ 5d ³ , 4f ¹ 6s ² 6p ¹ , 4f ² 6s ¹ 6p ¹ , 4f ¹ 5d ² 6p ¹ , 4f ² 5d ² ,	1920	293131	150839
Ce II	5d²4f¹ , 4f²6s¹ , 4f²5d¹ , 4f ¹ 5d ¹ 6s ¹ , 4f ¹ 6s ² , 4f ¹ 5d ¹ 6p ¹ , 4f ² 6p ¹ , 4f ¹ 6s ¹ 6p ¹	459	21239	21239
Ce III	4f ² , 4f ¹ 5d ¹ , 4f ¹ 6s ¹ , 5d ² , 4f ¹ 6p ¹ , 5d ¹ 6s ¹ , 4f ¹ 6d ¹ , 4f ¹ 7s ¹ , 5d ¹ 6p ¹ , 4f ¹ 5f ¹ , 4f ¹ 7p ¹ , 4f ¹ 8s ¹ , 4f ¹ 7d ¹ , 4f ¹ 6f ¹ , 4f ¹ 5g ¹ , 6p ² , 5d ¹ 6d ¹	237	6244	5556
Ce IV	5p⁶4f¹ , 5p ⁶ 5d ¹ , 5p ⁶ 6s ¹ , 5p ⁶ 6p ¹ , 5p ⁶ 6d ¹ , 5p ⁶ 7s ¹	10	16	16
Pr I	4f³6s² , 4f³6s¹5d¹ , 4f³6s¹6p¹ , 4f³6s¹7s¹ , 4f³6s¹8s¹ , 4f ² 6s ² 5d ¹ , 4f ² 6s ² 6p ¹ , 4f ² 5d ² 6s ¹ , 4f ² 5d ² 6p ¹ , 4f ² 5d ¹ 6s ¹ 6p ¹ ,	6516	2715879	663287
Pr II	4f³6s¹ , 4f³5d¹ , 4f ² 5d ² , 4f ² 5d ¹ 6s ¹ , 4f ³ 6p ¹ , 4f ² 5d ¹ 6p ¹	2007	364325	346451
Pr III	4f³ , 4f ² 5d ¹ , 4f ² 6s ¹ , 4f ² 6p ¹ , 4f ¹ 5d ² , 4f ¹ 5d ¹ 6s ¹ , 4f ² 7s ¹ , 4f ² 6d ¹ , 4f ² 5f ¹ , 4f ² 8s ¹ ,	653	42001	41920
Pr IV	4f² , 4f ¹ 5d ¹ , 4f ¹ 6s ¹ , 4f ¹ 6p ¹ , 5d ² , 4f ¹ 6d ¹ , 5d ¹ 6p ¹	90	926	926
Nd I	4f⁴6s² , 4f⁴6s¹5d¹ , 4f⁴6s¹6p¹ , 4f⁴6s¹7s¹ , 4f⁴6s¹8s¹ , 4f ³ 5d ¹ 6s ² , 4f ³ 5d ² 6s ¹ , 4f ³ 5d ¹ 6s ¹ 6p ¹	12215	11784658	371432
Nd II	4f⁴6s¹ , 4f⁴5d¹ , 4f ³ 5d ² , 4f ³ 5d ¹ 6s ¹ , 4f ⁴ 6p ¹ , 4f ³ 5d ¹ 6p ¹ , 4f ³ 6s ¹ 6p ¹	6888	3947992	2281283
Nd III	4f⁴ , 4f ³ 5d ¹ , 4f ³ 6s ¹ , 4f ³ 6p ¹ , 4f ² 5d ² , 4f ² 5d ¹ 6s ¹ , 4f ² 5d ¹ 6p ¹ , 4f ² 6s ¹ 6p ¹	2252	458161	225413

Table 2 continued

Table 2 (*continued*)

Ion	Configurations	Levels	Lines	Lines ^a
Nd IV	4f³ , 4f ² 5d ¹ , 4f ² 6s ¹ , 4f ² 6p ¹ , 4f ¹ 5d ² , 4f ¹ 5d ¹ 6s ¹ , 4f ¹ 5d ¹ 6p ¹	474	23864	15463
Pm I	4f⁵6s² , 4f⁵6s¹5d¹ , 4f⁵6s¹6p¹ , 4f⁵6s¹7s¹ , 4f ⁴ 6s ² 5d ¹ , 4f ⁴ 6s ¹ 5d ²	16294	17038373	321675
Pm II	4f⁵6s¹ , 4f ⁵ 5d ¹ , 4f ⁵ 6p ¹ , 4f ⁴ 6s ¹ 6p ¹ , 4f ⁴ 6s ¹ 5d ¹ , 4f ⁴ 5d ¹ 6p ¹	12372	9176295	3243150
Pm III	4f⁵ , 4f ⁴ 5d ¹ , 4f ⁴ 6s ¹ , 4f ⁴ 6p ¹	1994	320633	317305
Pm IV	4f⁴ , 4f ³ 5d ¹ , 4f ³ 6s ¹ , 4f ³ 6p ¹	817	57765	57765
Sm I	4f⁶6s² , 4f⁶6s¹5d¹ , 4f⁶6s¹6p¹ , 4f⁶6s¹7s¹ , 4f ⁵ 5d ¹ 6s ² , 4f ⁵ 5d ² 6s ¹	28221	43903718	54329
Sm II	4f⁶6s¹ , 4f⁷ , 4f ⁶ 5d ¹ , 4f ⁶ 6p ¹ , 4f ⁵ 5d ¹ 6s ¹ ,	9030	5807352	1448460
Sm III	4f⁶ , 4f ⁵ 5d ¹ , 4f ⁵ 6s ¹ , 4f ⁵ 6p ¹	3737	1045697	985731
Sm IV	4f⁵ , 4f ⁴ 5d ¹ , 4f ⁴ 6s ¹ , 4f ⁴ 6p ¹	1994	320633	320091
Eu I	4f ⁷ 6s ² , 4f ⁷ 5d ¹ 6s ¹ , 4f ⁷ 6s ¹ 6p ¹ , 4f ⁶ 5d ¹ 6s ² , 4f ⁷ 5d ¹ 6p ¹ , 4f ⁷ 6s ¹ 7s ¹ , 4f ⁶ 5d ² 6s ¹ , 4f ⁷ 5d ² , 4f ⁷ 6s ¹ 7p ¹ , 4f ⁷ 6s ¹ 6d ¹ , 4f ⁷ 6s ¹ 8s ¹ , 4f ⁷ 6s ¹ 5f ¹ , 4f ⁷ 6s ¹ 8p ¹ , 4f ⁷ 6s ¹ 7d ¹ , 4f ⁷ 6p ² ,	103229	736608820	4101
Eu II	4f⁷6s¹ , 4f ⁷ 5d ¹ , 4f ⁷ 6p ¹ , 4f ⁶ 5d ¹ 6s ¹ , 4f ⁶ 5d ² ,	22973	21396542	910949
Eu III	4f⁷ , 4f ⁶ 5d ¹ , 4f ⁶ 6s ¹ , 4f ⁶ 6p ¹	5323	2073702	1651778
Eu IV	4f⁶ , 4f ⁵ 5d ¹ , 4f ⁵ 6s ¹ , 4f ⁵ 6p ¹	3737	1045697	1044962
Gd I	4f⁷5d¹6s² , 4f ⁷ 5d ² 6s ¹ , 4f ⁸ 6s ² , 4f ⁷ 6s ² 6p ¹ , 4f ⁷ 5d ¹ 6s ¹ 6p ¹ , 4f ⁷ 5d ³	103013	703084537	31461
Gd II	4f⁷5d¹6s¹ , 4f⁷6s² , 4f⁷5d² , 4f ⁸ 6s ¹ , 4f ⁸ 5d ¹ , 4f ⁷ 6s ¹ 6p ¹ , 4f ⁷ 5d ¹ 6p ¹ , 4f ⁸ 6p ¹	46733	158102968	4161867
Gd III	4f⁸ , 4f ⁷ 5d ¹ , 4f ⁷ 6s ¹ , 4f ⁷ 6p ¹ , 4f ⁷ 7s ¹ ,	6637	2999281	1565172
Gd IV	4f⁷ , 4f ⁶ 5d ¹ , 4f ⁶ 6s ¹ , 4f ⁶ 6p ¹	5323	2073702	2012135
Tb I	4f⁹6s² , 4f ⁸ 5d ¹ 6s ² , 4f ⁸ 5d ² 6s ¹ , 4f ⁸ 6s ² 6p ¹ , 4f ⁹ 6s ¹ 6p ¹ , 4f ⁸ 5d ¹ 6s ¹ 6p ¹ , 4f ⁹ 5d ¹ 6s ¹	65817	311326160	492498
Tb II	4f⁹6s¹ , 4f ⁸ 5d ¹ 6s ¹ , 4f ⁸ 6s ² , 4f ⁸ 5d ² , 4f ⁹ 5d ¹ ,	19854	11978694	3279198
Tb III	4f⁹ , 4f ⁸ 5d ¹ , 4f ⁸ 6s ¹ , 4f ⁸ 6p ¹	5194	1943961	1516250
Tb IV	4f⁸ , 4f ⁷ 5d ¹ , 4f ⁷ 6s ¹ , 4f ⁷ 6p ¹	5983	2545975	2330682
Dy I	4f¹⁰6s² , 4f ⁹ 5d ¹ 6s ² , 4f ¹⁰ 6s ¹ 6p ¹ , 4f ¹⁰ 5d ¹ 6s ¹ , 4f ⁹ 5d ² 6s ¹ , 4f ⁹ 6s ² 6p ¹ , 4f ⁹ 5d ¹ 6s ¹ 6p ¹ , 4f ¹⁰ 6s ¹ 7s ¹	44669	145465351	19386
Dy II	4f¹⁰6s¹ , 4f¹⁰5d¹ , 4f ⁹ 5d ¹ 6s ¹ , 4f ⁹ 6s ² , 4f ⁹ 5d ² , 4f ¹⁰ 6p ¹ , 4f ⁹ 6s ¹ 6p ¹	16034	13700193	2227018
Dy III	4f¹⁰ , 4f ⁹ 5d ¹ , 4f ⁹ 6s ¹ , 4f ⁹ 6p ¹	3549	915339	829418
Dy IV	4f⁹ , 4f ⁸ 5d ¹ , 4f ⁸ 6s ¹ , 4f ⁸ 6p ¹	5194	1943961	1901856
Ho I	4f¹¹6s² , 4f ¹⁰ 5d ¹ 6s ² , 4f ¹¹ 6s ¹ 6p ¹ , 4f ¹⁰ 6s ² 6p ¹ , 4f ¹¹ 5d ¹ 6s ¹ , 4f ¹⁰ 5d ² 6s ¹ , 4f ¹⁰ 5d ¹ 6s ¹ 6p ¹ , 4f ¹¹ 6s ¹ 7s ¹ , 4f ¹¹ 6s ¹ 7p ¹	23182	41659671	16219
Ho II	4f¹¹6s¹ , 4f¹¹5d¹ , 4f ¹¹ 6p ¹ , 4f ¹⁰ 6s ¹ 6p ¹ , 4f ¹⁰ 6s ¹ 5d ¹ , 4f ¹⁰ 5d ¹ 6p ¹	9640	5254717	510917

Table 2 continued

Table 2 (continued)

Ion	Configurations	Levels	Lines	Lines ^a
Ho III	4f¹¹ , 4f ¹⁰ 5d ¹ , 4f ¹⁰ 6s ¹ , 4f ¹⁰ 6p ¹	1837	259812	239785
Ho IV	4f¹⁰ , 4f ⁹ 5d ¹ , 4f ⁹ 6s ¹ , 4f ⁹ 6p ¹	3549	915339	897163
Er I	4f¹²6s² , 4f¹²6s¹6p¹ , 4f¹²6s¹7s¹ , 4f¹²6s¹6d¹ , 4f¹²6s¹8s¹ , 4f ¹¹ 5d ¹ 6s ² , 4f ¹¹ 6s ² 6p ¹ , 4f ¹² 5d ¹ 6s ¹	1303	149737	11731
Er II	6s¹4f¹² , 4f¹²6p¹ , 4f¹²5d¹ , 4f¹¹6s² , 4f¹¹5d¹6s¹ , 4f¹¹5d² , 4f¹¹6s¹6p¹ , 4f¹¹5d¹6p¹	5333	1620729	828267
Er III	4f¹² , 4f ¹¹ 5d ¹ , 4f ¹¹ 6s ¹ , 4f ¹¹ 6p ¹	723	42671	40824
Er IV	4f¹¹ , 4f ¹⁰ 6s ¹ , 4f ¹⁰ 6p ¹ , 4f ¹⁰ 5d ¹ 4f ¹³ 6s ² , 4f¹³6s¹6p¹ , 4f¹³5d¹6s¹ , 4f¹³6s¹7s¹ , 4f¹³6s¹8s¹ ,	1837	259812	257750
Tm I	4f¹²5d¹6s² , 4f¹²6s²6p¹ , 4f¹³6s¹7p¹ , 4f¹³5d¹6p¹ , 4f¹³6s¹6d¹ , 4f ¹² 5d ¹ 6s ¹ 6p ¹ , 4f ¹³ 6p ² , 4f ¹³ 6s ¹ 8p ¹	1716	172582	25853
Tm II	4f¹³6s¹ , 4f¹²6s² , 4f¹³5d¹ , 4f¹³6p¹ , 4f¹²5d¹6s¹ , 4f¹²5d² , 4f¹²6s¹6p¹ , 4f¹²5d¹6p¹	1484	205258	158892
Tm III	4f¹³ , 4f ¹² 5d ¹ , 4f ¹² 6s ¹ , 4f ¹² 6p ¹ , 4f ¹¹ 5d ¹ 6s ¹ , 4f ¹¹ 5d ¹ 6p ¹ , 4f ¹¹ 6s ¹ 6p ¹	3666	824686	5582
Tm IV	4f¹² , 4f ¹¹ 5d ¹ , 4f ¹¹ 6s ¹ , 4f ¹¹ 6p ¹ 4f ¹⁴ 6s ² , 4f¹⁴6s¹6p¹ , 4f¹⁴6s¹5d¹ , 4f¹⁴6s¹7s¹ , 4f¹⁴6s¹6d¹ ,	723	42671	42671
Yb I	4f¹⁴6s¹7p¹ , 4f¹⁴6s¹8s¹ , 4f¹³6s²5d¹ , 4f¹³6s²6p¹ , 4f¹³6s¹5d² , 4f ¹³ 5d ¹ 6s ¹ 6p ¹ , 4f ¹⁴ 6p ²	446	20948	2821
Yb II	4f¹⁴6s¹ , 4f¹³6s² , 4f¹⁴5d¹ , 4f¹⁴6p¹ , 4f¹⁴7s¹ , 4f ¹³ 5d ¹ 6s ¹ , 4f ¹³ 5d ² , 4f ¹³ 6s ¹ 6p ¹ , 4f ¹³ 5d ¹ 6p ¹	265	8109	8024
Yb III	4f¹⁴ , 4f ¹³ 5d ¹ , 4f ¹³ 6s ¹ , 4f ¹³ 6p ¹ , 4f ¹³ 7s ¹ , 4f ¹³ 6d ¹ , 4f ¹² 5d ¹ 6s ¹ , 4f ¹² 5d ¹ 6p ¹ , 4f ¹² 6s ¹ 6p ¹	1039	71310	616
Yb IV	4f¹³ , 4f ¹² 5d ¹ , 4f ¹² 6s ¹ , 4f ¹² 6p ¹ 5d¹6s² , 6s ² 6p ¹ , 5d ¹ 6s ¹ 6p ¹ , 5d ² 6s ¹ , 6s ² 7s ¹ ,	202	3797	3797
Lu I	6s ² 6d ¹ , 6s ² 8s ¹ , 6s ² 7p ¹ , 6s ¹ 6p ² , 6s ² 5f ¹ , 6s ² 7d ¹	61	602	391
Lu II	4f¹⁴6s² , 4f ¹⁴ 5d ¹ 6s ¹ , 4f ¹⁴ 6s ¹ 6p ¹ , 4f ¹⁴ 5d ² , 4f ¹⁴ 5d ¹ 6p ¹ , 4f ¹⁴ 6s ¹ 7s ¹ , 4f ¹⁴ 6s ¹ 6d ¹ , 4f ¹⁴ 5d ¹ 7s ¹ , 4f ¹⁴ 5d ¹ 6d ¹	58	400	335
Lu III	4f¹⁴6s¹ , 4f ¹⁴ 5d ¹ , 4f ¹⁴ 6p ¹ , 4f ¹⁴ 7s ¹ , 4f ¹⁴ 6d ¹ , 4f ¹³ 5d ¹ 6s ¹ , 4f ¹³ 5d ¹ 6p ¹ , 4f ¹³ 6s ¹ 6p ¹	184	2784	1603
Lu IV	4f¹⁴ , 4f ¹³ 5d ¹ , 4f ¹³ 6s ¹ , 4f ¹³ 6p ¹ , 4f ¹³ 6d ¹ , 4f ¹³ 7s ¹	61	338	338
Hf I	5d²6s² , 5d ² 6s ¹ 6p ¹ , 5d ³ 6s ¹ , 5d ⁴ , 5d ³ 6p ¹ , 5d ² 6s ¹ 7s ¹	313	11138	4146
Hf II	5d¹6s² , 5d ² 6s ¹ , 5d ³ , 5d ¹ 6s ¹ 6p ¹ , 5d ² 6p ¹ , 5d ² 7s ¹ , 5d ¹ 6s ¹ 7s ¹	129	2418	2418
Hf III	5d² , 5d ¹ 6s ¹ , 6s ² , 5d ¹ 6p ¹ , 6s ¹ 6p ¹ , 5d ¹ 6d ¹ , 5d ¹ 7s ¹ , 5d ¹ 7p ¹	64	594	594
Hf IV	4f¹⁴5d¹ , 4f ¹⁴ 6s ¹ , 4f ¹⁴ 6p ¹ , 4f ¹⁴ 6d ¹ , 4f ¹⁴ 7s ¹ , 4f ¹⁴ 5f ¹ , 4f ¹⁴ 7p ¹ , 4f ¹⁴ 7d ¹	14	35	35

Table 2 continued

Table 2 (*continued*)

Ion	Configurations	Levels	Lines	Lines ^a
Ta I	5d³6s², 5d⁵, 5d⁴6s¹, 5d³6s¹6p¹, 5d²6s²6p¹, 5d ⁴ 6p ¹ , 5d ³ 6s ¹ 7s ¹ , 5d ³ 6s ¹ 8s ¹	705	58122	25703
Ta II	5d³6s¹, 5d²6s², 5d⁴, 5d³6p¹, 5d²6s¹6p¹, 5d ³ 7s ¹ , 5d ³ 6d ¹	487	27199	27162
Ta III	5d³, 5d²6s¹, 5d²6p¹, 5d¹6s², 5d¹6s¹6p¹, 5d ² 6d ¹ , 5d ² 7s ¹	188	4452	4452
Ta IV	5d², 5d¹6s¹, 5d¹6p¹, 6s², 6s¹6p¹, 5d ¹ 6d ¹ , 5d ¹ 7s ¹	52	336	336
W I	5d⁴6s², 5d⁵6s¹, 5d⁴6s¹6p¹, 5d⁵6p¹, 5d⁴6s¹7s¹,	808	61598	22278
W II	5d⁴6s¹, 5d⁵, 5d³6s², 5d³6s¹6p¹, 5d⁴6p¹, 5d ⁴ 7s ¹ , 5d ⁴ 6d ¹	851	84312	80301
W III	5d⁴, 5d³6s¹, 5d²6s², 5d³6p¹, 5d²6s¹6p¹, 5d ³ 7s ¹ , 5d ³ 6d ¹	487	27199	27199
W IV	5d³, 5d²6s¹, 5d²6p¹, 5d¹6s², 5d¹6s¹6p¹, 5d ² 7s ¹ , 5d ² 6d ¹	188	4452	4452
Re I	5d⁵6s², 5d⁶6s¹, 5d⁵6s¹6p¹, 5d⁴6s²6p¹, 5d⁵6s¹7s¹, 5d ⁶ 6p ¹ , 5d ⁵ 6s ¹ 6d ¹ , 5d ⁵ 6s ¹ 8s ¹ , 5d ⁴ 6s ² 7s ¹	1875	389214	18721
Re II	5d⁵6s¹, 5d⁴6s², 5d⁵6p¹, 5d⁶, 5d⁴6s¹6p¹, 5d ⁵ 7s ¹ , 5d ⁵ 6d ¹	1122	138447	102286
Re III	5d⁵, 5d⁴6s¹, 5d⁴6p¹, 5d³6s¹6p¹, 5d³6s², 5d ⁴ 7s ¹ , 5d ⁴ 6d ¹	851	84312	83853
Re IV	5d⁴, 5d³6s¹, 5d³6p¹, 5d²6s², 5d²6s¹6p¹, 5d ³ 7s ¹ , 5d ³ 6d ¹	487	27199	27199
Os I	5d⁶6s², 5d⁷6s¹, 5d⁶6s¹6p¹, 5d⁶6s¹7s¹, 5d⁷6p¹, 5d ⁷ 7s ¹ , 5d ⁷ 7p ¹ , 5d ⁷ 6d ¹	984	107910	27186
Os II	5d⁶6s¹, 5d⁶6p¹, 5d⁷, 5d⁶6p¹, 5d⁵6s¹6p¹, 5d ⁶ 7s ¹ , 5d ⁶ 6d ¹ , 5d ⁵ 6s ¹ 7p ¹	1435	195855	112108
Os III	5d⁶, 5d⁵6s¹, 5d⁵6p¹, 5d⁴6s¹6p¹, 5d⁵6d¹, 5d ⁵ 7s ¹	1088	130730	117655
Os IV	5d⁵, 5d⁴6s¹, 5d⁴6p¹, 5d³6s², 5d³6s¹6p¹, 5d ⁴ 7s ¹ , 5d ⁴ 6d ¹	851	84312	84312
Ir I	5d⁷6s², 5d⁹, 5d⁸6s¹, 5d⁷6s¹6p¹, 5d⁷6s¹7s¹, 5d ⁸ 6p ¹ , 5d ⁸ 7s ¹	385	16855	9449
Ir II	5d⁷6s¹, 5d⁸, 5d⁶6s², 5d⁷6p¹, 5d⁶6s¹6p¹, 5d ⁷ 7s ¹ , 5d ⁷ 7p ¹	699	32647	29639
Ir III	5d⁷, 5d⁶6s¹, 5d⁶6p¹, 5d⁵6s², 5d⁶6d¹, 5d ⁶ 7s ¹ , 5d ⁶ 7p ¹	818	76592	73814
Ir IV	5d⁶, 5d⁵6s¹, 5d⁵6p¹, 5d⁴6s², 5d⁵6d¹, 5d ⁵ 7s ¹ , 5d ⁵ 7p ¹	976	104622	104622
Pt I	5d⁹6s¹, 5d¹⁰, 5d⁹6p¹, 5d⁹7s¹, 5d⁸6s², 5d ⁸ 6s ¹ 6p ¹ , 5d ⁸ 6s ¹ 7s ¹	152	2729	1637

Table 2 continued

Table 2 (*continued*)

Ion	Configurations	Levels	Lines	Lines ^a
Pt II	5d⁹ , 5d ⁸ 6s ¹ , 5d ⁷ 6s ² , 5d ⁸ 6p ¹ , 5d ⁸ 7s ¹ , 5d ⁸ 6d ¹ , 5d ⁸ 8s ¹ , 5d ⁸ 7d ¹	248	4837	4759
Pt III	5d⁸ , 5d ⁷ 6s ¹ , 5d ⁷ 6p ¹ , 5d ⁷ 7s ¹ , 5d ⁶ 6s ¹ 6p ¹ ,	555	19157	18477
Pt IV	5d⁷ , 5d ⁶ 6s ¹ , 5d ⁶ 6p ¹ , 5d ⁶ 6d ¹ , 5d ⁶ 7s ¹ , 5d ⁶ 7p ¹	781	70102	70102
Au I	5d¹⁰6s¹ , 5d ⁹ 6s ² , 5d ¹⁰ 6p ¹ , 5d ⁹ 6s ¹ 6p ¹ , 5d ¹⁰ 7s ¹ , 5d ¹⁰ 7p ¹ , 5d ¹⁰ 6d ¹ , 5d ¹⁰ 8s ¹ , 5d ¹⁰ 8p ¹	36	141	101
Au II	5d¹⁰ , 5d ⁹ 6s ¹ , 5d ⁸ 6s ² , 5d ⁹ 6p ¹ , 5d ⁹ 7s ¹ , 5d ⁹ 6d ¹ , 5d ⁹ 7p ¹	60	516	516
Au III	5d⁹ , 5d ⁸ 6s ¹ , 5d ⁸ 6p ¹ , 5d ⁷ 6s ² , 5d ⁸ 7s ¹ , 5d ⁸ 6d ¹ , 5d ⁸ 7p ¹	210	5764	5690
Au IV	5d⁸ , 5d ⁷ 6s ¹ , 5d ⁷ 6p ¹ , 5d ⁶ 6s ² , 5d ⁷ 7s ¹ , 5d ⁷ 6d ¹ , 5d ⁷ 7p ¹	507	29606	29606
Hg I	5d¹⁰6s² , 5d ¹⁰ 6s ¹ 6p ¹ , 5d ¹⁰ 6s ¹ 7s ¹ , 5d ⁹ 6s ² 6p ¹ , 5d ¹⁰ 6s ¹ 7p ¹ , 5d ¹⁰ 6s ¹ 6d ¹ , 5d ¹⁰ 6s ¹ 8s ¹ , 5d ¹⁰ 6s ¹ 8p ¹ , 5d ¹⁰ 6s ¹ 7d ¹ , 5d ¹⁰ 6s ¹ 5f ¹ ,	41	229	177
Hg II	5d¹⁰6s¹ , 5d ⁹ 6s ² , 5d ¹⁰ 6p ¹ , 5d ⁹ 6s ¹ 6p ¹ , 5d ¹⁰ 7s ¹ , 5d ¹⁰ 6d ¹ , 5d ¹⁰ 7p ¹ , 5d ¹⁰ 8s ¹ , 5d ¹⁰ 5f ¹ , 5d ¹⁰ 7d ¹ ,	38	180	180
Hg III	5d¹⁰ , 5d ⁹ 6s ¹ , 5d ⁸ 6s ² , 5d ⁹ 6p ¹ , 5d ⁸ 6s ¹ 6p ¹ , 5d ⁹ 7s ¹ , 5d ⁹ 6d ¹	138	1948	1948
Hg IV	5d⁹ , 5d ⁸ 6s ¹ , 5d ⁸ 6p ¹ , 5d ⁷ 6s ² , 5d ⁸ 6d ¹ , 5d ⁸ 7s ¹	165	2882	2882
Tl I	6s²6p¹ , 6s²7s¹ , 6s²7p¹ , 6s ² 6d ¹ , 6s ² 8s ¹ , 6s ² 8p ¹ , 6s ² 7d ¹	12	30	30
Tl II	5d¹⁰6s² , 5d ¹⁰ 6s ¹ 6p ¹ , 5d ¹⁰ 6s ¹ 7s ¹ , 5d ⁹ 6s ² 6p ¹ , 5d ¹⁰ 6s ¹ 6d ¹ , 5d ¹⁰ 6p ² , 5d ¹⁰ 6s ¹ 7p ¹ , 5d ¹⁰ 6s ¹ 8s ¹ , 5d ¹⁰ 6s ¹ 5f ¹ , 5d ¹⁰ 6s ¹ 7d ¹ , 5d ¹⁰ 6s ¹ 8p ¹	46	312	312
Tl III	5d¹⁰6s¹ , 5d ¹⁰ 6p ¹ , 5d ⁹ 6s ² , 5d ⁹ 6s ¹ 6p ¹ , 5d ¹⁰ 7s ¹ , 5d ¹⁰ 6d ¹ , 5d ¹⁰ 7p ¹ , 5d ¹⁰ 5f ¹ , 5d ¹⁰ 8s ¹ , 5d ¹⁰ 7d ¹ , 5d ¹⁰ 8p ¹	40	195	195
Tl IV	5d¹⁰ , 5d ⁹ 6s ¹ , 5d ⁹ 6p ¹ , 5d ⁹ 6d ¹ , 5d ⁹ 7s ¹ , 5d ⁹ 8s ¹	43	234	234
Pb I	6s²6p² , 6s²6p¹7s¹ , 6s²6p¹7p¹ , 6s²6p¹6d¹ , 6s²6p¹8s¹ , 6s²6p¹8p¹ , 6s ² 6p ¹ 7d ¹ , 6s ² 6p ¹ 5f ¹ , 6s ² 6p ¹ 9s ¹ , 6s ² 6p ¹ 9p ¹ , 6s ² 6p ¹ 8d ¹	95	1398	1182
Pb II	6s²6p¹ , 6s ¹ 6p ² , 6s ² 7s ¹ , 6s ² 6d ¹ , 6s ² 7p ¹ , 6s ² 8s ¹ , 6s ² 5f ¹ , 6s ² 7d ¹ , 6s ² 8p ¹ , 6s ² 9s ¹ , 6s ² 6f ¹ , 6s ² 8d ¹	27	119	119
Pb III	5d¹⁰6s² , 5d ¹⁰ 6s ¹ 6p ¹ , 5d ¹⁰ 6p ² , 5d ¹⁰ 6s ¹ 7s ¹ , 5d ¹⁰ 6s ¹ 6d ¹ , 5d ⁹ 6s ² 6p ¹ , 5d ¹⁰ 6s ¹ 7p ¹ , 5d ¹⁰ 6s ¹ 5f ¹ , 5d ¹⁰ 6s ¹ 8s ¹ , 5d ¹⁰ 6s ¹ 7d ¹ , 5d ¹⁰ 6s ¹ 8p ¹ , 5d ¹⁰ 6s ¹ 6f ¹	50	343	343

Table 2 continued

Table 2 (*continued*)

Ion	Configurations	Levels	Lines	Lines ^a
Pb IV	5d¹⁰6s¹ , 5d ¹⁰ 6p ¹ , 5d ⁹ 6s ² , 5d ⁹ 6s ¹ 6p ¹ , 5d ¹⁰ 6d ¹ , 5d ¹⁰ 7s ¹ , 5d ¹⁰ 7p ¹ , 5d ¹⁰ f ¹ , 5d ¹⁰ 8s ¹ , 5d ¹⁰ 7d ¹ , 5d ⁹ 6p ² , 5d ¹⁰ 8p ¹	68	746	721
Bi I	6p²7s¹ , 6p³ , 6p ² 7p ¹ , 6p ² 6d ¹ , 6p ² 8s ¹ , 6p ² 8p ¹ , 6p ² 7d ¹ , 6p ² 9s ¹ , 6p ² 9p ¹ , 6p ² 8d ¹ ,	176	4986	270
Bi II	6s²6p² , 6s²6p¹7s¹ , 6s ¹ 6p ³ , 6s ² 6p ¹ 6d ¹ , 6s ² 6p ¹ 7p ¹ , 6s ² 6p ¹ 8s ¹ , 6s ² 6p ¹ 5f ¹ , 6s ² 6p ¹ 7d ¹ , 6s ² 6p ¹ 8p ¹ , 6s ² 6p ¹ 9s ¹ , 6s ² 6p ¹ 6f ¹ , 6s ² 6p ¹ 8d ¹	107	1685	744
Bi III	6s²6p¹ , 6s ¹ 6p ² , 6s ² 7s ¹ , 6s ² 6d ¹ , 6s ² 7p ¹ , 6s ² 5f ¹ , 6s ² 8s ¹ , 6s ² 7d ¹ , 6s ² 8p ¹ , 6s ² 6f ¹ ,	24	98	98
Bi IV	5d¹⁰6s² , 5d ¹⁰ 6s ¹ 6p ¹ , 5d ¹⁰ 6p ² , 5d ¹⁰ 6s ¹ 6d ¹ , 5d ¹⁰ 6s ¹ 7s ¹ , 5d ⁹ 6s ² 6p ¹ , 5d ¹⁰ 6s ¹ 7p ¹ , 5d ¹⁰ 6s ¹ 5f ¹ , 5d ¹⁰ 6s ¹ 8s ¹ , 5d ¹⁰ 6s ¹ 7d ¹ ,	42	262	262
Po I	6p⁴ , 6p³7s¹ , 6p³7p¹ , 6p³6d¹ , 6p³8s¹ , 6p ³ 8p ¹ , 6p ³ 7d ¹ , 6p ³ 9p ¹ , 6p ³ 8d ¹ , 6p ³ 10p ¹ ,	251	9553	135
Po II	6s²6p³ , 6s ¹ 6p ⁴ , 6s ² 6p ² 7s ¹ , 6s ² 6p ² 6d ¹ , 6s ² 6p ² 7p ¹ , 6s ² 6p ² 8s ¹ , 6s ² 6p ² 7d ¹ , 6s ² 6p ² 5f ¹ , 6s ² 6p ² 8p ¹ , 6s ² 6p ² 9s ¹ ,	165	4238	873
Po III	6s²6p² , 6s ¹ 6p ³ , 6s ² 6p ¹ 6d ¹ , 6s ² 6p ¹ 7s ¹ , 6s ² 6p ¹ 7p ¹ , 6s ² 6p ¹ 7d ¹ , 6s ² 6p ¹ 8s ¹	57	419	369
Po IV	6s²6p¹ , 6s ¹ 6p ² , 6s ² 6d ¹ , 6s ² 7s ¹ , 6s ² 7p ¹ , 6s ² 7d ¹ , 6s ² 8s ¹	18	48	48
At I	6p⁵ , 6p ⁴ 7s ¹ , 6p ⁴ 7p ¹ , 6p ⁴ 6d ¹ , 6p ⁴ 8s ¹ , 6p ⁴ 8p ¹ , 6p ⁴ 7d ¹	116	2136	3
At II	6s²6p⁴ , 6s ² 6p ³ 7s ¹ , 6s ¹ 6p ⁵ , 6s ² 6p ³ 6d ¹ , 6s ² 6p ³ 7p ¹ , 6s ² 6p ³ 8s ¹ , 6s ² 6p ³ 7d ¹ , 6s ² 6p ³ 5f ¹ , 6s ² 6p ³ 8p ¹ , 6s ² 6p ³ 9s ¹ , 6s ² 6p ³ 8d ¹ , 6s ² 6p ³ 6f ¹	289	11510	881
At III	6s²6p³ , 6s ¹ 6p ⁴ , 6s ² 6p ² 6d ¹ , 6s ² 6p ² 7s ¹ , 6s ² 6p ² 8s ¹ , 6s ² 6p ² 7d ¹ , 6s ² 6p ² 9s ¹ , 6s ² 6p ² 8d ¹	121	431	317
At IV	6s²6p² , 6s ¹ 6p ³ , 6s ² 6p ¹ 6d ¹ , 6s ² 6p ¹ 7s ¹ , 6s ² 6p ¹ 7d ¹ , 6s ² 6p ¹ 8s ¹ , 6s ² 6p ¹ 8d ¹ , 6s ² 6p ¹ 9s ¹	63	179	179
Rn I	6p⁶ , 6p ⁵ 7s ¹ , 6p ⁵ 7p ¹ , 6p ⁵ 6d ¹ , 6p ⁵ 8p ¹ , 6p ⁵ 7d ¹ , 6p ⁵ 9s ¹ , 6p ⁵ 5f ¹	65	634	0
Rn II	6s²6p⁵ , 6s ¹ 6p ⁶ , 6s ² 6p ⁴ 7s ¹ , 6s ² 6p ⁴ 6d ¹ , 6s ² 6p ⁴ 7p ¹ , 6s ² 6p ⁴ 8s ¹ , 6s ² 6p ⁴ 7d ¹ , 6s ² 6p ⁴ 5f ¹ , 6s ² 6p ⁴ 8p ¹ , 6s ² 6p ⁴ 9s ¹ ,	155	3685	477
Rn III	6s²6p⁴ , 6s ¹ 6p ⁵ , 6s ² 6p ³ 6d ¹ , 6s ² 6p ³ 7s ¹ , 6s ² 6p ³ 7p ¹ , 6s ² 6p ³ 5f ¹ , 6s ² 6p ³ 7d ¹ , 6s ² 6p ³ 8s ¹ , 6s ² 6p ³ 6f ¹ , 6p ⁶ ,	214	6052	1336
Rn IV	6s²6p³ , 6s ¹ 6p ⁴ , 6s ² 6p ² 6d ¹ , 6s ² 6p ² 7s ¹ , 6s ² 6p ² 5f ¹ , 6s ² 6p ² 7p ¹	100	1480	1368
Fr I	6p⁶7s¹ , 6p ⁶ 7p ¹ , 6p ⁶ 6d ¹	5	5	2
Fr II	6p⁶ , 6p ⁵ 7s ¹ , 6p ⁵ 6d ¹ , 6p ⁵ 7p ¹ , 6p ⁵ 8s ¹ , 6p ⁵ 7d ¹ , 6p ⁵ 5f ¹ , 6p ⁵ 8p ¹ , 6p ⁵ 9s ¹ , 6p ⁵ 6f ¹ , 6p ⁵ 8d ¹ , 6p ⁵ 9p ¹	103	1569	132

Table 2 continued

Table 2 (*continued*)

Ion	Configurations	Levels	Lines	Lines ^a
Fr III	6s²6p⁵ , 6s ¹ 6p ⁶ , 6s ² 6p ⁴ 6d ¹ , 6s ² 6p ⁴ 7s ¹ , 6s ² 6p ⁴ 7p ¹ , 6s ² 6p ⁴ 5f ¹ , 6s ² 6p ⁴ 7d ¹ , 6s ² 6p ⁴ 8s ¹ , 6s ² 6p ⁴ 8p ¹ , 6s ² 6p ⁴ 6f ¹ , 6s ² 6p ⁴ 9s ¹	185	4932	1231
Fr IV	6s²6p⁴ , 6s ¹ 6p ⁵ , 6s ² 6p ³ 6d ¹ , 6s ² 6p ³ 7s ¹ , 6s ² 6p ³ 7d ¹ , 6s ² 6p ³ 8s ¹ , 6s ² 6p ³ 8d ¹ , 6s ² 6p ³ 9s ¹	153	410	307
Ra I	7s² , 7s ¹ 7p ¹ , 7s ¹ 6d ¹ , 6d ¹ 7p ¹ , 7p ² ,	26	100	22
Ra II	6p⁶7s¹ , 6p ⁶ 6d ¹ , 6p ⁶ 7p ¹	5	5	5
Ra III	6p⁶ , 6p ⁵ 6d ¹ , 6p ⁵ 7s ¹ , 6p ⁵ 5f ¹ , 6p ⁵ 7p ¹ , 6p ⁵ 7d ¹ , 6p ⁵ 8s ¹ , 6p ⁵ 6f ¹ , 6p ⁵ 8p ¹ , 6p ⁵ 8d ¹ , 6p ⁵ 9s ¹	93	1251	252
Ra IV	6s²6p⁵ , 6s ¹ 6p ⁶ , 6s ² 6p ⁴ 6d ¹ , 6s ² 6p ⁴ 7s ¹ , 6s ² 6p ⁴ 7p ¹ ,	60	574	457
Ac I	6d²7s¹ , 6d¹7s² , 6d¹7s¹7p¹ , 7s ² 7p ¹ , 6d ² 7p ¹ , 6d ³ , 5f ¹ 6d ¹ 7s ¹ , 5f ¹ 7s ¹ 7p ¹	170	3624	248
Ac II	6d¹7s¹ , 6d² , 7s ¹ 7p ¹ , 6d ¹ 7p ¹ , 7s ¹ 5f ¹ , 6d ¹ 5f ¹ , 7s ¹ 8s ¹ , 5f ¹ 7p ¹	67	574	574
Ac III	6p⁶7s¹ , 6p ⁶ 6d ¹ , 6p ⁶ 5f ¹ , 6p ⁶ 7p ¹ , 6p ⁶ 8s ¹ , 6p ⁶ 7d ¹ , 6p ⁶ 6f ¹	12	22	8
Ac IV	6p⁶ , 6p ⁵ 5f ¹ , 6p ⁵ 6d ¹ , 6p ⁵ 7s ¹ , 6p ⁵ 7p ¹ , 6p ⁵ 7d ¹ , 6p ⁵ 8s ¹	55	422	206
Th I	6d²7s² , 6d³7s¹ , 5f¹6d²7s¹ , 5f ¹ 6d ¹ 7s ² , 6d ¹ 7s ² 7p ¹ , 6d ² 7s ¹ 7p ¹ , 5f ¹ 7s ² 7p ¹ , 6d ⁴ , 5f ¹ 6d ¹ 7s ¹ 7p ¹ , 5f ² 7s ² , 5f ¹ 6d ³	822	32601	4234
Th II	6d¹7s² , 6d²7s¹ , 5f¹7s² , 5f¹6d¹7s¹ , 6d³ , 5f¹6d² , 6d¹7s¹7p¹ , 5f ² 7s ¹ , 5f ¹ 7s ¹ 7p ¹ , 5f ¹ 6d ¹ 7p ¹ ,	343	13156	12529
Th III	5f¹6d¹ , 6d ² , 6d ¹ 7s ¹ , 7s ² , 5f ² , 5f ¹ 7p ¹ , 6d ¹ 7p ¹ , 7s ¹ 7p ¹ , 5f ¹ 8s ¹	79	768	768
Th IV	6p⁶5f¹ , 6p⁶6d¹ , 6p⁶7s¹ , 6p⁶7p¹ , 6p⁶7d¹ , 6p⁶8s¹ , 6p⁶6f¹ , 6p⁶8d¹ , 6p⁶9s¹	15	33	16
Pa I	5f²6d¹7s² , 5f³7s² , 5f²6d²7s¹ , 5f³6d¹7s¹ , 5f³7s¹7p¹ , 5f ² 6d ¹ 7s ¹ 7p ¹ , 5f ² 7s ² 7p ¹ , 5f ² 6d ² 7p ¹	6192	2537195	212971
Pa II	5f²7s² , 5f³7s¹ , 5f³6d¹ , 5f²6d² , 5f²6d¹7s¹ , 5f ³ 7p ¹ , 5f ² 6d ¹ 7p ¹	2020	369420	281986
Pa III	5f²6d¹ , 5f³ , 5f²7s¹ , 5f²7p¹ , 5f¹6d² , 5f ¹ 6d ¹ 7s ¹ , 5f ² 8s ¹ , 5f ² 7d ¹ , 5f ² 6f ¹ , 5f ² 9s ¹ ,	653	42001	14718
Pa IV	5f² , 5f¹6d¹ , 5f¹7s¹ , 5f¹7p¹ , 6d² , 5f ¹ 7d ¹ , 6d ¹ 7p ¹	90	926	926
U I	5f³6d¹7s² , 5f⁴7s² , 5f⁴7s¹6d¹ , 5f³6d²7s¹ , 5f⁴7s¹7p¹ , 5f ³ 6d ¹ 7s ¹ 7p ¹	11383	10433952	282287
U II	5f³7s² , 5f⁴7s¹ , 5f⁴6d¹ , 5f³6d² , 5f³6d¹7s¹ , 5f ⁴ 7p ¹ , 5f ³ 6d ¹ 7p ¹ , 5f ³ 7s ¹ 7p ¹	6929	4016742	2125586
U III	5f⁴ , 5f³6d¹ , 5f³7s¹ , 5f³7p¹ , 5f²6d² , 5f ² 6d ¹ 7s ¹ , 5f ² 6d ¹ 7p ¹ , 5f ² 7s ¹ 7p ¹	2252	458161	448914

Table 2 continued

Table 2 (*continued*)

Ion	Configurations	Levels	Lines	Lines ^a
U IV	5f³, 5f²6d¹, 5f²7s¹, 5f²7p¹, 5f¹6d², 5f¹6d¹7s¹, 5f¹6d¹7p¹	474	23864	23864

NOTE— ^a Number of transitions whose upper level is below the ionization potential.

We thank Shinya Wanajo for providing the results of nucleosynthesis calculations and Michel Busquet for the generous support on the HULLAC code. MT and KK thank the Yukawa Institute for Theoretical Physics for support in the framework of International Molecule-type Workshop (YITP-T-18-06), where a part of this work has been done. Numerical simulations presented in this paper were carried out with Cray XC30 and XC50 at Center for Computational Astrophysics, National Astronomical Observatory of Japan.

This research was supported by JSPS Bilateral Joint Research Project, Inoue Science Research Award from Inoue Foundation for Science, the Grant-in-Aid for Scientific Research from JSPS (16H02183,19H00694) and MEXT (17H06363), the NINS program of Promoting Research by Networking among Institutions (Grant Number 01411702). Gediminas Gaigalas thanks the Research Council of Lithuania for funding his research (grant No. S-LJB-18-1).

REFERENCES

- Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017a, Physical Review Letters, 119, 161101
—. 2017b, ApJL, 848, L12
—. 2017c, ApJL, 848, L13
Andreoni, I., Ackley, K., Cooke, J., et al. 2017, PASA, 34, e069
Arcavi, I., Hosseinzadeh, G., Howell, D. A., et al. 2017, Nature, 551, 64
Bar-Shalom, A., Klapisch, M., & Oreg, J. 2001, JQSRT, 71, 169
Barnes, J., & Kasen, D. 2013, ApJ, 775, 18
Barnes, J., Kasen, D., Wu, M.-R., & Martínez-Pinedo, G. 2016, ApJ, 829, 110
Baron, E., Hauschildt, P. H., Branch, D., et al. 1995, ApJ, 441, 170
Chornock, R., Berger, E., Kasen, D., et al. 2017, ApJL, 848, L19
Coulter, D. A., Foley, R. J., Kilpatrick, C. D., et al. 2017, Science, 358, 1556
Cowan, R. D. 1981, The theory of atomic structure and spectra
Cowperthwaite, P. S., Berger, E., Villar, V. A., et al. 2017, ApJL, 848, L17
Dessart, L., & Hillier, D. J. 2005, A&A, 437, 667
Díaz, M. C., Macri, L. M., Garcia Lambas, D., et al. 2017, ApJL, 848, L29
Drout, M. R., Piro, A. L., Shappee, B. J., et al. 2017, Science, 358, 1570
Eastman, R. G., & Pinto, P. A. 1993, ApJ, 412, 731
Evans, P. A., Cenko, S. B., Kennea, J. A., et al. 2017, Science, 358, 1565
Fernández, R., & Metzger, B. D. 2013, MNRAS, 435, 502
—. 2016, Annual Review of Nuclear and Particle Science, 66, 23
Fernández, R., Tchekhovskoy, A., Quataert, E., Foucart, F., & Kasen, D. 2019, MNRAS, 482, 3373
Fontes, C. J., Fryer, C. L., Hungerford, A. L., Wollaeger, R. T., & Korobkin, O. 2019, arXiv:1904.08781, arXiv:1904.08781
Fontes, C. J., Fryer, C. L., Hungerford, A. L., et al. 2017, arXiv:1702.02990, arXiv:1702.02990
Foucart, F., O'Connor, E., Roberts, L., et al. 2016, PhRvD, 94, 123016
Fujibayashi, S., Kiuchi, K., Nishimura, N., Sekiguchi, Y., & Shibata, M. 2018, ApJ, 860, 64
Gaigalas, G., Kato, D., Rynkun, P., Radžiūtė, L., & Tanaka, M. 2019, ApJS, 240, 29
Goriely, S., Bauswein, A., Just, O., Pllumbi, E., & Janka, H.-T. 2015, MNRAS, 452, 3894
Karp, A. H., Lasher, G., Chan, K. L., & Salpeter, E. E. 1977, ApJ, 214, 161
Kasen, D., Badnell, N. R., & Barnes, J. 2013, ApJ, 774, 25
Kasen, D., Fernández, R., & Metzger, B. D. 2015, MNRAS, 450, 1777
Kasen, D., Metzger, B., Barnes, J., Quataert, E., & Ramirez-Ruiz, E. 2017, Nature, 551, 80

- Kasen, D., Thomas, R. C., & Nugent, P. 2006, ApJ, 651, 366
- Kasliwal, M. M., Nakar, E., Singer, L. P., et al. 2017, Science, 358, 1559
- Kawaguchi, K., Shibata, M., & Tanaka, M. 2018, ApJL, 865, L21
- Kilpatrick, C. D., Foley, R. J., Kasen, D., et al. 2017, Science, 358, 1583
- Kramida, A., Ralchenko, Y., Reader, J., & NIST ASD Team. 2018, NIST Atomic Spectra Database (version 5.6.1), <https://physics.nist.gov/asd>. National Institute of Standards and Technology, Gaithersburg, MD.
- Kulkarni, S. R. 2005, arXiv:astro-ph/0510256, arXiv:astro-ph/0510256
- Kupka, F., Piskunov, N., Ryabchikova, T. A., Stempels, H. C., & Weiss, W. W. 1999, A&AS, 138, 119
- Kupka, F. G., Ryabchikova, T. A., Piskunov, N. E., Stempels, H. C., & Weiss, W. W. 2000, Baltic Astronomy, 9, 590
- Kurucz, R., & Bell, B. 1995, Atomic Line Data (R.L. Kurucz and B. Bell) Kurucz CD-ROM No. 23. Cambridge, Mass.: Smithsonian Astrophysical Observatory, 1995., 23
- Li, L.-X., & Paczyński, B. 1998, ApJL, 507, L59
- Lippuner, J., & Roberts, L. F. 2015, ApJ, 815, 82
- Lipunov, V. M., Gorbovskoy, E., Kornilov, V. G., et al. 2017, ApJL, 850, L1
- Mazzali, P. A. 2000, A&A, 363, 705
- McCully, C., Hiramatsu, D., Howell, D. A., et al. 2017, ApJL, 848, L32
- Metzger, B. D. 2017, Living Reviews in Relativity, 20, 3
- Metzger, B. D., & Fernández, R. 2014, MNRAS, 441, 3444
- Metzger, B. D., Martínez-Pinedo, G., Darbha, S., et al. 2010, MNRAS, 406, 2650
- Nicholl, M., Berger, E., Kasen, D., et al. 2017, ApJL, 848, L18
- Perego, A., Radice, D., & Bernuzzi, S. 2017, ApJL, 850, L37
- Pian, E., D'Avanzo, P., Benetti, S., et al. 2017, Nature, 551, 67
- Pinto, P. A., & Eastman, R. G. 2000, ApJ, 530, 757
- Piskunov, N. E., Kupka, F., Ryabchikova, T. A., Weiss, W. W., & Jeffery, C. S. 1995, A&AS, 112, 525
- Radice, D., Galeazzi, F., Lippuner, J., et al. 2016, MNRAS, 460, 3255
- Rosswog, S. 2015, International Journal of Modern Physics D, 24, 1530012
- Rosswog, S., Sollerman, J., Feindt, U., et al. 2017, arXiv:1710.05445, arXiv:1710.05445
- Ryabchikova, T. A., Piskunov, N. E., Kupka, F., & Weiss, W. W. 1997, Baltic Astronomy, 6, 244
- Sekiguchi, Y., Kiuchi, K., Kyutoku, K., & Shibata, M. 2015, PhRvD, 91, 064059
- Sekiguchi, Y., Kiuchi, K., Kyutoku, K., Shibata, M., & Taniguchi, K. 2016, PhRvD, 93, 124046
- Shappee, B. J., Simon, J. D., Drout, M. R., et al. 2017, Science, 358, 1574
- Shibata, M., Fujibayashi, S., Hotokezaka, K., et al. 2017, PhRvD, 96, 123012
- Siebert, M. R., Foley, R. J., Drout, M. R., et al. 2017, ApJL, 848, L26
- Smartt, S. J., Chen, T.-W., Jerkstrand, A., et al. 2017, Nature, 551, 75
- Soares-Santos, M., Holz, D. E., Annis, J., et al. 2017, ApJL, 848, L16
- Tanaka, M. 2016, Advances in Astronomy, 2016, 634197
- Tanaka, M., & Hotokezaka, K. 2013, ApJ, 775, 113
- Tanaka, M., Hotokezaka, K., Kyutoku, K., et al. 2014, ApJ, 780, 31
- Tanaka, M., Utsumi, Y., Mazzali, P. A., et al. 2017, PASJ, 69, 102
- Tanaka, M., Kato, D., Gaigalas, G., et al. 2018, ApJ, 852, 109
- Tanvir, N. R., Levan, A. J., González-Fernández, C., et al. 2017, ApJL, 848, L27
- Tominaga, N., Tanaka, M., Morokuma, T., et al. 2018, PASJ, 70, 28
- Troja, E., Piro, L., van Eerten, H., et al. 2017, Nature, 551, 71
- Utsumi, Y., Tanaka, M., Tominaga, N., et al. 2017, PASJ, 69, 101
- Valenti, S., David, Sand, J., et al. 2017, ApJL, 848, L24
- Villar, V. A., Guillochon, J., Berger, E., et al. 2017, ApJL, 851, L21
- Wanajo, S., Sekiguchi, Y., Nishimura, N., et al. 2014, ApJL, 789, L39
- Waxman, E., Ofek, E. O., Kushnir, D., & Gal-Yam, A. 2018, MNRAS, 481, 3423
- Wollaeger, R. T., Korobkin, O., Fontes, C. J., et al. 2018, MNRAS, 478, 3298
- Yaron, O., & Gal-Yam, A. 2012, PASP, 124, 668