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Sensitivity studies on the excited states of nuclei in beta decays in the r-process of neutron star mergers

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Abstract

Sensitivity studies conducted in this paper aim to examine the influence of uncertainties in beta decay rates on simulations of rapid neutron capture (r-process) nucleosynthesis. However, previous studies multiplied the ground states of the theoretical rates or the ground states of the experimental rates by 10, and most of the theoretical rates and the experimental rates consider only the beta decay rates of the ground states but not the rates in stellar conditions because of the thermally excited states. In this study, we performed the first sensitivity test on the excited states of nuclei having $A > 120$ in the r-process. The ground state beta decay rates and estimated excited state rates are folded together to estimate a thermal decay rate as a function of temperature. We examined how the thermally excited states affect the stellar rates for all $A > 120$ nuclei. We found that there is a slight change in the second peak of final abundance in the r-process by Lu isotopes. This is the same as that in Famiano's paper (Famiano and Boyd 2008 *J. Phys. G: Nucl. Part. Phys.* **35** 2).

Keywords: r-process, neutron star, nuclear astrophysics

(Some figures may appear in colour only in the online journal)

Introduction

The abundance of heavy elements (elements heavier than iron isotopes) in the Universe is thought to be produced by the s-process (slow neutron captures) and the r-process (rapid neutron captures). The astrophysical sites of the s-process are in the asymptotic giant branch [1–3] or occur in core helium (He) burning (and shell carbon (C) burning) in massive stars ($M > 15$ solar mass) [4]. However, the astrophysical sites for the r-process are still under debate. Researchers have proposed different potential sites for the r-process. Among them, the most promising sites include the high entropy winds in supernova collapse and neutron star mergers. However, both these sites have unresolved problems [5, 6]. In this paper, we concentrate on studying the r-process in neutron star mergers.

Beta decay rates are important in determining the final abundance of the r-process. However, many studies use either the theoretical ground state rates or experimental rates of the ground states of the nuclei. Sensitivity tests have studied the uncertainties in beta decays in the r-process. Mumpower *et al* [7] multiplied and divided the experimental rates directly by 10 to study how the final abundance was affected by the uncertainties in the beta decay rates. The experimental rates consider only the beta decay rates of the ground states but not the rates in stellar conditions due to the thermally excited states. Mumpower *et al* [8–10] also showed that the peak of the rare-earth abundances in the r-process are sensitive to the nuclear physics input including the beta decay rates. Famiano *et al* [11] used a phenomenological model to study the excited states of the beta decay with theoretical single energy levels under supernovae conditions. In this study, we examine how the thermally excited states affect the stellar rates in neuron star mergers. Although the rates of excited states of nuclei were not measured, we estimated these rates by assuming that the rates of the excited states are 10 times faster than the experimental/theoretical ground state rates. Furthermore, we used WinVN [12] to calculate the partition functions (including the information of the excited states), which depend on the thermal conditions. The ground state beta decay rates and estimated excited state rates were folded together to estimate a thermal decay rate as a function of temperature. We emphasize that instead of considering only the theoretical rates, we used the experimentally known ground state rates when they were available. We used theoretical ground state rates only when experimental values were not available, and we used the theoretical partition function in WinVN to study the effects of thermally excited states on the final abundance of the r-process.

In this paper, we study all the nuclei whose mass $A > 120$ in the r-process. However, instead of varying the experimental ground state of the half-lives of the nuclei as Mumpower *et al* [7] did, we used the ground state beta decay rates together with estimated excited states rates to estimate the thermal rates of beta decays. In the next section, we discuss the nuclear network and astrophysical conditions used in the study as well as how we estimated the thermal beta decay rates. In section 3, we present the results of the sensitivity tests, and section 4 concludes our study.

Method

We used the SkyNet [13] code to study the r-process in a neutron star merger. The SkyNet code is a general-purpose network code specially designed for r-process nucleosynthesis calculations. We used the trajectories of neutron star mergers both for neutron stars equal to 1 solar mass and for 7.63E-3 solar mass ejections [14–16]. The initial temperature was 18 GK (gigakelvin). The initial abundance of electrons was 0.017 84 with an initial density of 8.1E13 $\mathrm{g\,cm^{-3}}$. We assumed nuclear statistical equilibrium at the very beginning of the evolution. Figure 1 shows the plot of temperature and density versus time.

The SkyNet code was used to calculate the abundances of different nuclear species, which are as follows:

$$\frac{\mathrm{d}Y_i}{\mathrm{d}t} = \sum N_j^i \lambda_j Y_j + \sum N_{j,\kappa}^i \rho N_A \langle \sigma \upsilon \rangle_{j,\kappa} Y_j Y_\kappa, \tag{1}$$

where the sums are over reactions that produce or destroy the nucleus of species i with one or two reactant nuclei, respectively. λ represents the rate of a one-body reaction, and $\langle \sigma \nu \rangle$

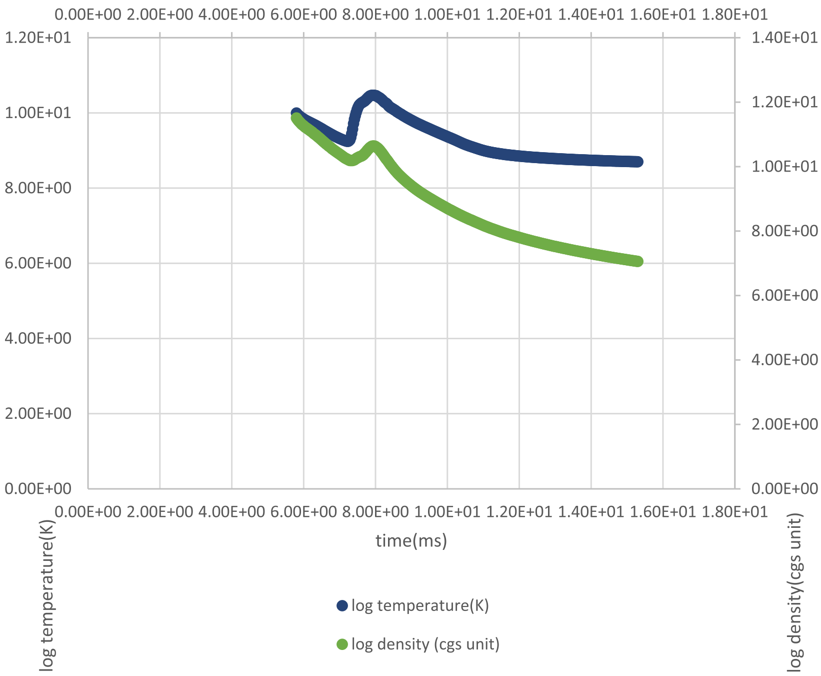

Figure 1. Temperature/density (log scale) versus time (the nuclear reactions before time 6 ms are assumed to be equilibrium).

represents the energy averaged from the astrophysical two-body reaction. N_i can be either a positive or a negative number that specifies how many particles of species i are created or destroyed in a reaction. The nuclear abundance depends on the number density of Ni in $Y_i = N_i \, \rho N_A$, where N_A is the Avogadro constant. These are the coupled, first-order, and nonlinear systems of equation.

For the nuclear reactions, we used the Jina Reaclib database from Cyburt *et al* [17] including the beta decay rates as the base rates. Reaclib uses experimental ground state beta decay rates if they are available or Möller *et al*'s [18] theoretical beta decay rates. Although the default SkyNet does not include the temperature-dependent beta decay rates, it allows the use of Fuller and Fowler (FFNU) [19] format temperature-dependent beta decay rates. Thus, we modified our sensitivity rates to the FFNU format and input them into the code. Fission was also included in the calculation. To study the thermally excited effects, we used the theoretical partition functions in the WinVN file.

The Q-values and the decay rates were already calculated in the finite range droplet model (FRDM) [20]. By comparing the calculated beta decay rates in FRDM model with the experimentally known rates, most of the calculated rates are within an order of magnitude of the true rate. For stellar environment, the nuclei were excited to excited states according to the partition function. The decay rates of the excited states are very uncertain. For instance, if we assume a shell model, single-particle excitations can be complicated. A single-particle excitation could cause a transition to go from GT to 1st forbidden, or it may even open Fermi decays. Furthermore, we know the theoretical/experimental ground state beta decay rates, we assumed that the half-lives of the excited states are 10 times faster than the theoretical/experimental ground state rates. Factor of 10 is an estimation, however, it is justified. For example, ^{150}Ba, it has 3 major brands $\lambda/\lambda_o = 0.75,1,2$ and λ_o is the ground state decay rate.

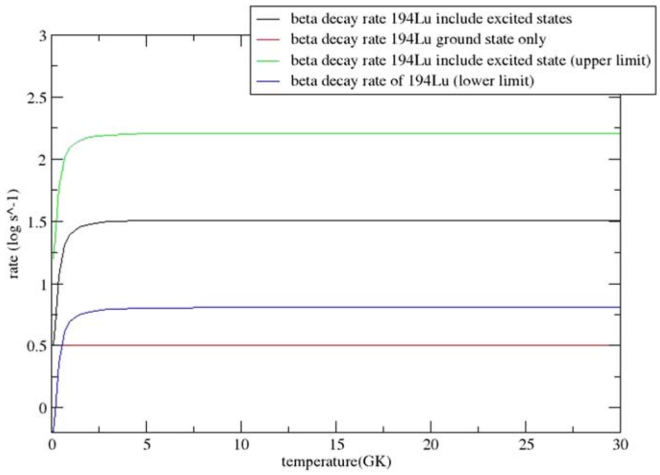

Figure 2. Beta decay rate of ^{194}Lu versus temperature with upper and lower limits of the excited state rate and ground state rate.

Thus, we expect that the rates of excited states can be a couple of factors larger. For some special cases, instead the decay rates of excited states increase, they decrease. Thus, we want to emphasize that the factor of 10 is just an estimation.

As the nuclei excitation depend on the partition function. The thermally excited beta-minus decay rate can be calculated as follows:

$$\lambda(T) = \frac{\sum_{i}^{Ei<Sn} \lambda_i \exp\left(-\dfrac{Ei}{kT}\right)}{\sum_{i}^{Ei<Sn} \exp\left(-\dfrac{Ei}{kT}\right)}, \tag{2}$$

where λ_i is the beta decay rate of the excited states except zero, Σ_i is the summation of the energy of the nuclei's excited state, and T is the temperature. The highest temperature reached approximately 18 GK in the neutron star mergers in our study. Although the temperature in the model changed, we used 1 GK as a point of illustration. Sn represents the neutron separation energy. We also used the partition function stated in WinVN. The partition function is given by the following equation:

$$G = 1 + \sum_{i=\text{lowest excited state}}^{Ei<Sn} \exp\left(\frac{-Ei}{kT}\right), \tag{3}$$

where G is the partition function.

Equation (3) can be modified by assuming that the rates of the excited states are 10 times faster than the ground state rates and using equation (4) as

$$\lambda = \frac{\lambda_0 + 10 \times \lambda_0 \times (G - 1)}{G}. \tag{4}$$

The value of the temperature is around ~1 MeV for 10 GK. The excited states are order of keV in order to have significant effects on the values of the partition functions. The spin is kind of uncertain in some cases. Thus, a rough estimation of partition function is the couple of factors. For simplification, we take the uncertainties of the partition function to be roughly a

Table 1. The beta decay rates (both in ground state and excited state) for the nuclei which have the largest F values.

Isotope	Ground state beta decay rate (log10)	Stellar beta decay rate (log10)	F values
^{194}Lu	0.5057	1.394	0.8032
^{196}Lu	0.6	1.281	0.4132
^{195}Lu	0.5027	1.154	0.2965

factor of 5. Figure 2 shows the beta decay rate of ^{194}Lu with upper and lower bound (the factor of 5) and it ground state beta decay rate.

Famiano *et al* [11] used a phenomenological model with theoretical single energy levels under supernovae conditions. In this paper, in addition to using the neutron star mergers situation, we used the beta decay rates in Reaclib but studied the effects of the excited states by assuming that they are 10 times faster than the ground state rates to see how sensitive the final abundances would be to the modified rates. Here we assumed that the half-lives of the excited states are usually shorter than the ground state half-lives. We chose nuclei with a mass number equal to or greater than 120.

Results

In this study, we performed a sensitivity test on the excited states of the r-process for each nucleus. We varied the rate of beta decay of each nucleus and studied its individual impact on the final abundance. To study how much the beta decay rate affects the final abundance quantitatively, we used the F values to measure the impact. The F value is defined in Mumpower *et al* [7] as

$$F = 100 \times \{\sum|AY_{\text{ground states}}(A) - AY_{\text{excited states}}|\}, \tag{5}$$

where A is the mass number, and Y is the abundance. To study this effect, table 1 summarizes the modified beta decay rates (all the excited state rates are 10 times more than the ground state rates), with F values larger than 0.25.

As shown in table 1, the modified beta decay rates are much faster than the ground state rates, even at temperature below 1 GK. The beta decay rate of ^{194}Lu has the largest impact on the final abundance.

As shown in the figure 3, the modified beta decay rate has little impact on the final abundance. Additionally, the second peak of the abundance is slightly modified by the Lu isotope. The r-process abundance residue is taken from reference [21].

To have a more general picture, a graph of F values of isotopes from $Z = 40$ to $Z = 75$ is plotted, as shown in figure 4. Previous studies [7] found that the r-process nuclei, which were 10–15 neutrons beyond stability, had the largest impact in the final abundance, and we confirmed this finding in our study. In figure 4, the deepest colour (which means the F values have the largest values) in this region implied similar results. We can see that in figure 8 shows the main changes roughly far from stable nuclei 10–15 nuclei.

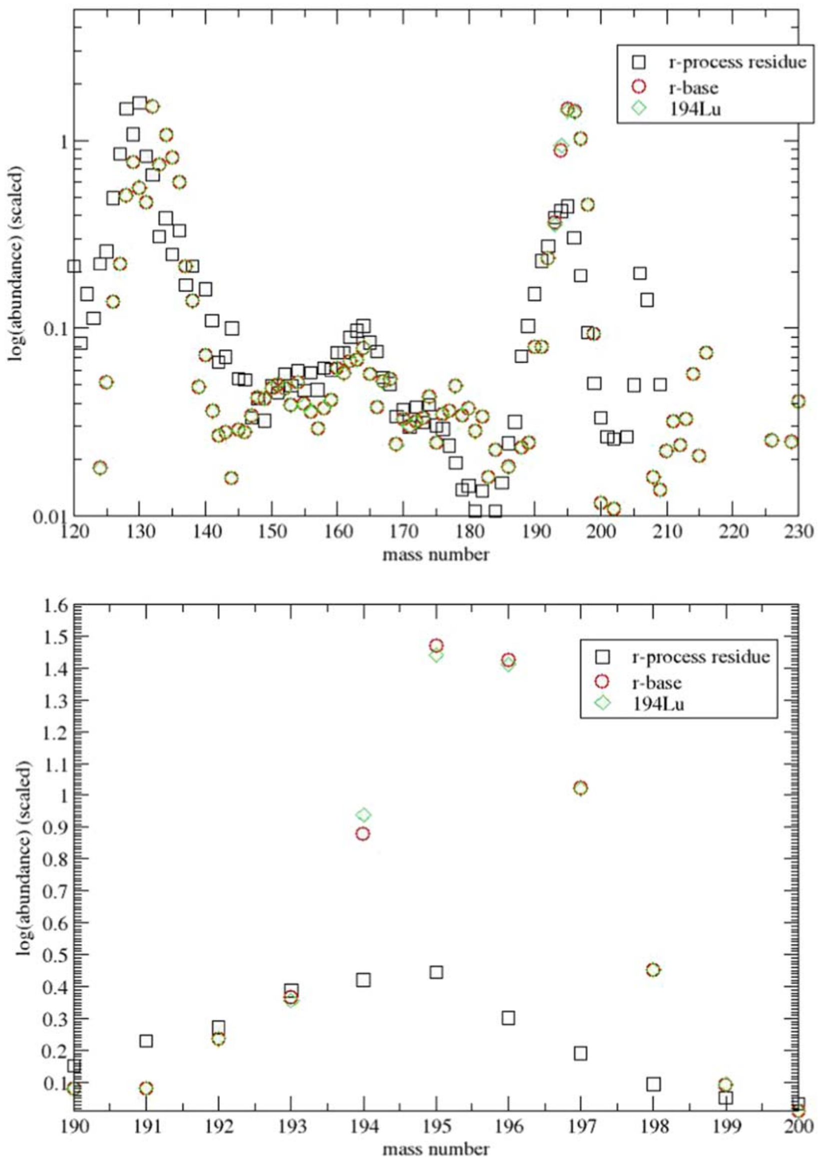

Figure 3. Shows the final abundances of the r-process with modified ^{194}Lu beta decay rate.

Conclusion

Instead of using theoretical transitional strengths as done in previous papers to calculate the beta decay rates in the r-process, this study examined the sensitivity of the final abundance of the r-process to the inclusion of thermal beta decay rates. We used the half-lives of the ground nuclei in Reaclib to study the sensitivities of the excited states of these r-process nuclei. In our study, the ($A \sim 196$) peak of the r-processes was slightly modified. However, as the excited states as well as the spins of the neutron-rich nuclei were not measured, we used the

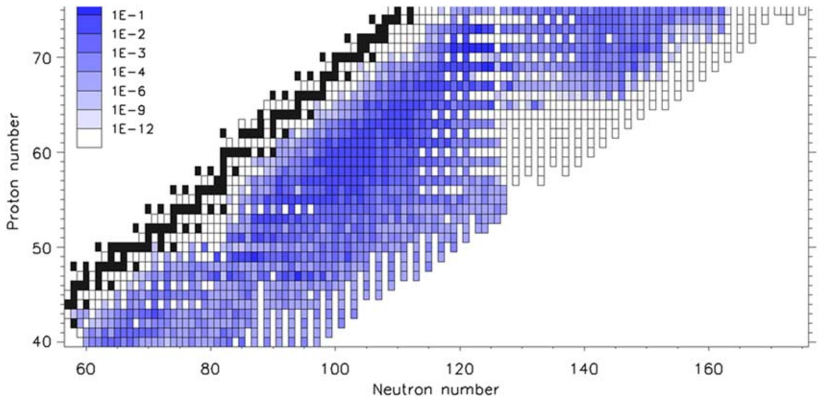

Figure 4. Shows the F values in the nuclei chart. The black squares represent the stable nuclei.

theoretical values of the partition functions. Similar results were also found in the x-ray burst situation but with larger impact [22]. The beta decay rates of the ground states as well as the excited states of the more neutron-rich nuclei and are expected to be measured in the future from FRIB. Furthermore, we used one set of neutron star merger trajectories in this calculation. The sensitivities of beta decays using different sets of neutron merger trajectories and even supernovae trajectories will be worth studying. We expect the thermally excited states may have little impact on r-process abundances.

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