The creation of the first r-process peak elements; effects of beta decay rates and nuclear masses

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Abstract. We present a study exploring the impact of nuclear masses and beta-decay rates on the creation of the first r-process peak. We explore a large range of conditions, matching the recent observations of the blue kilonova, and determine the appropriate conditions for creating the first r-process peak elements. We use the nuclear reaction code TALYS to calculate \((n, \gamma)\) reaction rates, and the GSINet code for reaction network calculations. We conclude that an electron fraction between 0.35 and 0.4 and entropy of (10-20) \(k_{\text{B}}/\text{baryon}\) should be considered to match the r-process residuals. Furthermore, we explore the impact of masses and beta-decays on the production of \(A \approx 80\) nuclei.

1. Introduction

Elements heavier than iron can be created through neutron-capture processes, namely the s-process and the r-process. The r-process nucleosynthesis is thought to be responsible for the creation of more than half of the heavy elements. The astrophysical environment under which the s-process operates is known \cite{1} but this is not the case for the r-process. Observations of ultra metal-poor (UMP) stars indicate that the r-process elemental abundances have contributions from at least two different sites. The elemental abundances in the atmosphere of UMP stars have a consistent pattern for \(Z \geq 56\). However, the abundances of light r-process elements \((Z<47)\) in these stars show variations. The two different contributions could be from different events in distinct astrophysical scenarios (i.e. supernova + neutron star mergers) or two different components of the same event (dynamical + post-merger ejecta).

Recent observations have established neutron star mergers (NSM) as a site of the r-process. Specifically, the observation of an NSM, and in particular, the electromagnetic counterpart \cite{2} that followed the gravitational wave detection GW170817 \cite{3, 4}, relates to the creation of lanthanides in the aftermath of NSMs. The observation of Sr at solar...
The creation of the first r-process peak elements; effects of beta decay rates and nuclear masses abundances \[5\] also provides evidence for the creation of the first r-process peak in the aftermath of NSM.

Several studies, considering conditions matching the ones of the observed NSM, have been conducted to investigate the creation of elements between the second and the third r-process peak. However, the creation of the first r-process peak is often overlooked. In the first part of this proceedings, we explore a range of astrophysical conditions for which the first r-process peak elements are created. In the second part, using the corresponding conditions, we estimate the impact of nuclear properties, like beta decay rates and nuclear masses, on the corresponding r-process pattern.

1.1. Interpretation of the kilonova observation

The electromagnetic counterpart following GW170817 was identified as a kilonova \[6, 7, 8, 9, 10\]. The energy released during the kilonova event results from the radioactive decay of r-process elements produced in the ejecta of the NSM. Observing the color of the EM turning from blue to red, we get indications for different opacities of the expanding material. The initial blue light emission indicates the absence of high opacity elements \[11, 12, 13, 14\], while the red color indicates that the medium is opaque. Lanthanides and actinides are known to have a complicated atomic structure. Thus their presence in the gas leads to high opacity \[15, 16, 17, 18\]. A distinction between lanthanide or actinide elements is not possible from the spectrum of the kilonova unless distinct spectrum lines of nuclei are identified. We focus on the early blue color component ejecta which corresponds to material that contains elements up to the second r-process peaks (lanthanide/actinide, free ejecta). The recent observation of Sr in the spectrum of the kilonova with solar r-process proportions provides direct evidence for the production of light elements in the aftermath of NSMs \[5\].

We examine the possibility of creating the total, or parts, of the first r-process peak in the aftermath of NSMs with the conditions speculated for the post-merger ejecta of a hyper massive neutron star that promptly collapses to a black hole. According to simulations, the post-merger ejecta, which account for roughly 0.001– 0.01 \(M_\odot\) \[19, 20, 21, 22, 23, 24, 25\], have an intermediate electron fraction \(Y_e \approx 0.25 \rightarrow 0.5\) \[20, 26\], an expansion timescale \(\tau\) of the order of milliseconds \[27, 28, 29, 30\] and moderate entropies in the range of \(S \approx 10 \rightarrow 30\) \(k_B/\text{baryon}\) \[31\]. This is consistent with observations of UMP stars since different initial masses of the NSM can result in different conditions of \(S\) and \(Y_e\) of the polar ejecta \[26\]. Subsequently, these different initial conditions will result in differences in the production of light elements.

1.2. The formation of the first r-process peak - connection to nuclear physics

The first r-process peak is the result of matter accumulating at the closed neutron shell of \(N = 50\). Due to the drastically lower \((n, \gamma)\) reaction rates of nuclei in the region of the closed neutron shell, neutron captures become slower and matter accumulates in this region. The competing \(\beta\)-decay half-lives of the nuclei in the region have similar
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![Figure 1](image)

**Figure 1.** Known masses and beta decay half-lives in the region of N=50. With blue we label the path of the r-process. The blue color coding corresponds to the abundance of each specific isotope at the freeze-out.

*timescales to neutron captures and photodisintegrations. Eventually, the matter that piles up at the closed neutron shell, will $\beta$-decay creating heavier elements with $Z'=Z+1$.

To model the exact path of the r-process we need the $\beta$-decay half-lives, and the corresponding neutron delayed emission probabilities of nuclei in the path of the r-process, as well as their cross sections for reactions at $E \leq 1$ MeV. These properties are very difficult to measure for unstable nuclei due to a number of experimental challenges (neutron targets are difficult to make, some of the nuclei are very short-lived, etc.). Modeling of the cross-sections is possible with the Hauser Feshbach statistical model which employs a number of assumptions. One of the key parameters entering the Hauser Feshbach calculations is the nuclear masses. The known beta-decays and masses in the region are summarized in Fig 1, together with the path of the r-process.

2. Methods

2.1. Estimating the appropriate astrophysical conditions

We investigate a large space of $Y_e$ (electron fraction) and $S$ (entropy): $0.26 \leq Y_e \leq 0.46$ and $10 \leq S \leq 100$ kB/baryon to account for all possible conditions of the post merger ejecta, as those were discussed in Section 1.1. Scenarios of production of the first r-process peak have already been investigated for higher entropies where $\alpha$ particles play a key role [32, 33, 34]. Here we focus on conditions that do not lead to an $\alpha$-rich freeze out and in addition no lanthanides are produced.

We use the nuclear reaction network code GSINet [35] to follow the evolution of the abundances of nuclei in the expanding gas. The network contains approximately
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7000 nuclei and their corresponding reaction channels. Masses and beta decays are taken from [36], unless they are experimentally known [37]. We initialized calculations at Nuclear statistical equilibrium (NSE), treating initial electron abundance $Y_{e,0}$ and initial specific entropy ($s_0$) as free parameters to investigate. The initial temperature was set at $T_0 = 10$ GK and the expansion time scale is $\tau = 7$ ms. We use the equation of state of Timmes [38] to determine the corresponding density $\rho$, assuming NSE. We assume that the density evolution of the ejecta initially follows an exponential expansion and at later times homologous expansion [39]:

$$
\rho(t) = \begin{cases} 
\rho_0 e^{-t/\tau} & \text{if } t \leq 3\tau \\
\rho_0 \left( \frac{3\tau}{t} \right)^3 & \text{if } t \geq 3\tau 
\end{cases}
$$

2.2. Estimating the impact of nuclear masses and beta decay models to the first r-process peak.

Using the range of astrophysical conditions under which the first r-process peak is produced we check the impact of nuclear masses and beta decays. To estimate the impact of specific masses to the r-process abundance pattern, we used the recently measured $^{84}$Ga-$^{85}$Ga [40]. First, we vary the masses using a Monte Carlo like approach within the corresponding uncertainty bands of AME16 [41] (200KeV and 300KeV respectively). The Monte Carlo sampling we use corresponds to pairs of $^{84}$Ga and $^{85}$Ga within $3\sigma$ uncertainty respecting the odd even staggering (i.e. $S_n(^{84}\text{Ga}) \leq S_n(^{85}\text{Ga})$). We use the nuclear reaction code TALYS to calculate the corresponding $(n,\gamma)$ reaction rates and detailed balance to estimate the inverse rates ($\gamma,n$). The new reaction rates were then used in GSInet. The resulting abundances are then compared to the AME16 recommended values, and the new Ga measurements. We use AME16 and NUBASE16 [42] information when available experimentally. Theoretical masses are taken from FRDM [36].

Besides, we explore the impact of the beta decays and beta delayed neutron emissions on the fine details of the pattern. First, we will use only theoretical data of $\beta$-decays from the FRDM model disregarding NUBASE16 to estimate the sensitivity of the fine details of the peak (local maximums at 80,84) to the $\beta$-decays. To get a better understanding of the impact of late neutron captures due to $\beta$-delayed neutron emissions we remove them in the next step. Finally, we discuss the impact of two specific measurements of $\beta$-delayed neutron emissions of $^{84}$Ga and $^{85}$Ga [43, 44] that are not included in the NUBASE16.
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Figure 2. Upper plot: Abundance of lanthanides color coded with red on $Y_e$ vs $S$ plot. Center plot: Abundance of $\alpha$ particles color coded with green. Lower plot: Abundance of first r-process peak elements color coded with blue. We contour with black the region where enough first r-process peak elements are created. With yellow we contour the limits of the Upper and Center plot.

3. Results

3.1. Astrophysical conditions

We find that lanthanides are created for $Y_e \leq 0.33$, as shown in the upper plot of Fig.2. Significant amounts of lanthanides are created for higher $S$ even at moderate $Y_e$ conditions ($\approx 25$ k$_B$/baryon).

Large amounts of $\alpha$ particles leading to $\alpha$ rich freeze-out are present for $S \geq 30$ and $Y_e \leq 0.45$. At higher $Y_e$ alpha particles are present throughout the range of entropies we explored (middle plot Fig.2). Finally the first r-process peak elements are mostly produced in a rather narrow window between $0.32 \leq Y_e \leq 0.39$ at $S \leq 20$ (lower plot Fig.2). The range of $Y_e$ becomes narrower and shifts to higher $Y_e$ with higher entropy. Assuming that NSMs are responsible for the total production of first r-process elements we can further narrow the range of possible $Y_e$'s by comparing with the r-process abundance pattern.

This can be seen in Fig. 3, where for $S = 15$ k$_B$/baryon, the region between the first and the second peak is overproduced, assuming a uniform distribution that includes $Y_e \leq 0.33$. Taking into account all the above we conclude that the first r-process peak can be made for $0.34 \leq Y_e \leq 0.40$ and $10 \leq S \leq 20$k$_B$/baryon. Assuming other distributions (i.e. Gaussian) we find similar conditions of $0.30 \leq Y_e \leq 0.42$. 

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3.2. Impact of masses and β delayed neutron emissions

The uncertainty in masses of $^{84,85}$Ga within their AME16 error bars (200keV,300keV respectively) results to variations of the (n,γ) reaction rates (RR) of $^{83}$Ga - $^{86}$Ga of up to two orders of magnitude (Fig. 4).

The effect of the variations of the (n,γ) RR can be seen in the abundance pattern of Fig. 5. The newly measured Ga masses [40] establish the production of the peak at A=84 under the specific conditions.

Overproduction of A = 81 could be attributed to uncertainties in half-lives and β-delayed neutron emissions of neutron rich nuclei with A = 81, 82, 83. In our calculation, A = 81 is produced mainly from β-delayed neutron emission of $^{82}$Zn, whose half-life exhibits inconsistencies in the literature (228(10)ms [45], 178(2.5)ms [46], 155(20)ms [47]).

The effect of β-decay ratios can be seen in Fig. 6. By using purely theoretical values from FRDM for β-decays and β-delayed neutron emissions we observe underproduction of the peaks at A=80, 84. The results when we don’t allow for β-delayed neutron emissions (same Fig. magenta line) are similar. The main difference is the odd-even staggering at A=80-84. Differences of abundances between these calculations are due to the reshuffling of the matter, at later stages of nucleosynthesis, due to the emission and re-capture of neutrons. We note that all calculations in Fig. 6 were normalized at A=82 in order to have a meaningful comparison.

Changes on β - delayed neutron emission probabilities affect mainly the abundances of nuclei with the same A. Fig. 7 shows the impact of the updated data on $^{84,85}$Ga β-delayed emission probabilities. The increased $P_{1n}$ (probability of emitting a neutron
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**Figure 4.** Variations in reaction rate (RR) of \( (n,\gamma), (n,2n) \) and \( (n,\alpha) \) of \( ^{85}\text{Ga} \) due to the difference in masses used in Hauser-Feshbach calculations. The masses used correspond to AME16 mass recommendations of \(^{84,85}\text{Ga}\) within a 3\(\sigma\) uncertainty.

**Figure 5.** Final abundance pattern for \( Y_e \) 0.35-0.38. Error bars correspond to the uncertainties of AME16 \(^{84,85}\text{Ga}\) masses. The new measurement establishes the creation of peak at \( A=84 \). Figure is adapted from [40].
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Figure 6. Comparison between calculations using the standard input (NUBASE16+FRDM) (blue line), to calculations where only the FRDM model for $\beta^-$ was used (green line), and finally calculations where (NUBASE16+FRDM) inputs were used for half-lives but $\beta$-delayed neutron emissions were set to 0 (magenta line).

after $\beta$ decay) from 40% to 50% for $^{84}$Ga [43] and from 35% to 70% for $^{85}$Ga [44] results in differences in the production of $A=85 \approx 30\%$ and slight differences of $\approx 10\%$ for $A=84$.

4. Summary

We conclude that it is possible to create the first r-process peak under conditions that may be realized in binary neutron star mergers. We estimated that $Y_e$ and $S$ in the range of $0.34 \leq Y_e \leq 0.40$ and $10 \leq S \leq 20$ are needed to create the first r-process peak without overproducing the region between the first and second r-process peak.

Assuming those astrophysical conditions we evaluated the impact of nuclear masses and specifically the $^{84,85}$Ga mass uncertainties to the formation of the first r-process peak showing that the newly measured masses allow for the formation of a local peak at $A = 84$ as seen in solar r-process abundance pattern. Furthermore, we estimated the effect of different $\beta$-decay half-lives and $\beta$-delayed emissions concluding that the fine structure of the peak is sensitive to changes in these quantities.
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Figure 7. Comparison between calculations using the standard input (NUBASE16+FRDM) compared to the measured latest measured values of $\beta^{-}$ delayed neutron emissions for $^{84,85}\text{Ga}$

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