Exploring the astrophysical conditions for the creation of the first r-process peak

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Abstract. We present a study exploring the conditions for the creation of the first r-process peak. We perform large-scale network calculations for a wide range of electron fraction and entropy using the *GSINet* code. Under conditions matching the recent observations of the blue kilonova, we conclude that electron fraction between 0.35 and 0.4 and entropy of $15k_b/baryon$ should be considered in order to match the r-process residuals.

1. Introduction

The creation of the heavy elements and where they are made is still one of the most puzzling questions in physics. Hydrogen, helium, and traces of lithium were created in big bang nucleosynthesis. Heavier elements up to iron can be made during the life of massive stars ($m > 10M_\odot$) through fusion reactions. To create elements heavier than iron we need to consider neutron capture reactions. These reactions lead to the production of nuclei away from stability, depending on how fast they happen and the availability of neutrons. We can separate neutron capture processes depending on the dynamical timescale, to the s-process (slow neutron capture process) and the r-process (rapid neutron capture process).

Each process has a contribution to the solar abundance pattern. The r-process is responsible for the creation of about half of heavy elements [1]. The contribution of r-process to the solar abundances can be estimated if we subtract from the solar abundances the s-process abundances. The contribution of the s-process to the solar abundances stands in good foundations though uncertainties/deviations depending on the method used to calculate them are quite possible [2]. While the site of the r-process was unknown until recently, the observation of a neutron star merger, and in particular the electromagnetic counterpart AT2017gfo [3] that followed the gravitation event GW170817 [4, 5], strengthens the speculation [6–10] that neutron star mergers is one, if not the main, site for the creation of heavy elements. The electromagnetic counterpart was the so called kilonova/macronova [11–15]. The energy released during the kilonova event results from the radioactive decay of heavy r-process elements produced and ejected during the merger process. The observation of the spectrum color turning from blue to red can be interpreted in multiple ways. One of the possible explanations is that early ejecta (i.e. dynamical ejecta) created a range of nuclei that did not include lanthanides or heavier than those elements. Lanthanides and actinides have a complicated atomic structure making the emission color red because of the absorption and re-emission of light. The absence of lanthanides mean simpler atomic spectra and thus the emission color is blue [16–19]. Later emissions (possible winds) were rich in nuclei with complicated atomic structure (such as lanthanides and maybe actinides) making the emission color of the ejecta to turn red [20–23]. In this work we explore the astrophysical conditions for creating the first r-process peak (thus lanthanide free ejecta) and how uncertainties in nuclear physics affect our calculations.

Modelling the r-process nucleosynthesis is a complicated problem with many parameters. Uncertainties in nuclear physics [24–31, 31–35] as well as in astrophysical conditions can drastically alter the resulting abundance pattern. Recently, parts of nuclear uncertainties have been studied for similar conditions. The impact of uncertainties of $^{82}Ga -^{85} Ga$ masses [36] to the distinct r-process peak at A=80, A=84 have been studied in detail under similar conditions. The results showed that even small uncertainties of the order of 100keV can significantly alter the resulting abundance pattern. Here we present a thorough investigation of the formation of the 1st r-process peak addressing a wide range of astrophysical scenarios.

2. Origin of the broad first r-process peak - nuclear physics connection

The broad first r-process peak is the result of matter decaying from the closed neutron shell N=50, where the neutron separation energy drastically falls, subsequently leading to lower (n,γ) rates which suppress the flow of matter towards higher N.

While for some of the elements participating in the creation of the first r-process peak in nuclesynthesis studies, masses and beta-decay rates have experimentally determined values with good accuracy, the exact astrophysical conditions responsible for the creation of the elements of the first r-process peak are largely unconstrained. The elements of the first r-process peak can be made in neutron rich conditions during the α-rich freeze out in supernovae and at moderately neutron rich conditions in neutron star mergers. Recent speculation indicates that at least some of the light r-process elements are made in neutron star mergers under conditions of intermediate electron fraction Y_e, expansion timescale τ at the order of milliseconds and moderate entropies S at $\approx 10 - 30\mathrm{k_B}/\mathrm{baryon}$.

Here we try to confine these conditions and explore under which combinations the first r-process peak can be created with only a small fraction of lanthanides, in order to have a consistent picture to the observed kilonova and to further constrain the astrophysical environments responsible for the formation of the 1st r-peak.

3. Procedure

We used the nuclear reaction network code *GSINet* [26] to simulate the evolution of the abundances of different r-process elements. The network contains approximately 7000 nuclei and their corresponding reaction channels. The reaction rates for each channel were calculated using the Hauser-Feshbach code Talys [37]. Fission properties are not relevant for this region. Masses and beta decays are taken from [38] unless they are experimentally known. 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. Initial density ρ_0 results from the equation of state (EOS) [39] assuming NSE. We assume that the density evolution of the ejecta follows an exponential expansion and at later times homologous expansion [40] and is described as:

$$\rho(t) = \begin{cases} \rho_0\, e^{-t/\tau} & \text{if } t \leq 3\tau \\ \rho_0 \left(\frac{3\tau}{et}\right)^3 & \text{if } t \geq 3\tau \end{cases} \tag{1}$$

The use of a constant τ in our calculation is justified due to the moderate Y_e values we explore. In the end of our calculations neutrons were already captured from the seed nuclei. In case of lower Y_e values, a slower decrease in ρ is needed for the few seed nuclei to capture the large flux of available neutrons. In that case a rapid expansion would lead to free neutrons after the freeze-out. Varying τ would have a large effect in the abundance of heavier elements (i.e. lanthanides) in case of more neutron rich material [40, 41].

4. Results

4.1. Dependence on Y_e

The electron fraction Y_e is largely unconstrained due to the neutrino fluxes which remain widely unknown from simulations. From calculations it is known that it is possible to create lanthanide free ejecta with $0.25 \leq Y_e \leq 0.40$ [42–44] with some variations depending on the specific astrophysical conditions and mass models. We explored a wide range of Y_e's (0.28-0.40) finding that the only case of recreating first r-process peak elements without overshooting on higher mass numbers can happen for a relatively narrow range corresponding to $0.34 \leq Y_e \leq 0.40$. This is illustrated in Fig. 1 for flat distributions. This overproduction is suppressed assuming a Gaussian distribution of Ye with width of 0.15 centered at $Y_e = 0.34$, $Y_e = 0.35$, $Y_e = 0.37$, $Y_e = 0.38$ accordingly (see Fig. 2). $Y_e > 0.4$ does not completely overcome the iron peak and only has small contributions to the region around $A = 80$.

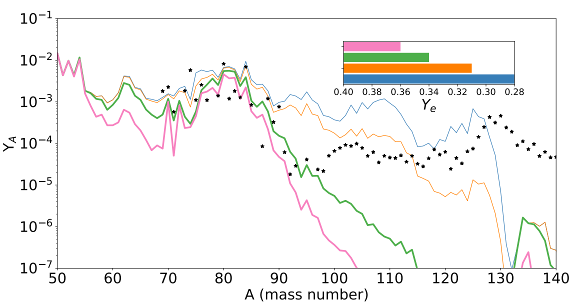

Figure 1. Y_A vs A for flat distribution ranges of Y_e.

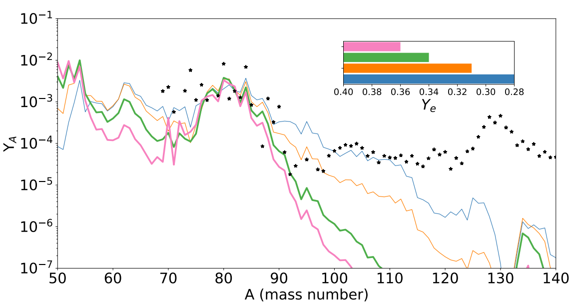

Figure 2. Y_A vs A for Gaussian distribution ranges of Y_e.

4.2. Dependence on entropy

Simulations from BNS, NS-NS mergers [40, 45] and magnetorotational supernovae [46, 47] show that the 1st r-process peak can be produced under moderate entropy and Y_e conditions. We explore a range $10 \leq S \leq 50$ for $Y_e = 0.38$. In the scenario we study no α particles are present at the end of the nucleosynthesis. This constrains the entropy range since in a lot of scenarios α particles are present after the end of the r-process. A clear cutoff at $\approx 25\mathrm{k_B}$/baryon is observed (see 4.2 upper left). For higher entropies we get a large amount of α particles, even at very low temperatures. Having more alpha particles also affect the amount of available neutrons. A difference of up to 2 order of magnitudes in the abundance of neutrons was observed (see 4.2 upper right). The average mass number depends on the entropy higher entropies produce in average higher mass (see 4.2 lower left). This is what we also observe in the final abundance pattern where there is a shift of the produced elements at A ≈ 105 for higher entropies (see 4.2 lower right). We conclude that entropies of up to ≈ $25\mathrm{k_B}$/baryon are consistent simulations of neutron star mergers and can recreate the first r-process peak.

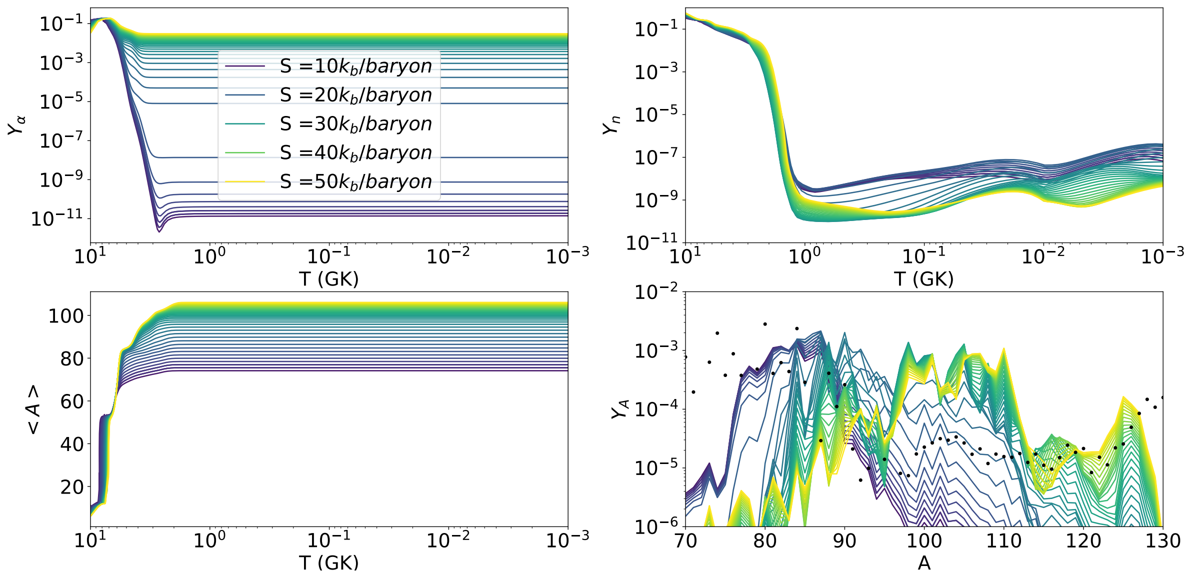

Figure 3. Upper left: Y_α vs $T(GK)$, a clear cut-off is clear at low temperatures between scenarios where no α particles are left and higher entropies. Upper right: Y_n vs $T(GK)$, the amount of α particles slightly changes the Y_n. Lower left shows the evolution of average mass number ($< A >$) vs temperature which is also affected largely by the entropy, higher entropies allow for a higher $< A >$. Lower right: Y_A vs A, large deviations are shown in the final abundances for different entropies. There is a clear shift in the r-process abundance peak for higher entropies leading to overshooting in the region of $A \approx 100$. Color coded is the entropy from deep blue $S = 10$ to yellow $S = 50$.

5. Conclusions

From our studies we conclude that binary neutron star mergers are able to produce the 1st r-process peak if a narrow range of intermediate Y_e conditions and S is present. In that narrow range we can identify the nuclei participating and check, if sufficient nuclear physics properties are determined in this region. This will allow us to investigate fine/detailed features of the solar abundance curve. Future facilities like FAIR and FRIB can help the community to complete the nuclear puzzle in the region and allow us to have more robust calculations that can be used to constrain the astrophysical scenarios even further.

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