# The $r$-process nucleosynthesis and related challenges

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**Abstract.** The rapid neutron-capture process, or $r$-process, is known to be of fundamental importance for explaining the origin of approximately half of the $A > 60$ stable nuclei observed in nature. Recently, special attention has been paid to neutron star (NS) mergers following the confirmation by hydrodynamic simulations that a non-negligible amount of matter can be ejected and by nucleosynthesis calculations combined with the predicted astrophysical event rate that such a site can account for the majority of $r$-material in our Galaxy. We show here that the combined contribution of both the dynamical (prompt) ejecta expelled during binary NS or NS-black hole (BH) mergers and the neutrino and viscously driven outflows generated during the post-merger remnant evolution of relic BH-torus systems can lead to the production of $r$-process elements from mass number $A \gtrsim 90$ up to actinides. The corresponding abundance distribution is found to reproduce the solar distribution extremely well. It can also account for the elemental distributions observed in low-metallicity stars. However, major uncertainties still affect our understanding of the composition of the ejected matter. These concern (i) the $\beta$-interactions of electron (anti)neutrinos with free neutrons and protons, as well as their inverse reactions, which may affect the neutron-richness of the matter at the early phase of the ejection, and (ii) the nuclear physics of exotic neutron-rich nuclei, including nuclear structure as well as nuclear interaction properties, which impact the calculated abundance distribution. Both aspects are discussed in the light of recent hydrodynamical simulations of NS mergers and microscopic calculations of nuclear decay and reaction probabilities.

## 1 Introduction

Among the various fields in nuclear astrophysics, nucleosynthesis is clearly the one the most closely related to nuclear physics, the nuclear physics imprint being found in the origin of almost all nuclides produced in the Universe [1]. Impressive progress has been made for the last decades in the various fields related to nucleosynthesis, especially in experimental and theoretical nuclear physics, as well as in ground-based or space astronomical observations and astrophysical modellings. In spite of these achievements, major problems and puzzles remain. Among the various nuclear astrophysics problems, one specific nucleosynthesis process remains extremely difficult to solve. It concerns the rapid neutron-capture process, or $r$-process, invoked to explain the production of the stable (and some

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long-lived radioactive) neutron-rich nuclides heavier than iron that are observed in stars of various metallicities, as well as in the solar system (for a review, see Ref. [2]). In recent years, nuclear astrophysicists have developed more and more sophisticated *r*-process models, trying to explain the solar system composition in a satisfactory way by adding new astrophysical or nuclear physics ingredients. The *r*-process remains the most complex nucleosynthetic process to model from the astrophysics as well as nuclear-physics points of view. The site(s) of the *r*-process is (are) not identified yet, all the proposed scenarios facing serious problems. Complex—and often exotic—sites have been considered in the hope of identifying astrophysical conditions in which the production of neutrons is large enough to lead to a successful *r*-process.

Progress in the modelling of type-II supernovae and *γ*-ray bursts has raised a lot of excitement about the so-called neutrino-driven wind environment [2–4]. However, until now a successful *r*-process has not been obtained *ab initio* without tuning the relevant parameters (neutron excess, entropy, expansion timescale) in a way that is not supported by the most sophisticated existing models [2, 3]. Early in the development of the theory of nucleosynthesis, an alternative to the *r*-process in high-temperature supernova environments was proposed. It concerns the decompression of cold neutron star (NS) matter that was found to be favorable for strong *r*-processing, as discussed below.

## 2 NS mergers as a potential *r*-process site

Recently, special attention has been paid to NS mergers following the confirmation by hydrodynamic simulations that a non-negligible amount of matter, typically about $10^{-3}$ to $10^{-2}M_{\odot}$, can be ejected. In contrast to the supernova site, investigations with growing sophistication have confirmed NS merger ejecta as viable sites for strong *r*-processing [5, and references therein]. In particular, recent nucleosynthesis calculations [5] show that the combined contribution of both the dynamical (prompt) ejecta expelled during the binary NS-NS or NS-black hole (BH) merger and the neutrino and viscously driven outflows generated during the post-merger remnant evolution of the relic BH-torus systems lead to the production of *r*-process elements from $A \gtrsim 90$ up to thorium and uranium with an abundance distribution that reproduces extremely well the solar distribution (Fig. 1), as well as the elemental distribution observed in low-metallicity stars [6]. In this specific *r*-process scenario, during the dynamical phase, the number of free neutrons per seed nucleus can reach a few hundreds. With such a neutron richness, heavy fissioning nuclei can be produced. As a consequence, the final composition of the ejecta is rather insensitive to details of the initial abundances and the astrophysical conditions, namely the mass ratio of the two NSs, the quantity of matter ejected, and the equation of state [7]. This robustness, which is compatible with the uniform solar-like abundance pattern of the rare-earth elements observed in metal-poor stars [6] supports the possible creation of these elements by fission recycling in NS merger ejecta.

The ejected mass of *r*-process material, combined with the predicted astrophysical event rate (around $10\,\mathrm{Myr}^{-1}$ in the Milky Way [8]) can account for the majority of *r*-material in our Galaxy [9]. Recent studies [10, and references therein] have also reconsidered the galactic or cosmic chemical evolution of *r*-process elements in different evolutionary contexts, and although they do not converge towards one unique quantitative picture, most of them got to the conclusion that double compact star mergers may be the major production sites of *r*-process elements. However, the recent observation of the kilonova GW170817 after the present conference presents the first clear evidence regarding the significant contribution of binary NS mergers in the *r*-process enrichment of the Galaxy [11].

Despite the success shown by the NS merger models, one major question still concerns the impact neutrino reactions can have on the predictions. In particular, relativistic NS-NS merger simulations [12, 13] found that neutrino reaction can significantly affect the electron fraction in the dynamical ejecta of systems with delayed collapse of the merger remnant. In this case, in addition to heavy
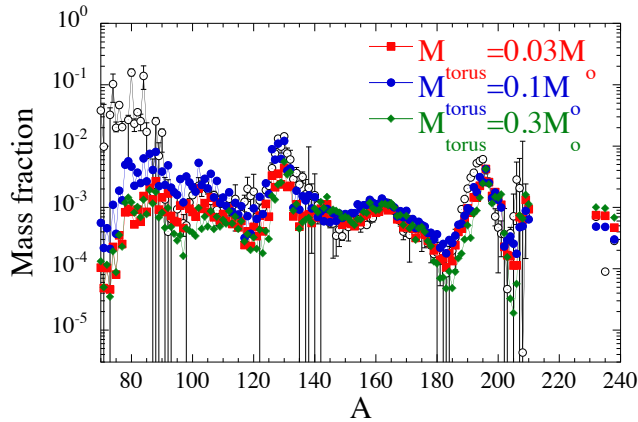
**Figure 1.** Abundance distribution as functions of the atomic mass $A$ for three combined systems (merger model plus remnant model) corresponding to models with torus masses $M_{torus} = 0.03, 0.1$ and $0.3 M_\odot$. All distributions are normalized to the $A = 196$ $r$-abundance in the Solar System (dotted circles). See Ref. [5] for more details.

$r$-process elements ($A > 140$), nuclei with lower mass numbers may also be created in the dynamical ejecta. It is still unclear whether the observed effects apply similarly strongly to all high-density equation of states and all binary systems that lead to a delayed collapse of the merger remnant.

The accurate inclusion of neutrino interactions in hydrodynamical simulations remains a highly complex task. For this reason, a simple, parametric study was conducted by Goriely et al. [14] in order to quantify the potential impact of weak interactions on the electron-fraction evolution in merger ejecta and thus to explore the consequences of charged-current neutrino-nucleon reactions for the nucleosynthesis and possible $r$-processing in these ejecta. More specifically, Goriely et al. [14] investigated the influence of $\beta$-interactions of electron neutrinos ($\nu_e$) and electron antineutrinos ($\bar{\nu}_e$) with free $n$ and $p$ and of their inverse reactions,

$$
\begin{aligned}
\nu_e + n &\rightleftharpoons p + e^- \\
\bar{\nu}_e + p &\rightleftharpoons n + e^+ \quad ,
\end{aligned}
\tag{1}
$$

on the $Y_e$ distribution and $r$-process nucleosynthesis at conditions representative of the dynamical ejecta expelled by hydrodynamical forces during NS-NS mergers. Only recently these reactions have been included in $r$-process nucleosynthesis studies [12, 13]; however, their quantitative effects depend on the details of the merger dynamics, the strength of the shock heating during the merging, and therefore on the adopted equation of state. The role of weak interactions for the electron fraction and the corresponding implications for $r$-process nucleosynthesis, however, demand further exploration in more detail, in particular also by basic, parametric modeling, because a multitude of uncertainties will prevent rigorous, self-consistent solutions of the full problem in the near future. Such uncertainties are associated with, for example, the extreme complexities of 3D energy-dependent neutrino transport in relativistic environments, with the neutrino opacities of dense, potentially highly magnetized matter, and with neutrino-flavor oscillations at rapidly time-variable, largely aspherical conditions of neutrino emission.

The major effect of the neutrino interactions on free $n$ and $p$ (Eq. 1) is to increase the electron fraction $Y_e$ that consequently may affect the efficiency of the $r$-process nucleosynthesis. The corre-

sponding asymptotic value of $Y_e$ can be approximated by [14]

$$Y_e^\infty \simeq \frac{L_{\nu_e}\langle E_{\nu_e}\rangle f_{\nu_e}^{\mathrm{mr}}}{L_{\nu_e}\langle E_{\nu_e}\rangle f_{\nu_e}^{\mathrm{mr}} + L_{\bar{\nu}_e}\langle E_{\bar{\nu}_e}\rangle f_{\bar{\nu}_e}^{\mathrm{mr}}} , \qquad (2)$$

where $L_{\nu_e/\bar{\nu}_e}$ are the (anti)neutrino luminosities, $\langle E_{\nu_e/\bar{\nu}_e}\rangle$ the mean energies of the radiated neutrinos, and $f_{\nu_e/\bar{\nu}_e}^{\mathrm{mr}}$ corresponds to the weak magnetism and recoil corrections [15]. For the present study, we consider a given representative neutrino luminosity and angle-averaged mean energies [12, 16], namely $L_{\nu_e} = 0.6\ 10^{53}$ erg/s, $\langle E_{\nu_e}\rangle = 12$ MeV and $\langle E_{\bar{\nu}_e}\rangle = 16$ MeV, but various values of the antineutrino luminosity to study their impact on nucleosynthesis. All of them are assumed to remain constant in time. Electron and positron captures on free nucleons are also included in these cases. For these mean energies, $f_{\bar{\nu}_e}^{\mathrm{mr}}/f_{\nu_e}^{\mathrm{mr}} \simeq 0.69$. The impact of the neutrino interaction is essentially to increase $Y_e$, as illustrated in Fig. 2, where the $Y_e$ distribution at the density $\rho_{\mathrm{net}}$ (at which the temperature drops below 10 GK; see [14] for more details) is illustrated for different values of the antineutrino luminosities and compared to the case where all weak interactions on nucleons have been neglected. The larger the antineutrino luminosity, the more efficient the $r$-process nucleosynthesis, as shown in Fig. 3. For $L_{\bar{\nu}_e} \gtrsim 3\ 10^{53}$ erg/s (*i.e.* about 5 times the neutrino luminosity), $Y_e^\infty$ drops below 0.20 and the ejected $r$-abundance distribution is seen to match relatively well the solar one for all nuclei with $A \gtrsim 90$. In contrast, for decreasing antineutrino luminosities, a weaker $r$-process is obtained with a second (first) $r$-process peak produced for $L_{\bar{\nu}_e}$ at least 3 (2) times higher than the neutrino luminosity[1].
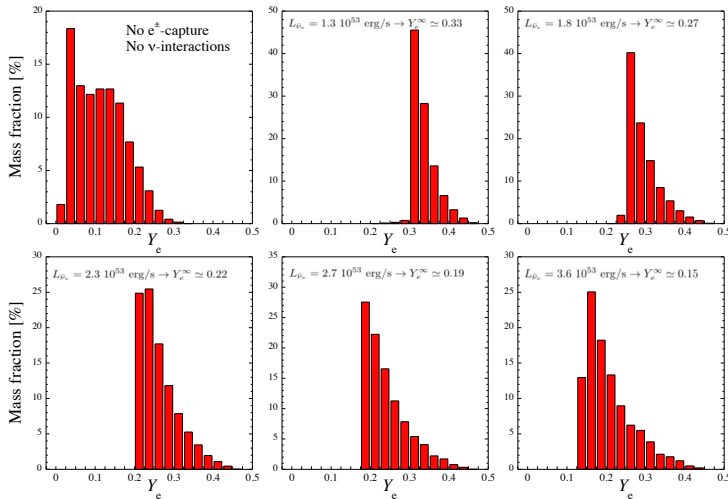


**Figure 2.** Histograms of fractional mass distributions of the $4.9 \times 10^{-3} M_\odot$ of matter ejected in the 1.35–1.35$M_\odot$ NS-NS merger model during the dynamical phase as a function of $Y_e$ at density $\rho_{\mathrm{net}}$ without any weak interaction of free nucleons and for five different values of the antineutrino luminosity. For these 5 cases, $L_{\nu_e} = 0.6\ 10^{53}$ erg/s, $\langle E_{\nu_e}\rangle = 12$ MeV and $\langle E_{\bar{\nu}_e}\rangle = 16$ MeV. Also given is each panel is the approximated value of $Y_e^\infty$ as given by Eq. 2. See Ref. [14] for more details.

It should be mentioned that our assumption of time-independent (anti)neutrino luminosities can be questioned, since the neutrino-ejecta interaction is a highly time-dependent problem, where the

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[1]Note that the $L_{\bar{\nu}_e} = 1.3\ 10^{53}$ erg/s case corresponds to Case 1 of Ref. [14], but differ in the nucleosynthesis predictions with the published version. This is due to a bug found in the nucleosynthesis code that has now been corrected and only affects Fig. 7 of Ref. [14].
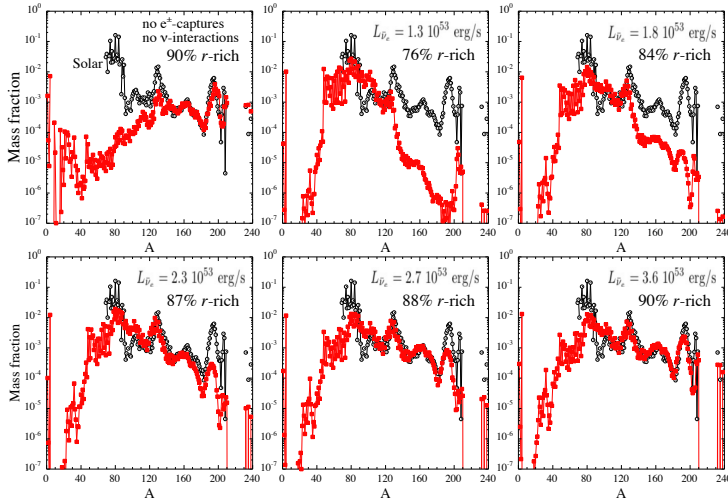
**Figure 3.** Impact of the neutrino interactions on the abundance distribution after ejection for the same 1.35-$1.35M_\odot$ NS merger model as in Fig. 2. The upper left panel is obtained without any weak interaction of free nucleons, the others for five different values of the antineutrino luminosity $L_{\bar{\nu}_e}$, together with $L_{\nu_e} = 0.6 \; 10^{53}$ erg/s, $\langle E_{\nu_e} \rangle = 12$ MeV and $\langle E_{\bar{\nu}_e} \rangle = 16$ MeV. Each panel is labelled by the mass fraction of $A > 69$ $r$-nuclei in the ejected material. See Ref. [14] for more details.

relative time between the growth of the neutrino emission and the mass ejection matters. However, this simple approximation is sufficiently good to demonstrate the impact of neutrino processes on the time evolution and mass distribution of the electron fraction and the corresponding consequences for the $r$-process. A predictive assessment of neutrino effects on the nucleosynthesis in merger ejecta would also have to take into account variations of the neutrino emission with different directions. Matter expelled towards the polar directions is exposed to different neutrino conditions than matter that leaves the system along equatorial trajectories.

## 3 Nuclear Physics

R-process nucleosynthesis calculations require a reaction network including about 5000 species from protons up to $Z \gtrsim 110$ lying between the valley of $\beta$-stability and the neutron drip line. All charged-particle fusion reactions on light and medium-mass elements that play a role when the nuclear statistical equilibrium freezes out need to be included in addition to radiative neutron captures and photodisintegrations. On top of these reactions, $\beta$-decays as well as $\beta$-delayed neutron emission probabilities and $\alpha$-decay rates need to be taken into account, but also fission processes, including neutron-induced, spontaneous, $\beta$-delayed and photofission, together with the corresponding fission fragment distribution for all fissioning nuclei. All rates are based on experimental information whenever available, but since only a extremely small amount of data are known experimentally, theoretical models are fundamental in providing the various predictions.

For such applications, the necessary ingredients (properties of cold and hot nuclei, nuclear level densities, optical potentials, $\gamma$-ray strength functions, fission properties, $\beta$-strength functions) should ideally be derived from *global*, *universal* and *microscopic* models. The large number of nuclides involved in the modelling of some nucleosynthesis mechanisms demands the use of global models.

On the other hand, a universal description of all nuclear properties within a unique framework for all nuclei involved ensures the essential coherence of the predictions of all unknown data. Finally, a microscopic description provided by a physically sound theory based on first principles ensures extrapolations away from experimentally known energy or mass regions that are likely to be more reliable than predictions derived from more or less parametrized approaches of various types and levels of sophistication. Nowadays, microscopic models can be tuned to the same level of accuracy as the phenomenological models, and therefore could replace them in practical applications.

Today, due to our ignorance on the exact conditions in which the *r*-process takes place, it remains difficult to estimate the precision with which the various relevant rates need to be estimated. In particular, it strongly depends if an (n,$\gamma$)-($\gamma$,n) equilibrium would be reached during the neutron irradiation or if, instead, a competition between neutron captures and $\beta$-decays would be responsible for the nuclear flow and final shaping of the r-abundance distribution. Much more work on the astrophysical modelling [2] is needed before providing such constraints that could shed light on the precision required from nuclear physics. In the meantime, a first educated guess would require the reaction rates to be estimated within a factor of 2 and $\beta$-decay rates within 50% for all nuclei that may be direct progenitors of r-nuclei, *i.e.* before the final $\beta$-decay cascade at the neutron freeze-out. Concerning the more exotic nuclei up to the neutron drip-line, depending if fission efficiently recycles material, *i.e.* depending on the number of neutrons per seed available, less stringent constraints could be envisioned. It also remains of first importance to estimate the statistical as well as systematic uncertainties affecting the predictions far away from the experimentally known region. Such a difficult task has been started regarding mass predictions [17], but remains to be performed for the reaction as well as $\beta$-decay rates. Our capacity to predict the fundamental nuclear ingredients for reaction models, namely nuclear masses, optical potentials, $\gamma$-ray strength functions, nuclear level densities, fission barriers, as well as the predictive power of the reaction and $\beta$-decay models are discussed in Ref. [17].

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