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The r-process nucleosynthesis and related challenges

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Summary. — 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 as well as 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 β-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 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. 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, and recently confirmed observationally as a potential site for the r-process nucleosynthesis, 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]. 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]. The ejected mass of r-process material, combined with the predicted astrophysical event rate (around $10\,\mathrm{Myr}^{-1}$ in the Milky Way [7]) can account for the majority of r-material in our Galaxy [8]. Recent studies (see e.g. Ref. [9]) 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 conclude that double compact star mergers may be the major production sites of r-process elements. The recent observation of the kilonova GW170817 presents the first clear evidence regarding the significant contribution of binary NS mergers in the r-process enrichment of the Galaxy [10].

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 [11, 12] found that neutrino reaction can significantly affect the electron fraction in the dynamical ejecta of systems with delayed collapse of the merger remnant.

The accurate inclusion of neutrino interactions in hydrodynamical simulations remains a highly complex task. For this reason, we conducted a simple parametric study [13] in order to quantify the potential impact of weak interactions on the electron-fraction evo-

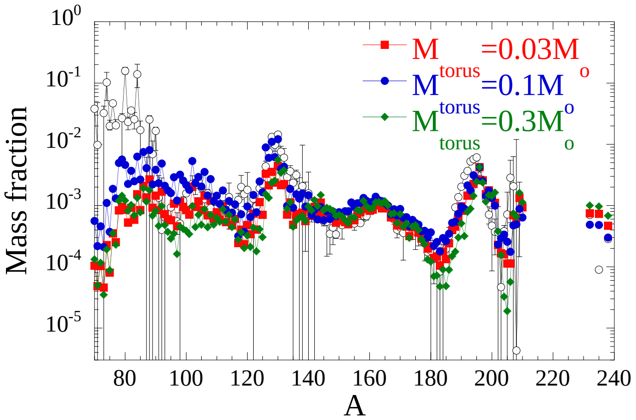

Fig. 1. – Abundance distribution as functions of the atomic mass A for three combined systems (merger model plus remnant model) corresponding to models with torus masses $M_{\rm torus} = 0.03, 0.1$ and $0.3 M_\odot$. All distributions are normalized to the $A = 196$ r-abundance in the Solar System (dotted circles). See Ref. [5] for more details.

lution 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. The major effect of the neutrino interactions on free n and p is to increase the electron fraction Y_e that consequently may affect the efficiency of the r-process nucleosynthesis. For a given representative neutrino luminosity and angle-averaged mean energies [11, 14], 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, and various values of the antineutrino luminosity, we show in Fig. 2 the impact of weak interactions on nucleosynthesis. The larger the antineutrino luminosity, the more efficient the r-process nucleosynthesis. For $L_{\bar\nu_e} \gtrsim 3\ 10^{53}$ erg/s (*i.e.* about 5 times the neutrino luminosity), Y_e^∞ 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}).

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 β-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, β-decays as well as β-delayed neutron emission probabilities and α-decay rates need to be taken into account, but also fission processes, including neutron-induced,

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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. [13], 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. [13].

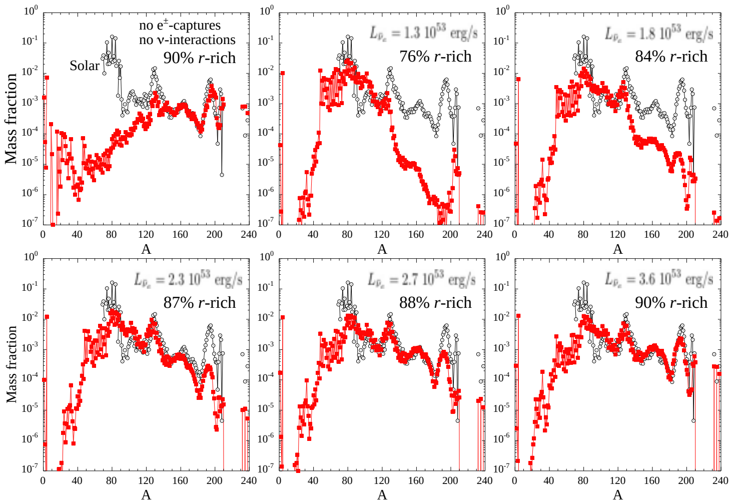

Fig. 2. – Impact of the neutrino interactions on the abundance distribution after ejection for the 1.35–1.35$M_\odot$ NS-NS merger model during the dynamical phase. The upper left panel is obtained without any weak interaction of free nucleons, the others for five different values of the antineutrino 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. [13] for more details.

spontaneous, β-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.

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 determined. In particular, it strongly depends if an (n,γ)-(γ,n) equilibrium would be reached during the neutron irradiation or if, instead, a competition between neutron captures and β-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 β-decay rates within 50% for all nuclei that may be direct progenitors of r-nuclei, *i.e.* before the final β-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 β-decay rates. Our capacity to predict the fundamental nuclear ingredients for reaction models, namely nuclear masses, optical potentials, γ-ray strength functions, nuclear level densities, fission barriers, as well as the predictive power of the reaction and β-decay models are discussed in Ref. [17]. An example is illustrated in Fig. 3 where

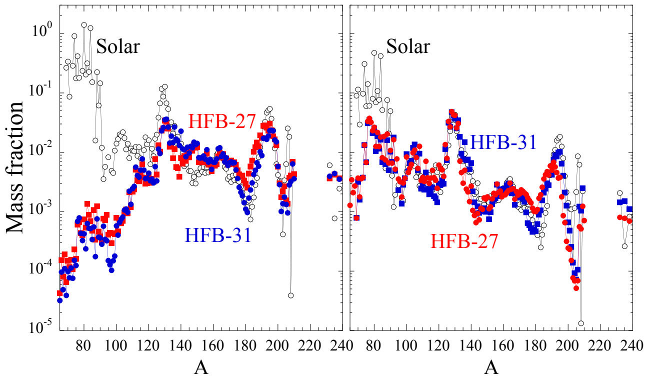

Fig. 3. – Mass fraction as functions of the atomic mass A for the dynamical (left panel) and disk ejecta (right panel) obtained with HFB-27 (red squares) [15] and HFB-31 (blue circles) [16] mass models in the calculation of the reaction rates. The Solar System mass fractions (dotted circles) are arbitrarily normalized. See Ref. [5] for more details.

the composition of the dynamical and disk ejecta are compared when making use of two different HFB mass models [15, 16].

In turn, the radiative neutron capture rates for nuclei of astrophysical interest are commonly calculated on the basis of the statistical Hauser-Feshbach (HF) reaction model, leading to smooth and monotonically varying temperature-dependent Maxwellian-averaged cross sections. The HF approximation is known to be valid if the number of resonances in the compound system is relatively high. However, such a condition is hardly fulfilled for keV neutrons captured on light or exotic neutron-rich nuclei. In this case, the neutron capture rates also needs to include the direct capture contribution [18] and an explicit account of the resolved resonance region [19]. Such contributions have been neglected up to now in r-process calculations. Much research work remains to be performed in this area.

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