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The production of transuranium elements by the r-process nucleosynthesis

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Abstract

The production of super-heavy transuranium elements by stellar nucleosynthesis processes remains an open question. The most promising process that could potentially give rise to the formation of such elements is the so-called rapid neutron-capture process, or r-process, known to be at the origin of approximately half of the $A > 60$ stable nuclei observed in nature. However, despite important efforts, the astrophysical site of the r-process remains unidentified. Here, we study the r-process nucleosynthesis in material that is dynamically ejected by tidal and pressure forces during the merging of binary neutron stars. Neutron star mergers could potentially be the dominant r-process site in the Galaxy, but also due to the extreme neutron richness found in such environment, could potentially synthesise super-heavy elements. R-process nucleosynthesis during the decompression is known to be largely insensitive to the detailed astrophysical conditions because of efficient fission recycling, producing a composition that closely follows the solar r-abundance distribution for nuclei with mass numbers $A > 140$. During the neutron irradiation, nuclei up to charge numbers $Z \simeq 110$ and mass number $A \simeq 340$ are produced, with a major peak production at the $N = 184$ shell closure, i.e. around $A \simeq 280$. Super-heavy nuclei with $Z > 110$ can hardly be produced due to the efficient fission taking place along those isotopic chains. Long-lived transuranium nuclei are inevitably produced by the r-process. The predictions concerning the production of transuranium nuclei remain however very sensitive to the predictions of fission barrier heights for such super-heavy nuclei. More nuclear predictions within different microscopic approaches are needed.

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1. Introduction

The r-process, or the rapid neutron-capture process, of stellar nucleosynthesis is 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. [1]). 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 give rise 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. However, until now a successful r-process cannot be 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]. So far, only modest r-processing has been found in the best case scenarios [2], so that the production of the lightest $A \lesssim 90$ r-process nuclei can possibly be envisioned, but at the present time, not the heavier species, and definitely not the transuranium nuclei. Only magneto-rotational supernova explosions with strong pre-collapse magnetic fields and fast rotation seem to provide favourable conditions for strong r-processing [4–6]. Although the supernova scenario remains promising, especially in view of their potential to significantly contribute to the galactic enrichment [7], they remain handicapped by large uncertainties associated mainly with the still incompletely understood mechanism that is responsible for the supernova explosion and the persistent difficulties to obtain suitable r-process conditions in self-consistent dynamical explosion and neutron-star cooling models [3,8,9]. In addition, predictions of the detailed composition of the ejected matter remain difficult due to the remarkable sensitivity of r-process nucleosynthesis to uncertainties of the ejecta properties [1].

Early in the development of the theory of nucleosynthesis, an alternative to the r-process in high-temperature supernova environments was proposed [10]. It relies on the fact that at high densities (typically $\rho > 10^{10}\ \mathrm{g/cm^3}$) matter tends to be composed of nuclei lying on the neutron-rich side of the valley of nuclear stability as a result of endothermic free-electron captures. The astrophysical plausibility of this scenario in accounting for the production of the r-nuclides has long been questioned. It remained largely unexplored until the study of the decompression of cold neutronised matter resulting from tidal effects of a black hole (BH) on a neutron star (NS) companion [11,12] or from the coalescence of two binary NS [13].

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}–$10^{-2} M_\odot$, can be ejected [14–24]. In contrast to the supernova site, investigations with growing sophistication have confirmed NS merger ejecta as a viable site for strong r-processing [1,18–20,22,25–30]. In particular, recent nucleosynthesis calculations [22] show that the combined contribution of both the dynamical (prompt) ejecta expelled during the binary NS–NS or NS–BH merger, as well as 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