The r-process nucleosynthesis: a continued challenge for nuclear physics and astrophysics

S. Goriely[a] *, P. Demetriou[a], H.-T. Janka[b] J.M. Pearson[c], and M. Samyn[a]

[a]Institut d'Astronomie et d'Astrophysique, ULB, CP 226, B-1050 Brussels, Belgium

[b]Max-Planck-Institut für Astrophysik, Postfach 1317, 85741 Garching, Germany

[c]Dépt. de Physique, Université de Montréal, Montréal (Qc) H3C 3J7, Canada

The identification of the astrophysical site and the specific conditions in which r-process nucleosynthesis takes place remain unsolved mysteries of astrophysics. The present paper emphasizes some important future challenges faced by nuclear physics in this problem, particularly in the determination of the radiative neutron capture rates by exotic nuclei close to the neutron drip line and the fission probabilities of heavy neutron-rich nuclei. These quantities are particularly relevant to determine the composition of the matter resulting from the decompression of initially cold neutron star matter. New detailed r-process calculations are performed and the final composition of ejected inner and outer neutron star crust material is estimated. We discuss the impact of the many uncertainties in the astrophysics and nuclear physics on the final composition of the ejected matter. The similarity between the predicted and the solar abundance pattern for $A \geq 140$ nuclei as well as the robustness of the prediction with varied input parameters makes this scenario one of the most promising that deserves further exploration.

1. Introduction

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. In recent years nuclear astrophysicists have developed more and more sophisticated r-process models, eagerly trying to add new astrophysical or nuclear physics ingredients to explain the solar system composition in a satisfactory way. 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 discovering astrophysical environments 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 model. However, until now no r-process can be simulated

*S.G. is FNRS research associate.

ab initio without having to call for an arbitrary modification of the model parameters, leading quite often to physically unrealistic scenarios.

On top of the astrophysics uncertainties, the nuclear physics of relevance for the r-process is far from being under control. The nuclear properties of thousands of nuclei located between the valley of β-stability and the neutron drip line are required. These include the (n, γ) and (γ, n) rates, α- and β-decay half-lives, rates of β-delayed single and multiple neutron emission, and the probabilities of neutron-induced, spontaneous, and β-delayed fission. When considering more complex astrophysics sites like the neutrino-driven wind, proton-, α-, and neutrino-capture rates need to be estimated, too.

New developments of both nuclear physics and astrophysics aspects of the r-process are discussed in this paper. Section 2 is devoted to the estimate of the neutron-capture rates and the fission probabilities by exotic neutron-rich nuclei. These properties are of particular relevance for determining the still poorly-known composition that results from the decompression of neutron-star (NS) crust matter, as shown in Sect. 3.

2. Neutron capture and fission by exotic n-rich nuclei

Although a great effort has been devoted in recent years to measuring decay half-lives and reaction cross sections, the r-process involves so many (thousands) unstable exotic nuclei for which so many different properties need to be known that only theoretical predictions can fill the gaps. To fulfill these specific requirements, two major features of nuclear theory must be contemplated, namely its *microscopic* and *universal* aspect. A microscopic description by a physically sound model based on first principles ensures a reliable extrapolation away from the experimentally known region. On the other hand, a universal description of all nuclear properties within one unique framework for all nuclei involved ensures a coherent prediction of all unknown data. A special effort has been made recently to derive all the nuclear ingredients of relevance in reaction theory from microscopic models [1]. It mainly concerns nuclear masses from a Hartree-Fock-Bogolyubov (HFB) model [2], nuclear level densities within the statistical model based on the microscopic HF pairing strength and single-particle scheme [3], γ-ray strength functions from the HFB+QRPA approach [4] and optical-model potentials from the Brueckner-HF approximation [5]. Microscopic estimates can lead to significant differences in comparison with more phenomenological approaches. These and their impact on the radiative neutron capture rate derived within the Hauser-Feshbach statistical model are discussed in detail in [1,6] and are not repeated here.

So far, all r-process calculations have made use of neutron capture rates evaluated within the Hauser-Feshbach statistical model. Such a model makes the fundamental assumption that the capture process takes place through the intermediary formation of a compound nucleus (CN) in thermodynamic equilibrium. The formation of a compound nucleus is usually justified if the level density in the compound nucleus at the projectile incident energy is large enough. However, when dealing with exotic neutron-rich nuclei, the number of available states in the compound system is relatively small and the validity of the Hauser-Feshbach model has to be questioned. In this case, the neutron capture process might be dominated by direct electromagnetic transitions to a bound final state rather than through the formation of a compound nucleus. Direct captures (DC) are known to play an important role for light or closed shell systems for which no resonant states are available. The direct neutron capture rates have been re-estimated for exotic neutron-rich nuclei as in [7] using a modified version of the potential model to avoid the uncertainties affecting the single-particle approach based on the one-neutron particle-hole configuration [7]. It expresses the neutron DC cross section at an energy E as

$$\sigma^{DC}(E) = \sum_{f=0}^{x} C_f^2 S_f \sigma_f^{DC}(E) + \int_{E_x}^{S_n} \sum_{J_f,\pi_f} \langle C^2 S\rangle \rho(E_f, J_f, \pi_f) \sigma_f^{DC}(E) dE_f \qquad (1)$$

where x corresponds to the last experimentally known level (in the final nucleus f) of excitation energy E_x (smaller than the neutron binding energy S_n). Above E_x, the summation is replaced by a continuous integration over the spin (J)- and parity (π)-dependent level density ρ, and the spectroscopic factor S and isospin Clebsch-Gordan coefficient C^2 by an average quantity $\langle C^2 S\rangle$. The DC cross section σ_f^{DC} to each final state is calculated within the potential model [7] in which the wave functions of the initial and final systems are determined by solving the respective Schrödinger equations. Because of the crucial sensitivity of the DC cross section to the spin and parity assignment of the low-energy states in the residual nucleus, only a microscopic combinatorial model of level density is appropriate to the DC calculation. New global calculations within the combinatorial method using the HFB single-particle level scheme and δ-pairing force are now available [8] and provide an accurate and reliable estimate of the intrinsic spin- and parity-dependent level density. The average spectroscopic factor remains very difficult to estimate. Experimental systematics suggest in a first approximation an energy-independent value $\langle C^2 S\rangle \simeq 0.06$ at energies lower than S_n [7]. More details on the sensitivity of the predicted DC rates to the uncertainties affecting the nucleus-nucleon potential and the spectroscopic factor can be found in [7]. The resulting DC rates are compared in Fig. 1 with the CN rates for all the nuclei involved in the r-process nucleosynthesis. Interestingly, the DC becomes larger than the CN contribution for many neutron drip nuclei. The lower limit imposed on the DC/CN ratio (Fig. 1) indicates that for some nuclei with low S_n the DC rates can become negligible, the selection rule forbidding the $E1$ or $E2$ transitions to any of the available levels. Both the DC and CN mechanisms may contribute to the radiative capture of a neutron. For this reason, the total capture rate is often taken as the simple sum of both contributions, neglecting all possible interferences. The statistical treatment inherent to the Hauser-Feshbach model might however overestimate the resonant capture for the most exotic nuclei. The damping procedure described in [7] is used here for the r-process calculations described in Sect. 3.

Another major difficulty in the nuclear modelling of the r-process concerns the probabilities of the various fission processes, i.e., of spontaneous, β-delayed, and neutron-induced fission. Most of the r-process calculations either do not take into account fission processes at all or only partially. HFB calculations are presently in progress to improve the predictions of fission barriers [9]. In the meantime, we have used the large-scale calculation of ETFSI fission barriers [10] to re-estimate the fission probabilities. Spontaneous and neutron-induced fission rates are determined within the Hill-Wheeler and Hauser-Feshbach models, respectively, as described in [11]. β-delayed fission rates are estimated considering the gross-theory β-strength function [12]. Fig. 2 shows the nuclear regions where the different fission modes influence the r-process flows. Because of the strong ETFSI

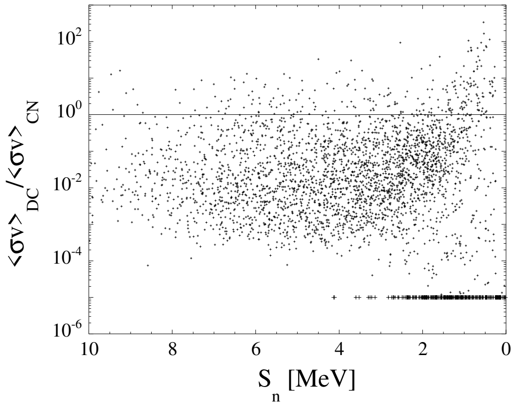

Figure 1. Comparison of the DC and CN (n, γ) rates for all nuclei with $20 \leq Z \leq 92$ located between the valley of stability and the neutron-drip line. A lower limit of 10^{-5} is imposed.

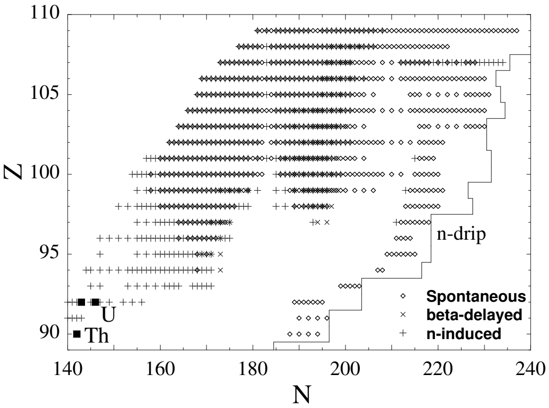

Figure 2. Circles and crosses (x) represent nuclei with a timescale against spontaneous and β-delayed fission smaller than 1s, the (+) those with a n-induced fission rate larger than the radiative capture.

shell effect on the fission barriers of neutron-rich nuclei around $N = 184$, no fission recycling is expected before crossing the $N = 184$ closure. Spontaneous fission can affect the r-process nuclear flow quite substantially even close to the neutron drip line. β-delayed fission is of small importance compared with the other decaying modes. Obviously, all the above conclusions should be taken with care, because of the uncertainties remaining in the determination of the fission barriers and fission probabilities. Future studies are needed, particularly in view of the importance of the fission processes at specific r-process conditions, as described in Sect. 3.

3. Decompression of initially cold NS matter

The origin of the r-process nuclei is still a mystery. One of the underlying difficulties is that the astrophysical site (and consequently the astrophysical conditions) in which the r-process takes place has not been identified. Many scenarios have been proposed. The most favoured sites are all linked to core-collapse supernova or gamma-ray burst explosions. Mass ejection in the so-called neutrino-driven wind from a nascent NS or in the prompt explosion of a supernova in case of a small iron core or an O-Ne-Mg core have been shown to give rise to a successful r-process provided the conditions in the ejecta are favorable with respect to high wind entropies, short expansion timescales or low electron number fractions. Although these scenarios remain promising, especially in view of their significant contribution to the galactic enrichment [13], 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 models. In addition, the composition of the ejected matter remains difficult to ascertain due to the remarkable sensitivity of r-process nucleosynthesis to the uncertain properties of the ejecta.

Another candidate site has been proposed as possibly contributing to the galactic enrichment in r-nuclei. It concerns the decompression of initially cold NS matter [14–16]. In particular, special attention has been paid to NS mergers due to their large neutron densities and the confirmation by hydrodynamic simulations that a non-negligible amount of matter can be ejected [17,18]. Recent calculations of the galactic chemical evolution [13], however, tend to rule out NS mergers as the dominant r-process site for two major reasons. First, their relatively long life times and in particular low rates of occurrence would lead to a sudden and late r-process enrichment that is not compatible with the observed r-process enrichment of ultra-metal-poor stars. Second, the significant mass of r-process material ejected by each event should lead to a large scatter of r-element overabundance in solar-like metallicity stars; this scatter is not confirmed observationally. However, this conclusion requires assumptions about the efficiency of mixing in the interstellar medium and is based on uncertain results from numerical models for the total amount of mass that is ejected by a single event. Moreover, it involves speculations about the NS-NS merger rate some 10 Gyr ago. Another uncertainty comes from the disregard of NS–black hole mergers that have been estimated to be about 10 times more frequent than their NS-NS counterparts, although the possibility of mass ejection is still unclear because of the unknown state of supranuclear matter in the NS [17,18]. But the ejection of initially cold, decompressed NS matter might also happen in astrophysical scenarios like the explosion of a NS below its minimum mass [19] or in the spin-down phase of very rapidly rotating supramassive or ultramassive NSs, which could lead to the equatorial shedding of material with high angular momentum. The present study aims at providing a first consistent calculation of the nucleosynthetic composition of dynamically ejected material from cold NSs. If the calculated abundances in the ejected matter turned out not to be in agreement with solar-like r-abundances, this would tend to confirm the growing opinion that the mergers of compact objects are unlikely to be important contributors to the galactic r-enrichment. A study of this kind is therefore of interest, filling a unfortunate gap in the existing literature. In fact, little effort has so far been devoted to determining the composition of the matter that undergoes the decompression from initially cold NS crust conditions. The first detailed calculation was performed by Meyer [15] in a systematic parametric study, but only included the decompression down to densities around the neutron drip density $\rho_{\mathrm{drip}} \simeq 3\ 10^{11}\mathrm{g/cm}^3$. A second study came from [16] but considered the decompression below the drip density only. In this latter study, the composition of the initial material was assumed to result from nuclear statistical equilibrium at high temperatures ($T_9 \simeq 6$), and its neutron-to-proton ratio was taken as a free parameter. It is not plausible that such high temperatures can be reached in unshocked NS crust material that gets dynamically stripped from the NS surfaces during a merger and subsequently expands very quickly. For this reason, we have performed new calculations to determine the final composition of clumps of initially cold NS inner and outer crust material after decompression with a detailed treatment of the microphysics and thermodynamics during the decompression. All details can be found in [20]. The evolution of the matter density is modeled by considering the pressure-driven expansion of a self-gravitating clump of NS matter under the influence of tidal forces on an escape trajectory. We characterize the expansion by defining the expansion timescale τ_{exp} as the time needed for the initial density to drop by three orders of magnitude.

As far as the outer crust is concerned, i.e., the NS material initially at a density below $\rho_{\rm drip}$, the final isobaric abundance distribution after decompression is essentially identical to the one prior to the ejection. Only β-decay (including β-delayed neutron emission) can change the initial composition. We have redone the calculation of [21] with updated nuclear physics data to estimate the outer crust composition. This calculation assumes the matter to be in complete thermodynamic equilibrium and minimizes the free Gibbs energy per cell to estimate the zero temperature composition. The energy of the body-centered cubic lattice and relativistic electrons is included. For densities above $3\ 10^9$g/cm^3, the matter is essentially made of $N = 50$ and $N = 82$ r-process nuclei. More precisely, we find for $10^9 \le \rho[\text{g/cm}^3] \le 6\ 10^{10}$, $N = 50$ nuclei with $80 \le A \le 86$. At these densities, experimental masses are available, so that this result is free from theoretical uncertainties. This is not the case at larger densities where we use the HFB-9 mass table [2] to complement the compilation of experimental masses. For $6\ 10^{10} \le \rho[\text{g/cm}^3] \le 3\ 11^{10}$, $N = 82$ nuclei with $120 \le A \le 128$ populate the outer crust and should therefore enrich the interstellar medium after ejection. The neutron emission by β-delayed processes as well as the temperature effects on the energy distribution should spread the matter over a wider mass range than the one originally found in the crust.

Regarding the inner crust, i.e initial densities $\rho > \rho_{drip}$, the situation is quite different due to the existence of the neutron sea in which the nuclei are immersed. The initial matter is assumed to be in β-equilibrium prior to the expansion. This equilibrium is estimated on the basis of a Thomas-Fermi equation of state (EOS) [22] with the BSk9 Skyrme force used to build the HFB-9 mass table [2]. This leads at an initial density $\rho \simeq 10^{14}$g/cm^3 to a composition characterized by the electron fraction $Y_e = 0.03$ corresponding to a cell made of a $Z = 39$ and $N = 157$ nucleus. The expansion is followed down to the neutron drip density as described in [15], allowing for the co-existence of Wigner-Seitz cells with different proton numbers obtained through β-transitions. β-decays are estimated according to [14] and found to heat the matter as soon as $\mu_n - \mu_p - \mu_e > 0$. When the matter reaches the neutron drip line, it is distributed over a relatively large range of elements with $Z = 40 - 70$, at least if relatively fast β-transition probabilities and slow expansion timescales are adopted (see [20] for more details).

At the time the neutron drip density is reached, the matter is composed of drip nuclei and of free neutrons at a typical density of $N_n \simeq 10^{35}$ cm^{-3}. The expansion is followed by a more "traditional" r-process reaction network including the full description of radiative neutron captures, photodisintegrations, β-decays, β-delayed neutron emissions as well as neutron-induced, β-delayed and spontaneous fission processes. The rates for the 5000 nuclei involved are taken from the microscopic calculations described in Sect. 2. The temperature increase is obtained with the adequate EOS of [23], the nuclear energy being supplied by the β-decays and fission reactions. In Fig. 3, the time evolution of the temperature as well as the neutron mass fraction X_n and average mass number of heavy nuclei $\langle A \rangle$ is illustrated for a clump of material with initial density $\rho = 10^{14}$g/cm^3, expanding on a timescale of $\tau_{\rm exp} = 6.5$ ms. The temperature does not exceed $T_9 \approx 0.8$ and for such an expansion timescale all neutrons are captured. Fission processes are found to recycle material leading to the oscillations of $\langle A \rangle$ shown in Fig. 3. The final abundance distribution obtained for such conditions is displayed in Fig. 4. The abundance distribution obtained for $A > 140$ is in relatively good agreement with the solar pattern. In

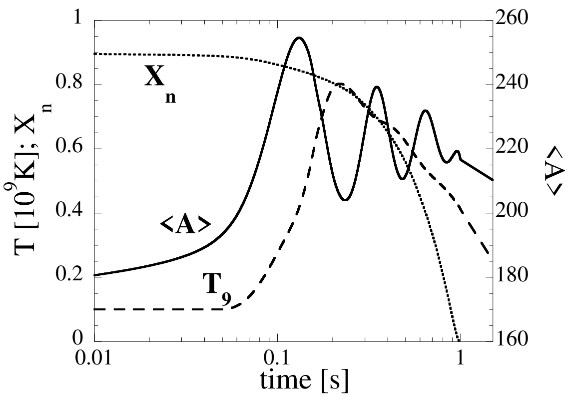

Figure 3. Evolution of the temperature, $\langle A \rangle$ and X_n for a clump of material with initial density $\rho = 10^{14}\mathrm{g/cm^3}$, expanding with $\tau_{\rm exp} = 6.5$ ms.

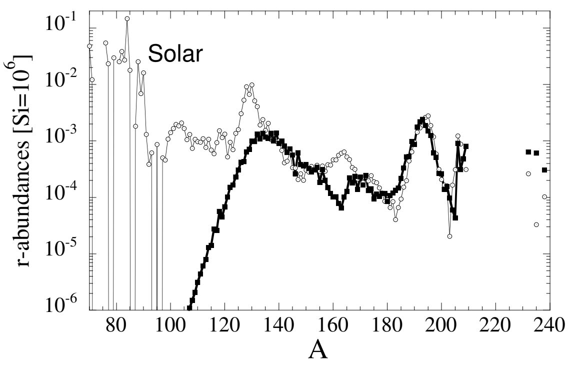

Figure 4. Final r-abundance distribution for the same clump of material as in Fig. 3. The solar system distribution is also shown.

particular the $A = 195$ peak is found at the right place with the right width. It should, however, be stressed that such an r-abundance distribution results from a sequence of nuclear mechanisms that significantly differ from those traditionally invoked to explain the solar r-abundances, namely the establishment of an $(n,\gamma)-(\gamma,n)$ equilibrium followed by the β-decay of the corresponding waiting point. In the present scenario, the neutron density is initially so high that the nuclear flow follows for the first hundreds of ms after reaching the drip density a path touching the neutron drip line. Fission keeps on recycling the material. After a few hundreds of ms, the density has dropped by a few orders of magnitude and the neutron density experiences a dramatic fall-off when neutrons get exhausted by captures (see Fig. 3). During this period of time, the nuclear flow around the $N = 126$ region follows the isotonic chain. When the neutron density reaches some $N_n = 10^{20}$ cm^{-3}, the timescale of neutron capture for the most abundant $N = 126$ nuclei becomes larger than a few seconds, and the nuclear flow is dominated by β-decays back to the stability line.

In this scenario, photodisintegration reactions do not play any major role. An almost identical abundance distribution is obtained when the temperature is kept at a constant value of $T_9 = 0.1$. The distribution shown in Fig. 4 is found to be robust to most of the nuclear uncertainties affecting masses, reaction rates and β-decay rates. The fission fragment distribution adopted mainly affects the abundance of the $A < 140$ nuclei. The most sensitive parameter appears to be the expansion timescale. As long as the expansion is relatively slow, all neutrons are captured and the freeze-out takes place at densities around $N_n = 10^{20}$ cm^{-3} leading systematically to an abundance distribution similar to the one shown in Fig. 4. In contrast, for fast expansions, i.e for $\tau_{\rm exp} < 3$ ms in the case of a clump at an initial density of $10^{14}\mathrm{g/cm^3}$, not all free neutrons are captured, and the neutron density falls proportional to the density. In this case, the final distribution becomes sensitive to the expansion timescale and can differ significantly from the solar pattern. More details are given in [20].

4. Conclusion

Most of the problems faced in r-process nucleosynthesis are related to our ignorance of the astrophysical site that is capable of providing the required large neutron flux. In this respect, understanding the r-process nucleosynthesis is essentially an astrophysics issue that will require improved hydrodynamic models to shed light on possible scenarios. Different sites have been proposed, the currently most favoured ones being related to neutrino-driven outflow during supernova or γ-ray burst explosions. Nevertheless, we have shown here that the decompression of initially cold NS matter is also extremely promising. In particular, it provides suitable conditions for a robust r-processing. The resulting r-abundance distribution is very similar to the solar one, at least for $A > 140$ nuclei. The underlying nuclear mechanisms, however, differ significantly from those acting in previous scenarios, in particular photoreactions do not play a major role. The similarity between the predicted and solar abundance patterns as well as the robustness of the prediction against variations of input parameters make this site one of the most promising that deserves further exploration with respect to various aspects such as nucleosynthesis, hydrodynamics and galactic chemical evolution. From the nuclear point of view, this site also represents a new challenge, since it will be necessary to determine β-decay, neutron-capture and fission rates for nuclei which, in contrast to the more conventional sites, are situated right at the neutron drip line.

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