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Review

# What are the astrophysical sites for the *r*-process and the production of heavy elements?

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ABSTRACT

This article addresses three of the four nucleosynthesis processes involved in producing heavy nuclei beyond Fe (with a main focus on the *r*-process). Opposite to the fourth process (the *s*-process), which operates in stellar evolution during He- and C-burning, they are all related to explosive burning phases, (presumably) linked to core collapse supernova events of massive stars. The (classical) *p*-process is identified with explosive Ne/O-burning in outer zones of the progenitor star. It is initiated by the passage of the supernova shock wave and acts via photodisintegration reactions like a spallation process which produces neighboring (proton-rich) isotopes from pre-existing heavy nuclei. The reproduction of some of the so-called lighter *p*-isotopes with $A < 100$ faces problems in this environment. The only recently discovered $\nu p$-process is related to the innermost ejecta, the neutrino wind expelled from the hot proto-neutron star after core collapse and the supernova explosion. This neutrino wind is proton-rich in its early phase, producing nuclei up to $^{64}$Ge. Reactions with neutrinos permit to overcome decay/reaction bottlenecks for the flow beyond $^{64}$Ge, thus producing light *p*-isotopes, which face problems in the classical *p*-process scenario. The understanding of the *r*-process, being identified for a long time with rapid neutron captures and passing through nuclei far from stability, is still experiencing major problems. These are on the one hand related to nuclear uncertainties far from stability (masses, half-lives, fission barriers), affecting the process speed and abundance peaks. On the other hand the site is still not definitely located, yet. (i) Later, possibly neutron-rich, high entropy phases of the neutrino wind (if they materialize!) could permit its operation. (ii) Other options include the ejection of very neutron-rich neutron star-like matter, occurring possibly in neutron star mergers or core collapse supernova events with jets, related to prior stellar evolution with high rotation rates and magnetic fields. Two different environments are required for a weak and a main/strong *r*-process, witnessed by observations of low metallicity stars and meteoritic inclusions, which could possibly be identified with the two options listed above, i.e. the weak *r*-process could be related to the neutrino wind when changing from *p*-rich to *n*-rich conditions.



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## 1. Introduction

Two of the three processes discussed in this overview are classical in the sense that they have long been introduced by their abundance features. The *p*-process is easily defined by all isolated stable isotopes on the proton-rich side of stability with typically 1% of the total element abundance (except for $A < 100$). This process is identified by solar abundances features and the question remains if only one astrophysical site is responsible. The paradigm relates it to zones of explosive Ne/O burning in core collapse supernovae, acting on pre-existing heavy nuclei and making it a secondary process in terms of galactic evolution (this applies also to suggested type Ia supernova sites, acting on accreted matter which experienced He-shell flashes plus being delayed by binary evolution). The observational indications for a lighter element primary process [1] (LEPP) at low metallicities point towards a primary origin of the lighter *p*-isotopes, which would indicate a direct production closer to the supernova core.

The *r*-process has been identified by the double peak structure near closed neutron shells in solar heavy element abundances. When subtracting *s*-process abundances (quite well understood via neutron captures in stellar evolution and nuclear physics at and close to stability [2]), it emerges as a process with a path far on the neutron-rich side of stability, requiring explosive environments with large neutron to seed nuclei ratios. There exist major advances in the nuclear physics involved, while many open questions remain and will be related to future rare isotope beam facilities. Within the present nuclear physics uncertainties, possible astrophysical environment conditions have been identified, ranging from entropy superpositions of slightly neutron-rich matter to highly neutron-rich environments with fission cycling. The main problem seems the apparent (non-)realization in astrophysical simulations/models. Observations of low metallicity stars indicate also here the probable splitting in two types of events: (a) a rare event, reproducing the heavy *r*-process abundances always in solar proportions, and (b) a more frequent event, responsible for the lighter *r*-abundances [3,4].

The $\nu p$-process has only been discovered in recent years [5–7] and resulted from progress in core collapse supernova efforts. While it was previously expected that the innermost ejected layers, close to the freshly formed neutron star, are neutron-rich and just automatically the site of the *r*-process, the latter expectation has actually been tempered. This seemed mainly due to the fact that sufficiently high entropies could not be attained [8,9]. On the other hand, recent explosion calculations, with careful accounting of the interaction with neutrinos, led to slightly proton-rich conditions in the early phase of the neutrino wind [10]. This results in a proton and alpha-rich freeze-out producing nuclei up to $^{64}$Ge with a long beta-decay half-life. Anti-neutrino capture on the remaining protons creates neutrons and the reaction $^{64}\mathrm{Ge}(n,p)^{64}\mathrm{Se}$ mimics a fast beta-decay, permitting then to move upward to nuclei with masses $A < 100$. This $\nu p$-process is a primary process, could explain observational results promoting the LEPP and can also fill in light *p*-isotopes which encountered difficulties in the classical *p*-process picture [11]. The question is whether, as a function of elapsed time after the initiation of the explosion shock, the neutrino wind changes from proton-rich to neutron-rich, passing during this transition through conditions of a "weak" *r*-process and even attaining neutron/seed ratios for the working of the main *r*-process. Thus, both of the latter two discussed processes are really related to the supernova explosion mechanism itself, while the classical *p*-process requires only the existence of a supernova shock wave. In the following sections we will therefore proceed from the more simple to the more problematic cases in the sequence discussing first the *p*-process, then the $\nu p$-process and finally the *r*-process after a short overview on core collapse supernova simulations.

## 2. Core collapse supernova explosions

The problem of core collapse supernova explosions is an old one and the attempt to understand the mechanism has been ongoing for more than 40 years, linking it to massive stars and the collapse of the Fe-core after having passed all nuclear burning stages. Since the sixties the explosion mechanism has been related to neutrino emission from the hot collapsed core and accreted matter, interrupted by a period when it was speculated that the strength of the bounce at nuclear densities could permit shock waves with sufficient energies to lead to prompt explosions [12]. Recent progress has mostly been linked to multi-D investigations with standing accretion shock instabilities, rotation and magnetic fields, or effects of the equation of state [13–19] and a solution (in 3D) seems close [20]. However, a fundamental understanding and robust predictions are still missing. Related to the explosion is also the so-called neutrino wind, emitted for seconds after the successful shock wave generation [6,5] and considered initially also as a possible source of the *r*-process to produce the heaviest elements via neutron captures [21–23,8,9,24,25]. Neutrino emission, from the hot proto-neutron star and its time and spectral characteristics [10] are essential for the supernova mechanism and related nucleosynthesis and influence also neutrino nucleosynthesis in the outer mass zones [26].

Given this situation, at present the self-consistent prediction of supernova nucleosynthesis yields seems impossible. However, supernova nucleosynthesis has a long tradition [27–31,20,32]. The past predictions relied on an artificially introduced explosion, either via a piston or a thermal bomb. This leaves the mass cut between neutron star and ejecta and the explosion energy as a free parameter, guided by constraints on $^{56}$Ni ejecta and/or entropy jumps. While the approach of artificially introduced explosions makes sense and is fully correct for the outer stellar layers (see the section on the classical *p*-process), it clearly is incorrect for the innermost ejected layers which should be directly related to the physical processes causing the explosion. This affects the Fe-group composition and the $\nu p$- and *r*-process. Here we will make use of 1D approximations [5,33] and free parameter studies [34,35], based on input for nuclear reaction rates [36,37], weak interaction (electron capture) rates [38,39], beta-decay properties from experiment or QRPA predictions [40], beta-delayed or neutron-induced fission predictions [41–45], and neutrino-induced reactions [46,47].

The resulting nucleosynthesis ejecta have to be confronted with observations related to galactic chemical evolution. Cool low-mass stars have an evolution time comparable to the lifetime of the Galaxy, and, at the present epoch, we can observe both young and very old objects among them. The study of chemical abundances in cool stars allows to determine the history of chemical enrichment of galactic matter because their atmospheres preserve much of the chemical composition of the gas out of which the star formed. Core collapse supernovae dominated nucleosynthesis in the early Galaxy, before the onset of type Ia supernova explosions and the main *s*-process. Detailed spectral analysis of the most metal-poor stars can, therefore, provide insight into the synthesis of the first heavy elements [48,49,4,50]. Several studies [51,48,50,3] have presented arguments supporting constant relative ratios of *r*-process element abundances during the history of the Galaxy for the elements with $Z = 56$–70. This suggests that a unique *r*-process exists in nature, at least for heavy elements. The lighter *r*-process and possibly *p*-process elements, including also $\nu p$-process nuclei observed as part of the LEPP [1], might have a different (and more frequent) origin than the main/heavy (apparently unique) *r*-process component.

## 3. The *p*-process

A number of proton-rich (*p*-)isotopes of naturally occurring stable nuclei cannot be produced by neutron captures along the line of stability. The currently most favored production mechanism for those 32 *p*-isotopes between Se and Hg is photodisintegration ($\gamma$-process) of intermediate and heavy elements at high temperatures in late evolution stages of massive stars [52,53]. However, not all *p*-nuclides can be produced satisfactorily, yet. A well-known deficiency in the model is the underproduction of the Mo–Ru region, but the region $151 < A < 167$ is also underproduced, even in recent calculations [54–56,11]. There exist deficiencies in astrophysical modeling and the employed nuclear physics. Recent investigations have shown that there are still considerable uncertainties in the description of nuclear properties governing the relevant photodisintegration rates. This has triggered a number of experimental efforts to directly or indirectly determine reaction rates and nuclear properties for the $\gamma$-process [57]. Here it is important to investigate the sensitivity of the location of the $\gamma$-process path with respect to reaction rate uncertainties.

Concerning the astrophysical modeling, only a range of temperatures has to be considered which are related to the explosive Ne/O-burning zones of a supernova explosion, i.e. $2$–$3 \times 10^9$ K. The $\gamma$-process starts with the photodisintegration of stable seed nuclei that are present in the stellar plasma. During the photodisintegration period, neutron, proton, and alpha-emission channels compete with each other and with beta-decays further away from stability. In general, the process, acting like "spallation" of pre-existing nuclei commences with a sequence of $(\gamma, n)$-reactions, moves the abundances to the proton-rich side. At some point in a chain of isotopes, $(\gamma, p)$ and/or $(\gamma, \alpha)$-reactions become faster than neutron emissions, and the flow branches and feeds other isotopic chains. At late times photodisintegrations become less effective, when decreasing temperatures shift the branching points and make beta-decays more important. Finally the remaining unstable nuclei decay back to stability. The branchings established by the dominance of proton and/or $\alpha$-emission over neutron emission are crucial in determining the radioactive progenitors of the stable *p*-nuclei and depend on the ratios of the involved reaction rates. Numerous efforts have been undertaken to improve the reaction input, especially with respect to open questions in optical potentials for alpha particles and protons [58–62].

Applications of *p*-process network calculations to the temperature profiles of initiated explosions have been performed [63,56,11]. A recent study [11] with two reaction rate libraries accounting for all experimental improvements, noticed that the nuclear uncertainties cannot change the underproduction of especially the light *p*-nuclei. Another process is required for these missing abundances. Meteoritic constraints related to $^{92}$Nb, Mo seem to argue against a very proton-rich production process [64].

## 4. The $\nu p$-process

Neutron-deficient nuclei can be produced via fusion reactions in the r*p*-process in X-ray bursts [65] (which, however, does not eject matter into the interstellar medium) and the recently discovered $\nu p$-process in core collapse supernovae [5–7] (for further options see Section 5). The $\nu p$-process occurs in explosive environments when proton-rich matter is ejected under the influence of strong neutrino fluxes. This includes the inner ejecta of core collapse supernovae and possible ejecta from black hole accretion disks in the collapsar model of gamma-ray bursts [66]. The matter in these ejecta is heated to temperatures well above $10^{10}$ K and becomes fully dissociated into protons and neutrons. The ratio of protons to neutrons is mainly determined by neutrino and antineutrino absorptions on neutrons and protons, respectively. Similar neutrino and antineutrino energy spectra and fluxes produce proton-dominated matter due to the *n*–*p* mass difference. Free neutrons and protons combine during the expansion into $\alpha$-particles which assemble in two subsequent capture reactions via unstable intermediate nuclei like $^8$Be or $^9$Be to nuclei beyond C. Once this has occurred, fast reactions permit to reach Fe-group nuclei. Depending on the density/entropy and the expansion of matter, large fractions of alpha-particles remain unburned (alpha-rich freeze-out). In case of a proton-rich environment, free protons are still available at the time of the alpha freeze-out. Once the temperature drops to about $2 \times 10^9$ K, the composition consists mostly of $^4$He, protons, and Fe-group nuclei with $N \approx Z$ (mainly $^{56}$Ni, but also $^{64}$Ge – decaying to $^{64}$Zn – which is strongly underproduced for environments with $Y_e \leq 0.5$,

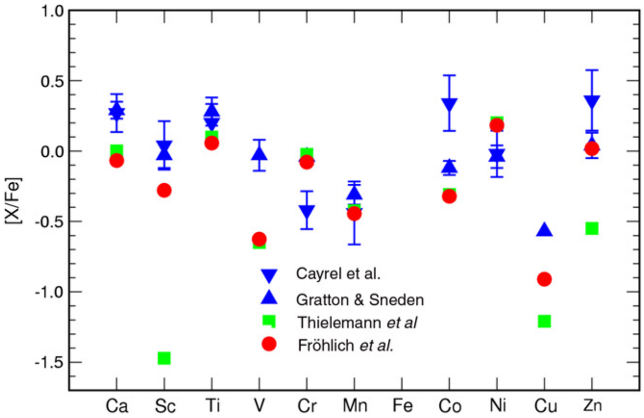


**Fig. 1.** The proton-rich environment in the innermost ejecta improves the composition of the Fe-group [67] of earlier studies neglecting the effect of neutrinos on the $Y_e$ of the innermost ejecta [27,28,32]. Higher entropies (hypernovae) can cause a similar effect for Zn, but require a large hypernova rate [31,68].

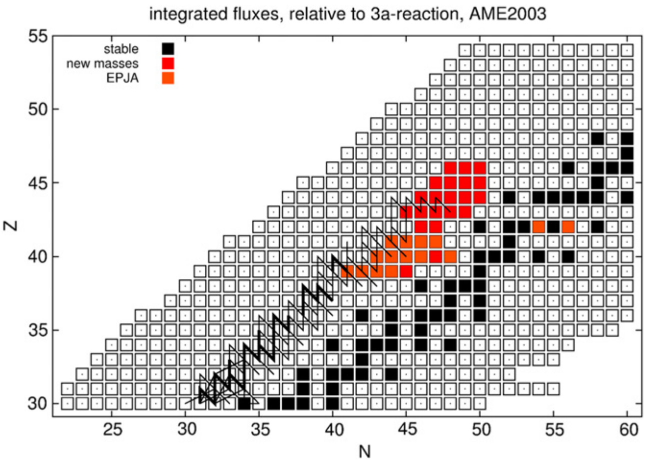


**Fig. 2.** $\nu p$-process path employing AME2003 [69] and latest mass maesurements [33]. This process can produce nuclei up to $A = 100$ and beyond, to an extent dependent on the early and late (anti-)neutrino flux.

Fig. 1). Without neutrinos, synthesis of nuclei beyond $^{64}$Ge becomes very inefficient, due to its long beta-decay half-life and small proton-capture cross section.

The large neutrino/antineutrino flux from the proto-neutron star causes negligible neutrino captures on the dominant neutron-deficient nuclei (due to energetics), but capture rates of antineutrinos – both on free protons and on heavy nuclei – with timescales of a few seconds. Due to the larger proton abundance, antineutrino captures occur predominantly on protons, leading to neutron densities of $10^{14}$–$10^{15}$ cm$^{-3}$ for several seconds. These neutrons are easily captured by heavy neutron-deficient nuclei, e.g. via $^{64}$Ge$(n, p)$, on time scales much shorter than the beta-decay half-life. This permits further proton captures and allows the nucleosynthesis flow to continue to heavier nuclei with $A > 90$ [5–7,70]. Recent calculations [33] with two sets of astrophysical reactions utilized [36], testing the sensitivity to mass uncertainties (AME2003 compilation [69] against latest mass measurements [33]), led to quite similar results, with minor differences for a few nuclei in the mass range $85 < A < 95$, namely $^{87,88}$Sr, $^{89}$Y, and $^{90,91}$Zr (Fig. 2). This can be directly traced back to the large change in the mass of $^{88}$Tc ($\Delta M = 1031$ keV). The total flow reaching $^{94}$Pd is very similar in both cases. These results show that the $\nu p$-process can easily produce light $p$-nuclei which are deficient in classical $p$-process calculations. The amount and further processing towards heavier nuclei depends on the neutron star mass, expansion (speed) of matter and the overlying mass/structure of ejecta, causing reverse shocks [71].

## 5. The weak and main *r*-process

A rapid neutron-capture process ($r$-process) in an explosive environment is traditionally believed to be responsible for the nucleosynthesis of about half of the heavy elements above Fe. While for a number of years now the high entropy (neutrino) wind (HEW) of core collapse supernovae has been considered to be one of the most promising sites, hydrodynamical simulations still encounter difficulties to reproduce the required conditions. This guided parameter studies

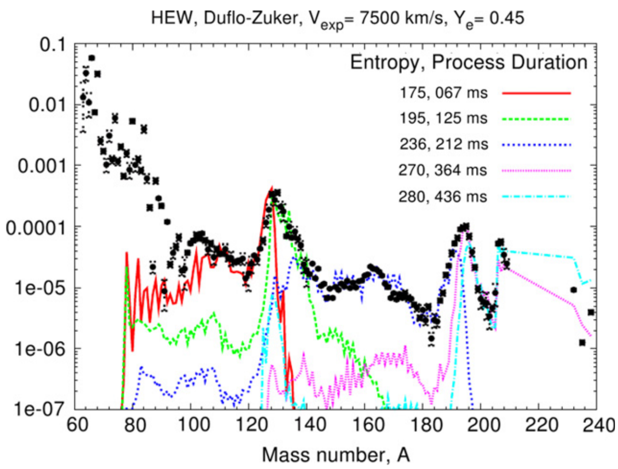


**Fig. 3.** High entropy neutrino wind results [35], utilizing the mass model Duflo–Zucker [82] and variations in extropy, expansion parameters and electron fraction $Y_e$.

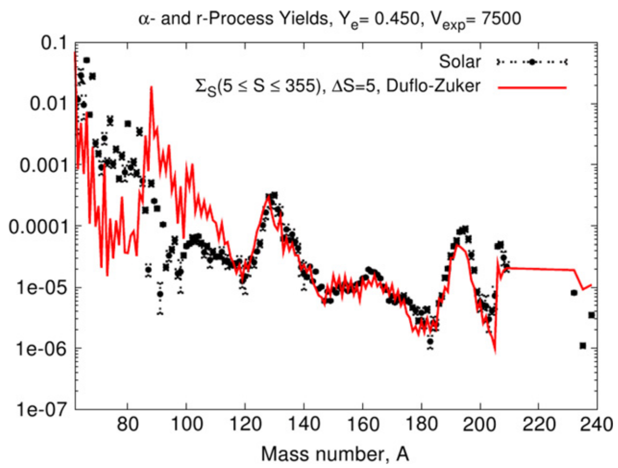


**Fig. 4.** A superposition of entropies [35] reproducing the main $r$-process component very well. See discussion of lower entropy contributions responsible for abundances with $A \leq 110$.

with choices for the entropy of matter $S$, its electron fraction $Y_e$ and an expansion timescale $\tau_{exp}$, in order to obtain abundance distributions reproducing certain mass regions of the solar $r$-process pattern. Whether the entire solar $r$-process abundances are fully reproduced in each astrophysical event, i.e., whether each such event encounters the full superposition of conditions required, is a matter of debate [72,73,48,4,74,34,35,75,76]. In realistic astrophysical environments with time variations in $n_n$ and $T$, it has to be investigated whether at all and for which time duration $\tau$ the supposed $(n, \gamma)$–$(\gamma, n)$-equilibrium, identifying a typical neutron separation energy of the $r$-process path, will hold and how freeze-out effects change this behavior. In general, late neutron captures may alter the final abundance distribution. In this case neutron capture reactions will be important. Also $\beta$-delayed neutrons can play a role in forming and displacing the peaks after freeze-out.

### *5.1. The high entropy neutrino wind*

For many years since [22,21,23] the high entropy wind has been considered as the most promising (realistic?) environment, expelled from newly formed (hot) neutron stars in core collapse supernovae, which continue to release neutrinos after the supernova shock wave is launched. These neutrinos interact with matter of the outermost proto-neutron star layers which are heated and ejected in a continuous wind. The question, whether the late neutrino flux also leads to moderately neutron-rich matter [23] via interactions with neutrons and protons and causes matter ejection with high entropies, depends on the neutrino and anti-neutrino spectra and luminosities [77]. Problems were encountered when attaining entropies sufficiently high in order to produce the heaviest $r$-process nuclei [8,9,24]. Recent hydrodynamic simulations for core collapse supernovae support the idea that these entropy constraints can be fulfilled in the late phase (after the initial explosion) when a reverse shock is forming [78–80], but at times when temperatures decreased to too low values for an $r$-process to operate [81].

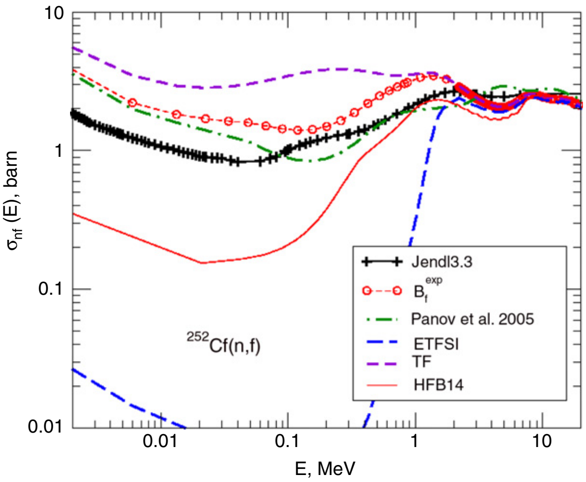


**Fig. 5.** $^{252}$Cf$(n, f)$ cross section [44] from our calculations with experimental fission barriers $B_f^{exp}$ as well as ETFSI, TF, and HFB predictions in comparison to experiment (JENDL3.3) [99] and an older version of our code (Panov [43]).

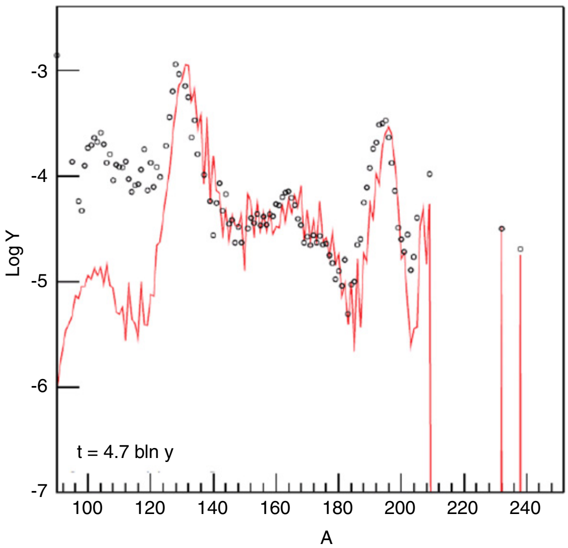


**Fig. 6.** $r$-process results from neutron-star merger ejecta conditions [100] with fission-cycling [98] based on our set of $(n, f)$-cross sections [44], utilizing semi-empirical fragment distributions and a decay time of $4.7 \times 10^9$ y after the event.

Despite the lack of support from supernova simulations, exploratory parameter studies for an $r$-process in expanding high-entropy matter have been undertaken by a number of groups [83–85,9,24,86,87,81]. Our recent investigations [35] focussed (a) on the effects of varying nuclear physics input (mass models FRDM [88], ETFSI-1 [89], ETFS-Q [90], (DUFLO-ZUKER) [82] and HFB-17 [91]) and (b) the detailed understanding of the nuclear flow through the chart of nuclides, testing equilibria, freeze-out and delayed neutron capture. These effects were investigated with a full network, containing up to 6500 nuclei (with the corresponding nuclear masses, cross sections and $\beta$-decay properties) for an extensive parameter study in terms of entropy $S$, electron fraction $Y_e$ and expansion velocity $V_{exp}$, the latter being related to the expansion timescale $\tau_{exp}$ [92,35]. Here we only show the results utilizing the Duflo–Zuker mass model (a) for a range of entropies (Fig. 3) and (b) a superposition of entropies with weights corresponding to equal mass ejecta per entropy interval (Fig. 4). This assumes that in the late phases of the neutrino wind of a deleptonized neutron star conditions with $Y_e < 0.5$ can materialize (see discussion in Section 6). It can be noticed that for $A \leq 110$ the abundances (resulting mainly from charged-particle alpha-rich freeze-out without substantial neutron processing) do not reflect a pure $r$-process component. Low entropies, in fact, can produce a combination of $s$, light $p$, and $r$-process nuclei [83,70,34,93].

### 5.2. Strong $r$-processes with fission cycling

Either higher entropies than utilized in the previous subsection or conditions with intrinsically high neutron densities (like expanding neutron star matter with $Y_e \approx 0.1$–$0.2$) can lead to neutron/seed ratios which are sufficiently high to reach fissionable nuclei in the $r$-process. The fission fragments can again capture neutrons and produce fissionable nuclei, leading to an $r$-process with fission recycling [94,47]. It was shown recently that under such conditions neutron-induced fission is more important than beta-delayed fission [95,47]. This requires reliable fission barriers (and fission fragment distributions) to perform such calculations correctly and to test the possibility for the production of superheavy elements. Recent efforts have provided such compilations of neutron-induced fission rates [43,45,44]. Comparison of rates obtained with different sets of mass and fission barrier predictions have been discussed by [44], based on extensions of [36,43] for the full region $84 \leq Z \leq 110$. In Fig. 5 we display $^{252}$Cf$(n, \gamma)$ cross sections of fission barrier predictions (ETFSI [42], TF [96], FRDM [97], and HFB [45]) in comparison to the experiment. One realizes that there exist still large uncertainties in fission barrier predictions, even near stability where experimental information is available. This situation worsens towards heavier nuclei and far from stability. Exploratory tests, whether under such conditions also superheavy nuclei can be formed, have been performed recently [98] (Fig. 6).

## 6. Conclusions

In the preceding sections we have discussed the status of three processes, the (classical) $p$- and $r$-process and the recently discovered $\nu p$-process. All of them seem to be related to massive stars, and very probably to core collapse supernova events. The classical $p$-process is identified with moderate photodisintegration processing, acting like spallation on previously existing heavy nuclei in the outer shells of explosive Ne/O burning. This is a secondary process, requiring existing heavy nuclei from previous stellar populations. In recent years the nuclear physics basis of this process has been quite firmly established and can explain the abundance of the proton-rich $p$-isotopes, amounting to typically 1% of the elemental abundance. This is different for the light $p$-isotopes, where this fraction increases up to 10% and all attempts to explain them by a classical $p$-process fail [11]. The newly discovered $\nu p$-process can provide light $p$-nuclei and seems also be able to explain the observed LEPP (''light'' element primary process) abundances in low metallicity stars. The related innermost core collapse supernova ejecta of the early neutrino wind are proton-rich, of primary origin and produce nuclei up to $A = 100$. Such conditions also improve the agreement of the Fe-group composition (e.g. Zn) in comparison to early galactic evolution observations [49].

The origin of the $r$-process remains a problem. A moderately neutron-rich, high entropy neutrino wind has been suggested as the site of the $r$-process for many years now. Recent core collapse studies, however, indicate the neutrino wind to be proton-rich for many seconds. A major question is how this turns to be neutron-rich in late phases, what physics causes this change (the nuclear EoS or neutrino properties?) and how very high entropies can be attained to produce also the heaviest nuclei. Present observations indicate that in most cases the latter is not taking place, causing only a weak $r$-process [75], dominated by alpha-rich freeze-out abundances which can contribute a combination of light $s$-, $p$- and $r$-process nuclei [83,34,93]. Whether either high entropies are only attained in exceptional cases or other sites of low entropy, highly neutron-rich matter, ejected in e.g. neutron star mergers [100] or jets from core collapse supernovae [101,102], are the origin of the main $r$-process has to be explored, in parallel to nuclear physics far from stability.

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