

The r-, p-, and ν p-Process

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Abstract. The processes discussed in this review are three of the four nucleosynthesis processes involved in producing heavy nuclei beyond Fe (not counting the rp-process in X-ray bursts). 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 ν p-process is related to the innermost ejecta, the neutrino wind expelled from the hot proto-neutron star after core collapse in the supernova explosion. This neutrino wind is proton-rich in its early phase and reactions with neutrinos permit to overcome decay/reaction bottlenecks for the flow beyond the Fe-group, thus permitting the production of those 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 and half-lives), affecting the process speed and abundance peaks, on the other hand the site is still not definitely located, yet. Later neutron-rich, high entropy phases of the neutrino wind could permit its operation, other options include the ejection of very neutron-rich neutron star matter. Two different environments are required for a weak and a main/strong r-process, witnessed by observations of low metallicity stars.

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 lower mass numbers). This process is identified by solar abundances features and the question remains whether only one astrophysical site is responsible. The paradigm relates it to zones of explosive Ne/O burning in the outer part of core collapse supernovae, acting on pre-existing heavy nuclei and making it a secondary process in terms of galactic evolution. The observational indications for a lighter element primary process [91](LEPP) at

low metallicities points 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 [41]), 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, the necessary astrophysical environment conditions have been identified. 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 [35, 82, 15, 38, 37].

The ν p-process has only been discovered in recent years [26, 70, 95] 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 [88, 93]. 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 [51, 8, 21]. This results in a proton and alpha-rich freeze-out producing nuclei up to ^{64}Ge , where a long beta-decay half-life is encountered. Anti-neutrino capture on the remaining protons creates neutrons and the reaction $^{64}\text{Ge}(n, p)^{64}\text{Se}$ mimics a fast beta-decay, permitting then to move upward to nuclei with masses $A < 100$. This ν p-process is a primary process, could explain the observational results promoting the LEPP and can also fill in the light p-isotopes which encountered difficulties in the classical p-process picture [16]. 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 and thus would permit to originate an 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 ν p-process and finally the r-process, after first giving a short overview on the status of the core collapse supernova explosion mechanism.

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, 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 [6]. However, this became questionable when previously neglected neutrino scattering processes were introduced (e.g. neutrino-electron scattering), which permitted to replace lost low energy neutrinos, leading to a continuous energy leakage and to the death of the prompt shock within 10 ms after bounce. Since then, and with the first neutrino detection from a core collapse supernova (SN1987A), the hope has been that further improvement would lead to successful explosions via energy deposition through neutrino and anti-neutrino captures on neutrons and protons. Two different paths were explored. 1. Convective instabilities, but with still simplified neutrino transport, causing either (a) convective transport in the core and leading to higher

neutrino luminosities [45] or (b) higher energy deposition efficiencies in convective regions [34].

2. Improved neutrino transport schemes, leading to higher neutrino luminosities via the full solution of the Boltzmann transport equation for neutrino scattering and neutrino reactions [56]. There has been substantial progress in 1D-3D supernova explosion simulations over recent years [51, 89, 39, 90, 9, 8, 27, 10, 3, 40, 52, 24, 20, 21] and a solution (in 3D) seems close. 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 [70, 26] and considered also as a possible source of the r-process to produce the heaviest elements via neutron captures [84, 100, 71, 88, 93, 85, 89]. Neutrino emission, from the hot and dense matter in the proto-neutron star and from infalling matter, and its time and spectral characteristics [20, 21] lies at the focus of the supernova mechanism and related nucleosynthesis and influences also neutrino nucleosynthesis in the outer mass zones [33].

Given this situation, at present the self-consistent prediction of supernova nucleosynthesis yields seems not possible. However, supernova nucleosynthesis has a long tradition [101, 87, 61, 13, 62]. All of the past predictions relied on an artificially introduced explosion, either via a piston or a thermal bomb introduced into the progenitor star model. In this approach, the mass cut between the ejecta and the remnant does not emerge from the simulation and is freely chosen, 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 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 νp - and r-process. Here we will make use of 1D approximations [26, 97] and free parameter studies [18, 19]. The relevant thermonuclear reaction rates to be employed in such calculations have been provided by experiment [12, 2] or theory [98, 76, 29]. The weak interaction rates stem from phenomenological approaches or shell model calculations [28, 50], beta-decay properties from experiment or QRPA predictions [58], beta-delayed or neutron-induced fission predictions are related to mass models and fission barriers [86, 53, 65, 67, 30], neutrino-induced reactions make use of RPA calculations [46, 54].

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 chemical analysis of the most metal-poor stars can, therefore, provide insight into the synthesis of the first heavy elements [82, 11, 37, 38]. Several studies [35, 82, 38, 15] 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, while the lighter r-process and possibly p-process elements might be produced in different supernovae with varying amounts, including also νp -process nuclei observed as part of the LEPP [91].

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 35 p-isotopes between Se and Hg is photodisintegration of intermediate and heavy elements at high temperatures in late evolution stages of massive stars [99, 79]. 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 [77, 4, 74, 16]. 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 γ -process [78]. Here it is important to investigate the the sensitivity of the location of the γ -process path with respect to reaction rate uncertainties.

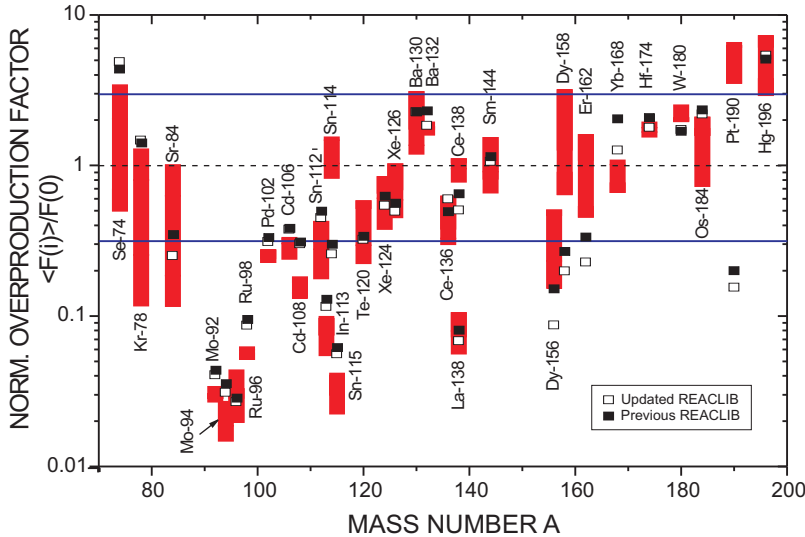


Figure 1. Normalized overproduction factors of p-process nuclei derived with the [74] (open squares) and [16] (full squares) reaction library. In addition, the results from a range of stellar models ($10\text{-}25M_{\odot}$) from [80] are given for comparison. A value equal to unity corresponds to relative solar abundances.

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. $2\text{-}3 \times 10^9 \text{K}$. The γ -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 (γ, n) -reactions, moves the abundances to the proton-rich side. At some point in a chain of isotopes, (γ, p) and/or (γ, α) -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 α -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 experimental and theoretical efforts have been undertaken to improve the reaction input, especially with respect to open questions in optical potentials for alpha particles and protons [32, 43, 44, 102].

Applications of p-process network calculations to the temperature profiles of initiated explosions have been performed [80, 74, 16]. Here we present the results of a $25M_{\odot}$ mass model [16] with two reaction rate libraries without and with inclusion of all experimental improvements, existing at that point. It is noticed that the nuclear uncertainties cannot change the underproduction of especially the light p-nuclei. Another process seems to be required to supply these missing abundances.

4. The νp -Process

Neutron-deficient nuclei can be produced by two astrophysical nucleosynthesis processes: the rp-process in X-ray bursts (which, however, does not eject matter into the interstellar medium

[92, 81, 22] and the recently discovered νp -process in core collapse supernovae [26, 70, 95]. The νp -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 supernova [8, 90, 52] and possible ejecta from black hole accretion disks in the collapsar model of gamma-ray bursts [83]. The matter in these ejecta is heated to temperatures well above 10^{10} 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. When the matter expands and cools, the free neutrons and protons combine into α -particles. Later, at temperatures around 5×10^9 K, alpha-particles assemble into heavier nuclei via unstable intermediate nuclei, e.g. the triple- α reaction via unstable ^8Be , but - depending on the entropy and the expansion of matter - only a fraction of those form iron-group nuclei (alpha-rich freeze-out). In case of a proton-rich environment, there are also still free protons available at the time of the alpha freeze-out. Once the temperature drops to about 2×10^9 K, the composition of the ejecta consists mostly of ^4He , protons, and iron group nuclei with $N \approx Z$ (mainly ^{56}Ni) in order of decreasing abundance. Without neutrinos, synthesis of nuclei beyond the iron peak becomes very inefficient due to bottleneck (mainly even-even $N = Z$) nuclei with long beta-decay half-lives and small proton-capture cross sections. However, the matter is subject to a large neutrino/antineutrino flux from the proto-neutron star.

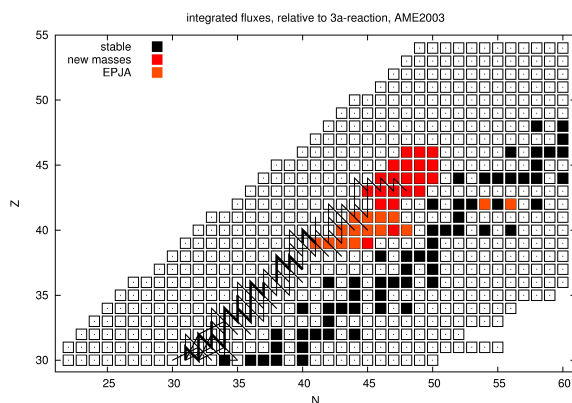


Figure 2. νp -process path employing AME2003 [5] and latest mass measurements [97].

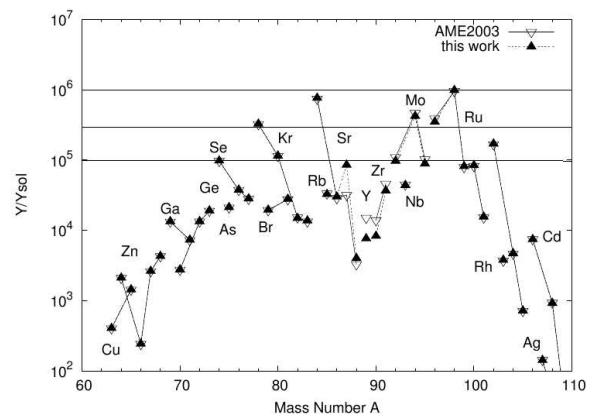


Figure 3. Final abundances normalized to solar after decay for two sets of thermonuclear reaction rates/masses. Matter up to $A = 100$ can be produced easily.

While neutrons are bound in neutron-deficient $N = Z$ nuclei and neutrino captures on these nuclei are negligible due to energetics, antineutrinos are readily captured both on free protons and on heavy nuclei on a timescale of a few seconds. As protons are more abundant than heavy nuclei, antineutrino captures occur predominantly on protons, leading to residual neutron densities of $10^{14} - 10^{15} \text{ cm}^{-3}$ for several seconds. These neutrons are easily captured by heavy neutron-deficient nuclei, for example ^{64}Ge , inducing (n, p) reactions with 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. The νp -process [26] is this sequence of (p, γ) -reactions, followed by (n, p) -reactions or beta-decays, where the neutrons are supplied by antineutrino captures on free protons. Here we show νp -process nucleosynthesis for the explosion of a $15 M_{\odot}$ star [39], also utilized in [70, 23], which synthesizes efficiently nuclei with

$A > 90$. Two sets of astrophysical reaction rates were used in the reaction network, both based on theoretical rates from the NON-SMOKER code [76], but once with the latest excited state information and masses from the AME2003 compilation [5] and another set also with the latest mass measurements [42, 97].

Fig. 3 shows the final abundances normalized to solar abundances after decay to stability for these two sets of thermonuclear reaction rates. Only nuclei produced in the p-rich ejecta are shown. As is clearly seen, there is no difference in the yields for the two different sets of rates except for a few nuclei in the mass range $85 < A < 95$, namely $^{87,88}\text{Sr}$, ^{89}Y , and $^{90,91}\text{Zr}$. This can be directly traced back to the large change in the mass of ^{88}Tc ($\Delta M = 1031$ keV). This change in mass leads to an increase in the reaction rate for $^{88}\text{Tc}(\gamma, p)^{87}\text{Mo}$ at the relevant temperatures and therefore a relative suppression of the opposite capture rate. Fig. 2 shows the time-integrated reaction flows relative to the triple-alpha-reaction employing the masses from AME2003 only and the masses including the latest measurements, respectively. The total flow reaching ^{94}Pd is very similar in both cases. These results show that the ν p-process can easily produce the light p-nuclei of Mo and Ru, which are deficient in p-process calculations. Further processing depends on the expansion (speed) of matter and the overlying mass of ejecta.

5. The 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 in recent years 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 astrophysical conditions under which this process occurs. The classical “waiting-point” approximation, with the basic assumptions of an Fe-group seed, an $(n, \gamma) - (\gamma, n)$ -equilibrium for constant neutron densities n_n at a chosen temperature T over a process duration τ , and an instantaneous freezeout, has helped to gain improved insight into the systematics of an r-process in terms of its dependence on nuclear-physics input and astrophysical conditions [14, 47, 48]. Taking a specific seed nucleus, the solar r-process pattern peaks can be reproduced by a variation/superposition of neutron number densities n_n and durations τ . Whether the solar r-process abundances $N_{r,\odot} \simeq N_{\odot} - N_{s,\odot}$ 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 [96, 69, 82, 37, 73, 18]. 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 τ the supposed $(n, \gamma) - (\gamma, n)$ -equilibrium of the classical approach 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 β -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 [100, 84, 71] 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 late neutrino flux also leads to moderately neutron-rich matter [71] via interactions with neutrons and protons and causes matter ejection with high entropies. Problems were encountered to attain entropies sufficiently high in order to produce the heaviest r-process nuclei [88, 93, 85]. 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 [27, 3, 10, 40, 66].

The question is whether such high entropies occur at times with sufficiently high temperatures when an r-process is still underway [49]. Exploratory calculations to obtain the necessary conditions for an r-process in expanding high-entropy matter have been undertaken by a number of groups [36, 55, 63, 93, 85, 94, 103, 49]. Our recent investigations focussed (a) on the effects of varying nuclear physics input [mass models FRDM (Finite Range Droplet Model [57], ETFSI-1 (Extended Thomas-Fermi with Strutinsky Integral) [1], ETFS-Q with quenching of shell closures far from stability [68], the mass formula by Duflo & Zuker (DUFLO-ZUKER) [17] and HFB-17 (a recent Hartree-Fock-Bogoliubov approach) [31]] and (b) the detailed understanding of the nuclear flow through the chart of nuclides, testing equilibria, freeze-out and delayed neutron capture. To investigate these effects we have applied a full network containing up to 6500 nuclei and the corresponding nuclear masses, cross sections and β -decay properties.

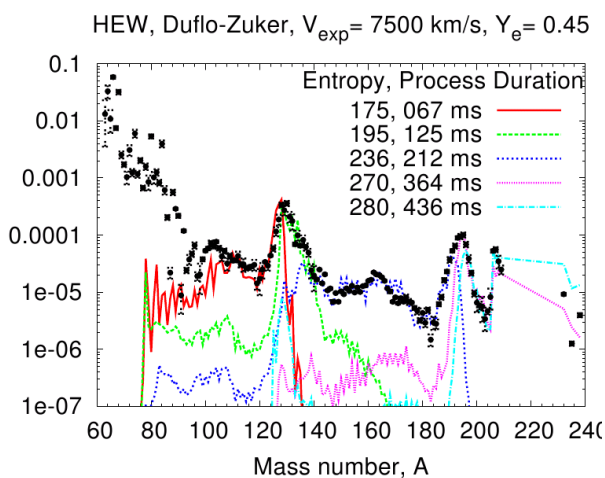


Figure 4. High entropy neutrino wind results for the mass model Duflo-Zucker [17], expansion parameters and proton/nucleon ratio Y_e as given in the label, for a variation in entropies per baryon and k_B .

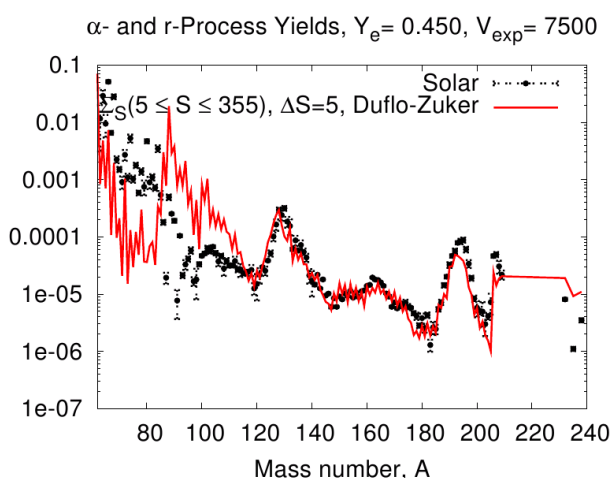


Figure 5. A superposition of entropies (assuming equal mass ejecta per entropy interval). It is obvious that the light r-process abundances are not reproduced correctly for such Y_e 's.

The calculations presented here are based on trajectories for densities and temperatures originating from expansions of a complete parameter study in terms of entropy S , electron fraction Y_e and expansion velocity V_{exp} , the latter being related to the expansion timescale τ_{exp} [25, 19]. Here we only show the results utilizing the Duflo-Zucker mass model (a) for a range of entropies and (b) a superposition of entropies with weights corresponding to equal mass ejecta per entropy interval. We assume that in the late phases of the neutrino wind of a deleptonized neutron star conditions with $Y_e < 0.5$ prevail (see discussion in section 6).

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 [75, 54]. This requires reliable fission barriers (and fission fragment distributions) to test the possibility for the production of superheavy elements. It was shown recently that neutron-induced fission is more important in r-process nucleosynthesis than beta-delayed fission [64, 54]. Thus, the need to provide a compilation of neutron-induced fission

rates is obvious and has been performed recently [65, 30, 67]. Comparison of rates obtained with different sets for mass and fission barrier predictions give a measure of the uncertainties involved. In order to explore a range of synthesis conditions realistically, our aim is to provide a range of reaction rates within the presently existing nuclear uncertainties.

We show here results of [67], based on extensions of [76] and [65] for the full region $84 \leq Z \leq 110$, in order to provide the necessary input for nucleosynthesis studies under high neutron densities. Results for neutron-induced fission are given in Fig. 6 for a variety of fission barrier predictions (ETFSI [53], TF [60], FRDM Moller08 [59], and HFB [30]) in comparison to experiment. One realizes that there exist still large uncertainties in fission barrier predictions, even near stability where experimental information is available for comparison. This situation worsens towards heavier nuclei and far from stability. As shown in Fig. 7, it can be seen that even for the most recent advances, (n, f) cross sections obtained with theoretically predicted barriers seem to diverge from experimental values for the heaviest nuclei.

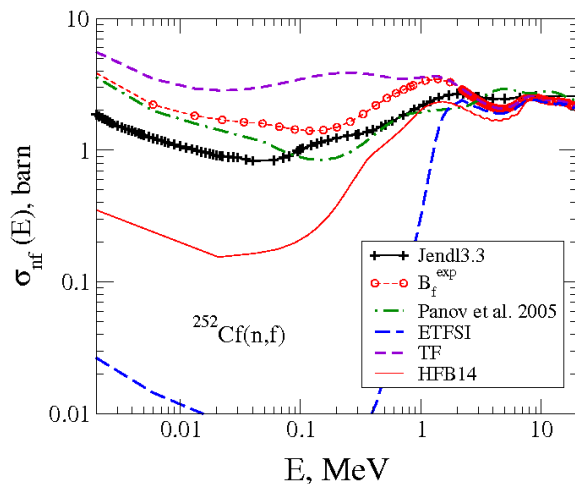


Figure 6. $^{252}\text{Cf}(n, f)$ cross section from our calculations with experimental fission barriers B_f^{exp} , ETFSI, TF, and HFB predictions as well as an older version of our code (Panov 2005) in comparison to experiment (JENDL3.3).

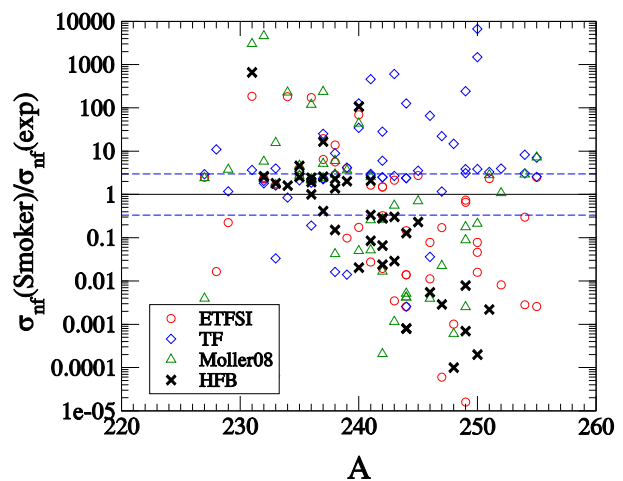


Figure 7. Ratio of (n, f) -cross section predictions with different fission barrier sets in comparison to experiment. In some cases the ratios seem to diverge towards heavier mass numbers A .

6. Conclusions

In the preceding sections we have discussed the status of three processes, the (classical) p- and r-process and the recently discovered νp -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. The newly discovered νp -process can just fill this gap and seems also be able to explain the observed LEPP ("light" element primary process) abundances in low metallicity stars. The ejecta innermost core collapse supernova ejecta of the early neutrino wind

are proton-rich, of primary origin and produce nuclei up to $A = 100$. The origin of the r-process stays a problem. A moderately neutron-rich, high entropy neutrino wind has been identified with 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. Whether either high entropies are only attained in exceptional cases or other origins of low entropy, highly neutron-rich matter is the origin of the main r-process has to be explored, in parallel with the still remaining challenges of nuclear physics far from stability.

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