

The νp -process: critical nuclear physics and astrophysical implications

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Abstract. The neutrino-p-process is thought to occur in the innermost proton-rich layers ejected in core-collapse supernovae. The importance of the νp -process lies in the fact that it may contribute to the abundances of elements above Nickel and possibly the light p-nuclei. The reaction path of the νp -process lies in a region where nuclear masses are partly unknown and all involved reaction rates are based on theoretical predictions. Detailed studies of the νp -process nucleosynthesis and its uncertainty due to the nuclear physics are presented, with a focus on the reaction path at and above ^{56}Ni . The νp -process path is found to be mainly determined by nuclear structure and thus is trajectory independent. Critical nuclear physics input are identified and the impact of uncertainties on the resulting nucleosynthesis is discussed.

1. Introduction

Neutrino-driven winds from core collapse supernovae are an important site for the nucleosynthesis of elements beyond iron. After the explosion, the newly formed, hot proto-neutron star cools emitting neutrinos. The interaction of these neutrinos with the stellar matter results in energy deposition in the outer layers of the proto-neutron star and leads to a supersonic outflow, the neutrino-driven wind. Neutrino-driven winds are typically considered the site for the production of heavy elements through the r-process [1]. However, recent simulations [2, 3, 4, 5] cannot reproduce the extreme conditions required for the r-process (e.g. [6]): The ejecta is proton-rich (electron fraction $Y_e > 0.5$) and the entropy is too low (entropy $s < 100k_B/\text{nuc}$). While these conditions do not allow for the formation of the heaviest elements, lighter elements, e.g. Sr, Y, Zr, can be formed.

In these proton-rich winds, matter is initially hot and fully dissociated. As the matter expands and cools, freeze-out from full nuclear statistical equilibrium (NSE) to quasi-equilibrium (QSE) takes place and nuclei up to ^{56}Ni and even up to ^{64}Ge are formed once the temperature drops below 3 GK. For temperatures between 3 GK and 1.5 GK, sequences of p-capture reactions and β^+ -decays dominate. Nuclei with low proton-capture Q -values and long β -decay half-lives act as bottlenecks and hinder the nucleosynthesis flow towards heavier elements. In the νp -process, the decay of these nuclei is accelerated by (n,p) reactions. These neutrons are produced by anti-neutrino capture reactions on free protons ($\bar{\nu}_e + p \rightarrow n + e^+$). This allows for the synthesis of heavier elements beyond iron through the νp -process [7, 8, 9, 10, 11]

The importance of the νp -process lies in the fact that it is a primary process (i.e. it does not require pre-existing seed nuclei) contributing to the abundances of heavy elements beyond iron. This is in agreement with recent observations of metal-poor stars (e.g., [12]), which exhibit

enhanced abundances of elements such as Sr, Y, and Zr. Thus, the νp -process may serve as the Light Element Primordial Process (LEPP) proposed to explain the observed abundances of these elements at the lowest metallicities [13]. In addition, the νp -process may contribute to the light p-nuclei – neutron-deficient stable isotopes above iron which cannot be produced by the s- and r-processes. Recent isotopic data from meteoritic material puts tight constraints on the possible contribution to ^{92}Mo from the proton-rich side [14, 15] but lighter p-nuclei may receive a considerable contribution from the νp -process.

In section 2, we summarize the observational clues for an additional nucleosynthesis process at the lowest metallicities. In section 3, we analyze the details of the νp -process nucleosynthesis both with respect to the nuclear physics inputs and the astrophysical implications. A summary is presented in section 4.

2. Abundance clues

Spectroscopic studies of abundances in metal-poor halo stars can reveal hints about the nucleosynthesis processes in the early Galaxy. These low-mass stars are old and carry in their photosphere the abundance signature of the conditions when they were formed. A subclass of these extremely metal-poor stars with $[\text{Fe}/\text{H}] \approx 3$ is strongly enhanced with elements such as Eu ($[\text{Eu}/\text{Fe}] > 0.5$). These stars show a heavy element pattern ($56 \leq Z < 83$) which is in extraordinary agreement with the r-process contribution to the solar system abundances [16]. In addition, the abundance pattern in these stars is remarkably robust from star to star. The robustness of the abundance pattern and the remarkable agreement with the solar system r-process contributions imply a universal r-process abundance distribution since these metal-poor stars are thought to be enriched by only one or a few nucleosynthetic events. However, for the lighter heavy elements (elements beyond iron with $Z \leq 47$) the situation is more complex. The abundances of these elements in the same Eu-enhanced stars do not agree with the solar system r-process contribution, indicating the contribution of an additional nucleosynthesis process (or the r-process is not robust in this region and depends on the conditions). Further evidence for such an additional nucleosynthesis process stems from meteoritic abundances [17, 18]. The larger scatter in $[\text{Sr}/\text{Ba}]$ in low-metallicity stars (e.g. [19, 20]) is consistent with a second, independent process at low metallicities which produces Sr but no or little Ba. Chemical evolution studies [13] also find a large scatter in Sr, Y, Zr and postulate an additional process, the Lighter Element Primary Process (LEPP) which produces Sr, Y, Zr but little Ba and Eu. In addition, non-correlation of the elements Sr, Y, Zr, Pd, and Ag with Eu can be demonstrated [21, 22].

3. The νp -process

The details of the νp -process nucleosynthesis depend on the nuclear physics inputs (e.g. reaction rates, reaction Q -values, nuclear masses) and on the astrophysical conditions (e.g. the existence and location of the wind termination shock, expansion timescale, and neutrino luminosities and energies). The reaction path of the νp -process partly lies in a region where nuclear masses are unknown [10, 23]. Furthermore, all involved reaction rates are based on theoretical predictions. Since there is not much experimental information (such as level schemes, deformations, decay schemes, scattering and reaction cross sections) available far from stability, the uncertainties in the rates have to be considered in astrophysical studies of the νp -process. A possibility to investigate properties of, and perhaps reactions with, highly unstable nuclei is offered by radioactive ion beam facilities.

The νp -process synthesizes neutron-deficient nuclei through a sequence of rapid (p, γ) reactions, followed by (n,p) reactions or β -decays, where the neutrons are supplied by antineutrino captures on free protons. This is similar to the rp -process in proton-rich thermonuclear burning on the surface of a mass-accreting neutron star [24, 25]. The waiting points in the rp -process (characterized by slow proton-capture reactions and long β -decay

lifetimes) are overcome in the νp -process by the (n,p) reactions. In addition, the νp -process occurs at lower proton density $\rho_p = \rho Y_p$ than the rp -process. Here, ρ denotes the matter density and Y_p is the proton abundance. Hence, the νp -process path is slightly closer to stability, initially following the $N = Z$ line and moving towards stability at higher masses. This influences which nuclei are waiting points in the νp -process. We examine how variations in the nuclear input physics influence the νp -process. The focus is on the reaction rates of important reactions. Sensitivities on the nuclear masses will also be discussed. The nucleosynthesis results presented here are based on the explosion of a $15M_\odot$ star [26], also utilized in [8], which efficiently synthesizes nuclei with $A > 90$. The nuclear reaction network used is the same as in [23]. The reaction rates are taken from a recent REACLIB compilation [27, 28, 29] which contains experimental rates (where available) and theoretical Hauser-Feshbach rates. This is supplemented with weak interaction rates [30, 31, 32] and neutrino and antineutrino capture rates on nucleons and nuclei [33]. The nuclear masses employed for the Hauser-Feshbach rates were taken from [34, 35] and partially replaced by more recent mass measurements of proton-rich nuclei [23, 36].

Here, we focus on reaction rates on nuclei at and above nickel where the reaction rates mostly stem from Hauser-Feshbach predictions. The effect of uncertainties on selected reaction rates on light nuclei has been investigated in Ref. [10]. The (n,p) reactions of special importance in the νp -process are $^{56}\text{Ni}(n,p)^{56}\text{Co}$, $^{64}\text{Ge}(n,p)^{64}\text{Ga}$, and $^{96}\text{Pd}(n,p)^{96}\text{Rh}$ [37]. The nucleus ^{56}Ni acts as seed nucleus from which the νp -process starts at temperatures $T \sim 3\text{GK}$. The nucleus ^{64}Ge is the first major bottleneck in the νp -process which has to be bridged by (n,p) reactions. Comparing calculations with and without neutrinos, the abundance pattern is very similar up to and including ^{64}Ge . However, without neutrinos the abundance distribution drops precipitously at $A \approx 64$. The νp -process path always proceeds through ^{96}Pd ($N = 50$) which has been predicted to be a “second seed nucleus” for the νp -process [10]. The (n,p) reactions on these three nuclei have been varied individually. In addition, global rate variations of all (n,p) or (p, γ) reactions in a region of nuclei have been performed. For all variations, the rates have been varied by a constant factor, either multiplied or divided by a factor of five. This is appropriate for the global uncertainties of (n,p) rates in this region of the nuclear chart. The regions for the global rate variations are defined by ^{56}Ni , ^{64}Ge , and ^{96}Pd .

For variations of only the $^{56}\text{Ni}(n,p)^{56}\text{Co}$ rate we find – in agreement with [10] – that a slower rate results in larger abundances for the nuclei with $A > 96$. A slower rate means that fewer neutrons are captured on ^{56}Ni , and hence, more neutrons are available to be captured on nuclei heavier than ^{56}Ni along the νp -process path [37]. In this case, the νp -process nucleosynthesis can proceed to higher mass numbers (see figure 1, dashed line). Conversely, a faster rate for $^{56}\text{Ni}(n,p)$ leads to the nucleosynthesis ending at lower mass numbers (see figure 1, dotted line) because more neutrons are used on ^{56}Ni and hence are not available anymore elsewhere. A reduced rate for $^{56}\text{Ni}(n,p)$ shifts material from the $60 \lesssim A \lesssim 100$ region to the $A \gtrsim 100$ region. However, it should be noted that an increase in mass number A does not necessarily imply an increase in Z due to the (n, γ) reactions acting at later time on nuclei with large A [37].

As shown in Fig. 2, variations of the $^{64}\text{Ge}(n,p)^{64}\text{Ga}$ rate only have much smaller effects on the abundances than for $^{56}\text{Ni}(n,p)$. A reduction of the (n,p) rate on ^{64}Ge affects the abundances in two ways: The abundance of the nucleus ^{64}Ge increases as the flow is inhibited from continuing beyond ^{64}Ge . At the same time, fewer neutrons are used in (n,p) reactions on ^{64}Ge and hence are available for capture on heavier nuclei on the νp -process path. This has the strongest effect on nuclei with $A \gtrsim 100$ as these nuclei have low abundances. Similarly, the relative depletion in the $70 \lesssim A \lesssim 100$ region is small. The increase in abundances for nuclei with $A \gtrsim 100$ is much smaller here than in the case of variations of the $^{56}\text{Ni}(n,p)^{56}\text{Co}$ rate. Global variations of all (n,p) rates on and above ^{64}Ge (Fig. 3) exhibit the opposite behavior: A reduction of all (n,p) rates on and above ^{64}Ge reduces the abundances of nuclei with $A \gtrsim 96$, while an increase of all

(n,p) rates increases the abundances of nuclei with $A \gtrsim 96$. This behavior is an indication that once the νp -process has reached ^{64}Ge the efficiency of the process is determined by how fast it can proceed, i.e., how much the (n,p) reactions speed up the nucleosynthesis flow compared to β^+ decays [37]. An increase in the abundances of nuclei with $A \gtrsim 96$ is accompanied by a slight decrease in the abundances of nuclei with $64 \lesssim A \lesssim 96$ as this material is shifted to higher mass numbers.

The nucleus ^{96}Pd has been predicted to be a second seed nucleus for the νp -process. However, variations of only the rate of $^{96}\text{Pd}(n,p)^{96}\text{Rh}$ have only a small effect on the resulting abundances [37], as seen in Fig. 4. For variations of all (n,p) rates on and above ^{96}Pd the situation is very similar to the ^{64}Ge case: Increased (n,p) rates enable the νp -process to proceed faster and hence lead to increased abundances for $A > 96$. Abundances closely above ^{96}Pd are moved into nuclei with even higher masses when the rates of all (n,p) reactions are increased.

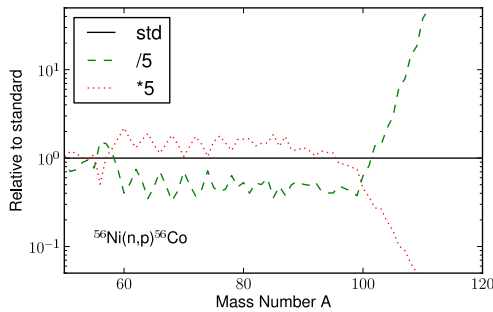


Figure 1. Abundance ratios relative to the standard case from a variation of the $^{56}\text{Ni}(n,p)^{56}\text{Co}$ rate.

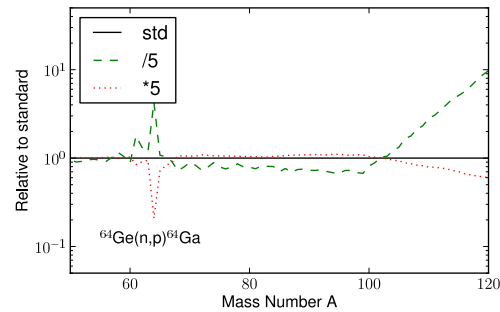


Figure 2. Abundance ratios relative to the standard case from a variation of the $^{64}\text{Ge}(n,p)^{64}\text{Ga}$ rate.

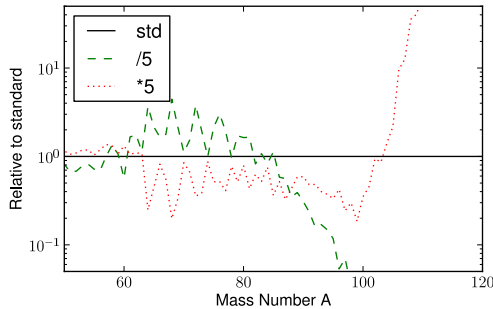


Figure 3. Abundance ratios relative to the standard case from variations of all (n,p) rates above and including ^{64}Ge .

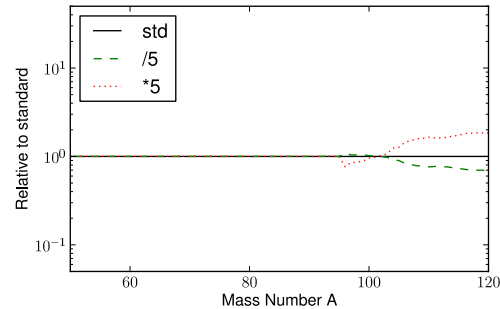


Figure 4. Abundance ratios relative to the standard case from a variation of the $^{96}\text{Pd}(n,p)^{96}\text{Rh}$ rate.

Another important nuclear physics input are the nuclear masses. Uncertainties in the nuclear masses affect the proton-capture Q -values and hence determine the ratio between forward capture and reverse photodisintegration rates. This, in turn, determines whether another proton can be captured before an (n,p) reaction (or β -decay) occurs. The nuclear masses used here are taken from AME03 [34, 35], supplemented by the recent mass measurements of [23, 38, 39, 40]. The impact of a few selected or a range of masses on details of the reaction path has been studied in Refs. [10, 41] and in Ref. [23], respectively.

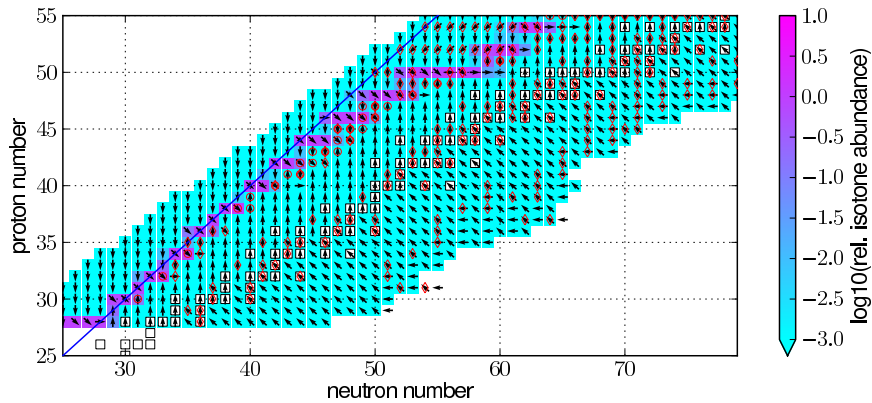


Figure 5. Abundance distribution from (p,γ) - (γ,p) equilibrium in each isotonic chain for typical νp -process conditions. Arrows indicate the dominating net flux per nucleus. The $N = Z$ line is also marked. Circles denote nuclei where uncertainties in the Q -values (masses) impacts the dominating reaction flow. Diamonds mark nuclei where the path direction is uncertain due to uncertainties in the reactions.

The location of the νp -process path is robust and remains unaffected by variations of the astrophysical conditions, such as entropy, expansion timescale, or details of the reverse shock [37, 42, 43, 8, 10, 11]. Variations of reaction rates have at most a small effect on the location of the νp -process path [37, 42, 10]. This is due to the fact the (p,γ) - (γ,p) equilibrium is upheld until late times. Hence, the abundance maximum in each isotonic chain is given by the equilibrium abundance, as seen in figure 5. Figure 6 shows the effective lifetimes for each nucleus. The maximum abundance within a chain is characterized by a low (p,γ) reaction Q -value because the relative speed of forward and reverse rate depends exponentially on the Q -value [37, 29]. The largest flux into the next isotonic chain occurs at these nuclei, which would be waiting points in a pure rp -process [24]. As can be seen in figure 6, these nuclei indeed exhibit longer lifetimes. Nevertheless, if the neutron abundance is sufficiently high they may still be overcome. This implies that a variation of the neutron density or the (n,p) rate on these waiting points will mostly affect how fast nuclei with larger Z can be reached within the timescale of the expansion. If the neutron density is sufficiently high at late times, (n,γ) reactions can become the fastest reactions, even faster than β -decays, and the νp -process path is pushed towards stability at and above the Sn isotopes by (n,γ) reactions [11], providing a strong barrier for the efficient production of elements beyond Sn. The fact that the location of the νp -process path is largely determined by nuclear physics properties make any conclusions on the sensitivity of the final abundances to the nuclear physics inputs robust. A detailed list of the critical nuclear reactions, including implications for experiments, can be found in Ref. [37].

4. Summary

The νp -process nucleosynthesis and its uncertainty due to nuclear physics has been studied. The main trajectory dependence originates from the possible variation of the neutron abundance Y_n , and thus of the neutron density $\rho_n = \rho Y_n$, due to different ν_e fluxes experienced during the expansion of the matter. This has a similar impact as a variation of the reaction cross sections of neutron-induced reactions. From detailed reaction variation studies, a different role has been found for ^{56}Ni and the nuclei above the iron group. The nucleus ^{56}Ni - which is the seed nucleus for the νp -process - acts as neutron poison due to its high abundance.

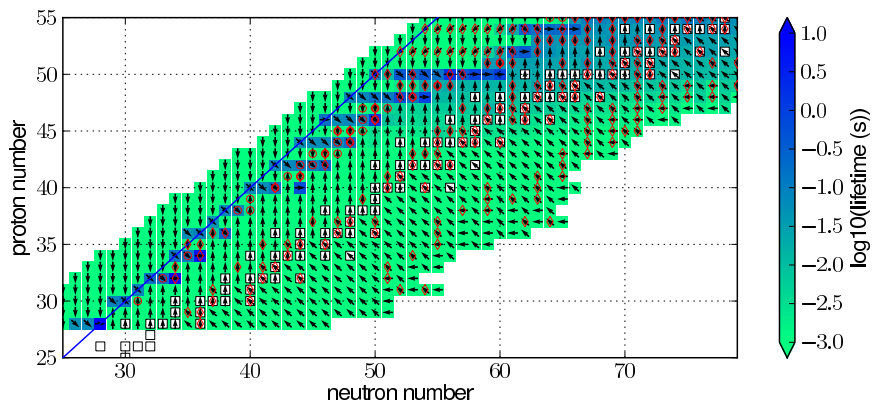


Figure 6. Same as figure 5, but with destruction lifetimes against the dominating reaction.

Neutron capture reactions on nuclei above the iron group govern the flow from one isotonic chain into the next and hence determine how fast nuclei with large Z can be reached. The time evolution of the hydrodynamic quantities determines how long favorable conditions for νp -process nucleosynthesis can be sustained. The location of the νp -process path has been found to mainly depend on the nuclear physics and hence results are independent of the trajectory variations.

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