

# Neutrino-nucleus reactions and their role in supernova nucleosynthesis

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**Abstract.** Neutrino reactions on nuclei play important roles for the dynamics of supernovae and their associated nucleosynthesis. This manuscript summarizes the current status in deriving the relevant cross sections for supernova neutrinos and discusses the importance of neutrino-nucleus reactions for supernova nucleosynthesis. In particular we report on the first study of neutrino nucleosynthesis which consistently considers time-dependent spectra for all neutrino flavors as predicted by supernova simulations.

## 1. Introduction: Neutrinos and core-collapse supernovae

Neutrinos are key-players for the supernova dynamics [1, 2]. During the collapse phase the main neutrino source is electron capture on nuclei [3, 4]. By lowering the electron-to-nucleon ratio  $Y_e$  this process reduces the pressure which electrons can stem against the gravitational collapse of the core. Furthermore, at sufficiently low densities the electron neutrinos generated by the capture process can leave the star unhindered keeping the core at relatively low entropies so that heavy nuclei survive the collapse. At densities in excess of about  $10^{12}$  g/cm<sup>3</sup> neutrinos get trapped in the core, mainly by elastic scattering on nuclei. The thermalization of neutrinos with the other core matter occurs by energy exchange via inelastic scattering on electrons and, in a lesser extent, on nuclei. In the final collapse phase at high densities pair production of neutrinos of all flavors becomes relevant. This occurs mainly by nucleon-nucleon bremsstrahlung [5, 6], but also nuclear deexcitation has been identified recently as an important additional source of neutrinos other than electron neutrinos [7]. After core bounce, energy transport by neutrinos from hotter core regions to the matter behind the stalled shock helps to revive the shock [8, 2]. The dominating processes are absorption of electron neutrinos and anti-neutrinos on neutrons and protons. The competition of these two absorption processes also determines the proton-to-neutron ratio for the subsequent explosive nucleosynthesis which might occur either in proton-rich environment ( $\nu p$  process [9, 10, 11]) or in neutron-rich environment. The later scenario has been favored for many years as the possible site for the astrophysical r-process (neutrino-driven wind model, [12]), but recent supernova simulations indicate that the conditions in the neutrino-driven wind are probably only sufficient to support a weak r-process which contributes to the observed r-process abundances up to the barium mass region (second r-process peak, e.g. [13]). There have been several suggestions how neutrino reactions on nuclei might contribute to supernova r-process nucleosynthesis (e.g. [14, 15, 16]), but recent studies point to no significant



influence of these processes [17, 18]. Neutrino-induced spallation reactions, however, are crucial, for the production of selected nuclei ( $\nu$  process [19]). Finally, the observation of supernova neutrinos by earthbound detectors is an eminent tool to verify our understanding of the supernova dynamics and mechanism. One requisite here is the knowledge of the neutrino reaction cross sections for the nuclei comprising the detector material.

There has been a recent extensive review of neutrino-nucleus reactions and their role in supernovae which might be consulted for more details [20].

## 2. Cross section models

Supernova neutrinos, independently of their production mechanism by electron capture and nuclear deexcitation during collapse or by pair production in the cooling phase of the proto-neutron star, have relatively low energies (up to a few 10's of MeV). At these energies the cross sections are dominated by allowed transitions. Forbidden transitions become relevant at the higher neutrino energies and in cases where allowed transitions are strongly suppressed [21]. The Fermi contribution to the cross sections are defined by the position of the Isobaric Analog State and the respective sum rule. Charge-exchange experiments have progressed our understanding of Gamow-Teller (GT) distributions significantly in the last two decades [27, 28]. The distributions are strongly fragmented. This is caused by nucleon-nucleon correlations and is well described by nuclear models like the diagonalization shell model which accounts for such correlations [29, 4, 30]. In fact, the combined progress due to experimental GT data from charge-exchange experiments and their detailed description by shell model calculations (except for a constant renormalization factor) have led to a rather reliable description of stellar electron capture (and electron neutrino absorption as its inverse process) [31, 32, 33, 34]. Recent residual shell model interactions (improved parametrizations of [35]), motivated by detailed GT data for selected nuclei (e.g. [36]) have led to improved estimates of the electron capture rates on nuclei in the iron-nickel mass range [37]. However, its impact on the supernova dynamics is rather limited. For example, the new capture rates change the abundance yields of medium-mass nuclei in thermonuclear supernovae by at most a few percent [38] compared to studies [4, 39] using the original shell model rates [31]. It should be stressed that these original rates, however, being more than an order of magnitude smaller than the until then default capture rates of Fuller et al. [40], solved a longstanding puzzle in type Ia supernova nucleosynthesis related to the notable overproduction of neutron-rich nuclei [41, 39].

Electron capture is the dominating weak interaction process during the collapse phase [2, 3, 42, 43]. The absorption of neutrinos on nuclei is the inverse process of electron and positron capture. Its calculation has also benefitted from the advances in describing GT distributions. In supernova simulations it is incorporated via detailed balance with the inverse capture processes. Forbidden transitions become relevant at neutrino energies high enough that reliable cross section calculations only require the reproduction of the energy centroids and total strengths of the respective transitions distributions, but not their detailed description. These requirements are fulfilled by the Random Phase Approximation (RPA). Hence a 'hybrid model' has been proposed in which the allowed contributions to the neutrino-nucleus cross sections are calculated by the shell model and the forbidden contributions within the RPA formalism [44]. For specific nuclei, which are relevant for neutrino nucleosynthesis like  $^{12,13}\text{C}$  and  $^{16}\text{O}$ , there exist detailed shell model calculations of the relevant cross sections in appropriate model spaces performed by Suzuki and collaborators [22, 23, 24, 25, 26].

Inelastic neutrino-nucleus scattering can be also evaluated within the hybrid model ansatz for temperature  $T = 0$ . Validation for this procedure can be derived from precision M1 data for spherical nuclei, measured by inelastic electron scattering, which are dominated by the same nuclear transitions [45]. At stellar temperatures, however, transitions mediated from thermally populated excited nuclear states modify the cross sections at low neutrino energies significantly.

Two approaches have been proposed to incorporate these modifications: i) by extending the hybrid model to include selected GT transitions involving excited states [45] and ii) within the consistent extension of the RPA to finite temperatures (Thermal Quasiparticle RPA) [46, 47, 48].

Neutrino-nucleus reactions often excite the daughter nucleus to states above particle thresholds which then subsequently decay by particle emissions. The probabilities for decay into different particle channels can be calculated within the statistical model. Nuclear spallation reactions are important for supernova nucleosynthesis and potentially also as detection signal for certain supernova neutrino detectors [49].

### 3. Neutrino-nucleus reactions in supernova dynamic and nucleosynthesis

In this section we briefly summarize selected recent examples in which the role of neutrino-nucleus reactions have been investigated for the production of selected nuclei in various neutrino nucleosynthesis processes.

#### 3.1. The $\nu p$ process

The continuous emission of neutrinos from the protoneutron star drives a low-mass outflow (the neutrino-driven wind). Due to the high temperature involved the matter is ejected as free protons and neutrons. Upon reaching cooler regions further away from the neutron star, the matter can assemble into nuclei. The outcome of this nucleosynthesis depends crucially on the proton-to-neutron ratio and can support the  $\nu p$  process if  $Y_e > 0.5$ .

The proton-to-neutron ratio is mainly determined by the neutrino and antineutrino charged-current reactions with the free neutrons and protons [51]. It is important that in the kinematics of the neutrino-nucleon reactions corrections due to the nuclear interaction are included. The dominant contribution is due to mean-field corrections, induced by the astrophysical environment and accounted for in the Equations of State [52, 53]. Also the interaction of neutrinos with light nuclides (deuterons,  $^3\text{H}$ ,  $^3\text{He}$ , and  $^4\text{He}$ ) has an impact on the average energies of neutrinos and antineutrinos [54].

Supernova simulations indicate that during some period after bounce the hot matter ejected from the surface of the freshly born neutron star is proton-rich (e.g. [55]). The alpha rich freeze-out of such proton-rich matter favors the production of  $\alpha$  nuclei (mainly  $^{56}\text{Ni}$ ) with some free protons left [56]. We note that this freeze-out also results in enhanced abundances of selected nuclei in the Ca-Fe mass range bringing them into better agreement with observation [9].

Heavier nuclides can be synthesized from the freeze-out abundance distribution by subsequent proton captures, competing with  $\beta^+$  decays. We note that this reaction sequence is realized in the so-called rapid-proton capture process (i.e. explosive hydrogen burning on the surface of neutron stars in X-ray bursts) [57]. However, in this scenario the mass flow to heavier nuclides is strongly hampered by the increasing Coulomb barrier of the produced elements and, in particular, by the so-called waiting point nuclei. These are  $\alpha$  nuclei like  $^{56}\text{Ni}$ ,  $^{64}\text{Ge}$ ,  $^{68}\text{Se}$ ... which have relatively long  $\beta$  half lives and for which the proton capture is strongly hindered due to the small or negative proton binding energies of the final nuclei (e.g.  $^{57}\text{Cu}$ ,  $^{65}\text{As}$ ,  $^{69}\text{Br}$ , ...). In contrast to the nucleosynthesis in X-ray bursts, the process occurs in the supernova environment in the presence of extremely intense neutrino fluxes which influences and alters the matter flow to heavier nuclei substantially. While the energy of supernova  $\nu_e$  neutrinos is too small to induce sizable reaction rates on  $N \sim Z$  nuclei, this is different for antineutrinos that are captured in a typical time of a few seconds in the conditions of the hot neutrino bubble, both on protons and nuclei, at the distances at which nuclei form ( $\sim 1000$  km). This time scale is much shorter than the weak-decay half-life of the most abundant heavy nuclei (e.g.  $^{56}\text{Ni}$ ,  $^{64}\text{Ge}$ ). As protons are more abundant than heavy nuclei, antineutrino capture occurs predominantly on protons, causing a steady supply of free neutrons for several seconds [10]. The neutrons produced via antineutrino absorption on protons can easily be captured by neutron-deficient  $N \sim Z$  nuclei

(for example  $^{64}\text{Ge}$ ), which have large neutron capture cross sections. The amount of nuclei with  $A > 64$  produced is then directly proportional to the number of antineutrinos captured. While proton capture,  $(p, \gamma)$ , on  $^{64}\text{Ge}$  takes too long, the  $(n, p)$  reaction dominates (with a lifetime of 0.25 s at a temperature of 2 GK), permitting the matter flow to continue to nuclei heavier than  $^{64}\text{Ge}$  via subsequent proton capture up to the mass range  $A \sim 80 - 100$  (for a mass-flow diagram see, for example, Ref. [58]). This nucleosynthesis process, operating in proton-rich supernova environment, is called the  $\nu p$ -process [10]. How far the mass flow within the  $\nu p$  process can proceed strongly depends on the environmental conditions, most noticeable on the  $Y_e$  value of the ejected matter.

### 3.2. Neutrino nucleosynthesis

When neutrinos, produced in the hot supernova core, pass through the outer shells of the star, they can induce nuclear reactions and in this way contribute to the elementsynthesis (the  $\nu$ -process, [19]). For example, the nuclides  $^{11}\text{B}$  and  $^{19}\text{F}$  are produced by  $(\nu, \nu'n)$  and  $(\nu, \nu'p)$  reactions on the quite abundant nuclei  $^{12}\text{C}$  and  $^{20}\text{Ne}$ . These reactions are dominantly induced by  $\nu_\mu$  and  $\nu_\tau$  neutrinos and their antiparticles (combined called  $\nu_x$  neutrinos) [19]. As found in detailed stellar evolution studies [59] the rare odd-odd nuclides  $^{138}\text{La}$  and  $^{180}\text{Ta}$  are mainly made by the charged-current reaction  $^{138}\text{Ba}(\nu_e, e^-)^{138}\text{La}$  and  $^{180}\text{Hf}(\nu_e, e^-)^{180}\text{Ta}$ . Hence, the  $\nu$ -process is potentially sensitive to the spectra and luminosity of  $\nu_e$  and  $\nu_x$  neutrinos, which are the neutrino types not observed from SN1987a.

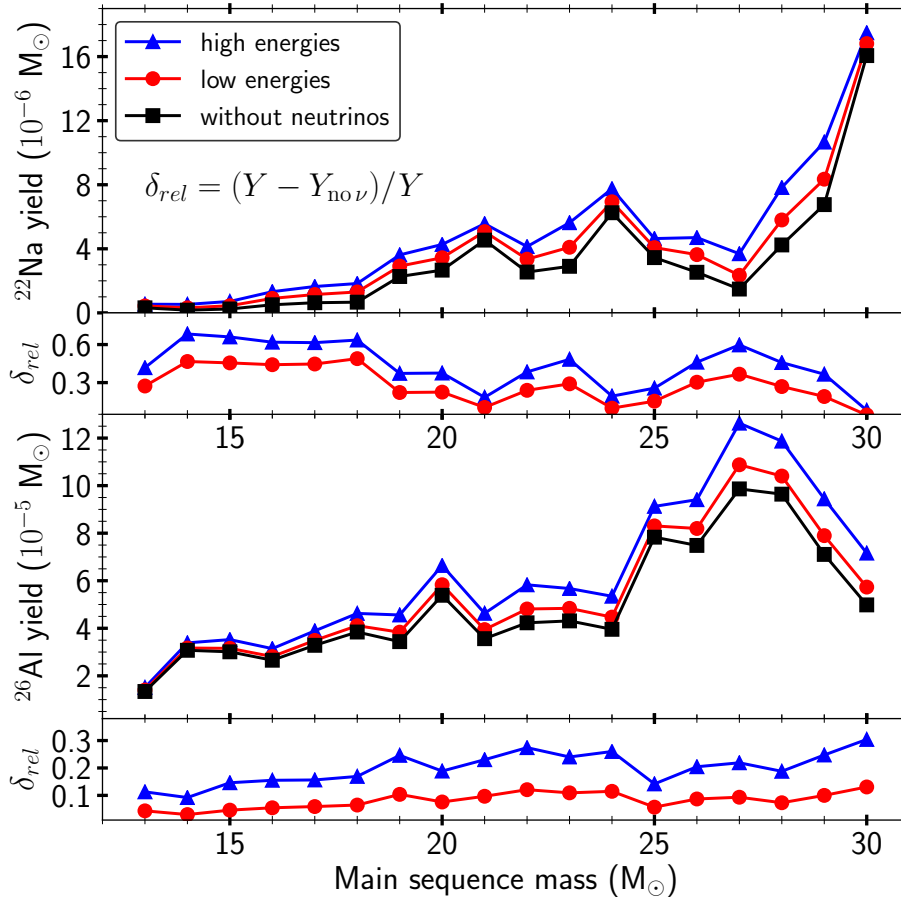
We note that, as a major improvement, it has been possible to measure the GT strengths on  $^{138}\text{Ba}$  and  $^{180}\text{Hf}$  below the particle thresholds and to convert these data into the relevant  $(\nu_e, e^-)$  cross sections [60]. It is found that the new cross sections are slightly larger than the RPA predictions.

It is expected that the average energies for supernova neutrinos obey an energy hierarchy:  $(\langle E_{\nu_e} \rangle < \langle E_{\nu_x} \rangle)$ . Based on this assumption, neutrino oscillations should increase the average  $\nu_e$  energy and consequently also the charged-current cross section induced by supernova neutrinos. As pointed out by Kajino and collaborators, this makes the ratio of  $^7\text{Li}$  and  $^{11}\text{B}$  sensitive to the  $\theta_{13}$  mixing angle and to the mass hierarchy [61, 62, 63]. Despite this intriguing sensitivity, an accurate derivation of the  $^7\text{Li}/^{11}\text{B}$  abundance ratio requires reliable stellar model calculations and neutrino and nuclear cross sections, but must also consider the production of the elements from other astrophysical sources;  $^7\text{Li}$  is, for example, also produced by Big Bang nucleosynthesis [64].

We report now about recent studies of neutrino nucleosynthesis which decisively and conceptually improved the treatment of neutrino luminosities, energies and spectra as well as of reaction network.

Recent supernova simulations, with improved descriptions of neutrino matter interactions, indicate that the average neutrino energies are smaller than previously assumed. Furthermore, the average energies of  $\bar{\nu}_e$  and  $\nu_x$  neutrinos (derived from the cooling phase) are quite similar, while the  $\nu_e$  average energies are somewhat smaller. The lowering of the average energies should result in reduced neutrino-induced cross sections and hence lower elemental production rates. This has been the motivation of a recent neutrino nucleosynthesis study performed for stars with masses between 15 and 30  $M_\odot$  and including neutrino-nucleus cross sections for a large set of nuclei with  $Z < 78$ . As an additional improvement in comparison to previous calculations these nucleosynthesis studies considered differential cross sections for multi-particle emissions [66]. Mainly due to the change in neutrino spectra, this study finds slightly smaller abundances for  $^7\text{Li}$ ,  $^{11}\text{B}$ ,  $^{138}\text{La}$  and  $^{180}\text{Ta}$ , however, it confirms the production of these nuclides by neutrino nucleosynthesis [67].

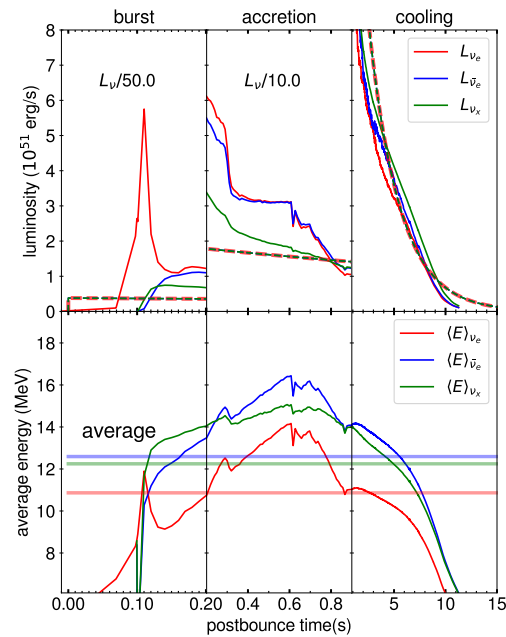
As is shown in Fig. 1, the study also finds that neutrino-induced reactions, either directly or indirectly by providing an enhanced abundance of light particles, noticeably contribute to



**Figure 1.** Yields of  $^{26}\text{Al}$  and  $^{22}\text{Na}$  for various progenitor stars as well as the relative change due  $\delta_{rel}$  due to the  $\nu$  process. The calculations have been performed with the modern low-energy supernova neutrino spectrum (red circles), the high-energy spectrum considered in previous studies (e.g. [59]) (blue triangles) and without consideration of neutrino-nucleus reactions (black squares). (from [67])

the production of the radioactive nuclides  $^{22}\text{Na}$  and  $^{26}\text{Al}$ , which are both prime candidates for gamma-ray astronomy. However, the studies do not find significant production of two other candidates,  $^{44}\text{Ti}$  and  $^{60}\text{Fe}$ , due to neutrino-induced reactions. It is noted that these calculations could use data from charge-exchange reaction measurements to constrain the GT part of the neutrino-induced reaction cross sections for  $^{20}\text{Ne}$  and  $^{26}\text{Mg}$ , which both impact the  $^{26}\text{Al}$  abundance.

As can be seen in Fig. 2, neutrino luminosities and average energies change with time after core bounce. For the luminosities this was approximately considered in previous studies (e.g. [19, 59, 67]). Very recently Sieverding *et al.* investigated the effect of the time-dependent average neutrino energies on the  $\nu$ -process abundances [68] adopting the neutrino spectra from a supernova simulation of a  $27M_{\odot}$  star reported in Ref. [65]. In particular these authors included for the first time also the neutrino burst and accretion phases into their studies of neutrino nucleosynthesis [68]. We note that the neutrino burst is due to electron capture on protons just after dissociation of heavy nuclei by the shock wave. The burst is solely in  $\nu_e$  neutrinos and, although it lasts only for some milliseconds, carries about 10% of the total  $\nu_e$  luminosity. Considering the time dependence of the neutrino spectra has a significant effect on



**Figure 2.** Neutrino luminosities and average energies as function of time after core bounce (taken from [65]).

nucleus	model 1a $\alpha = \alpha(t)$	model 1b $\alpha = 2.3$	model 2 $\alpha = 2.3$	model 3 $\alpha = 2.3$ D
${}^7\text{Li}$	0.04	0.04	0.03	0.02
${}^{11}\text{B}$	0.30	0.31	0.28	0.18
${}^{15}\text{N}$	0.06	0.05	0.05	0.04
${}^{19}\text{F}$	0.12	0.12	0.11	0.10
${}^{138}\text{La}$	0.69	0.74	0.66	0.41
${}^{180}\text{Ta}^m$	1.32	1.33	1.27	1.09

**Table 1.** Neutrino nucleosynthesis production factors normalized to  ${}^{16}\text{O}$ , comparing different models to describe the various neutrino spectra. Model 1a considers the time-dependent spectra as calculated in the supernova simulation for a  $27 M_\odot$  star [65]. In all other models the neutrino spectral form resembles a Fermi-Dirac distribution (with the parameter  $\alpha$  in the quasithermal distribution given in [69] set to  $\alpha = 2.3$ ). Model 1b uses the time-dependent neutrino luminosities and average energies from [65]. Model 2 accounts also for all phases of neutrino emission (burst, accretion, cooling), but assumes constant (time-independent) average neutrino energies. Model 3 resembles the previous treatment of neutrino spectra in the literature, assuming constant neutrino average energies defined from the cooling phase only. (quoted from [68])

the neutrino nucleosynthesis. This is summarized in Table 1. In particular the abundance of nuclides which are produced by  $(\nu_e, e^-)$  reactions, like  $^{138}\text{La}$  and  $^{180}\text{Ta}$ , are increased noticeably compared to calculations which assumed neutrino spectra with constant average energies that do not take into account the early phases of emission (model 1a vs model 3). This is due to additional contributions to the abundances coming mainly from the burst and accretion phases. Due to the non-linear energy dependence of the neutrino-nucleus cross sections, energies that are higher than the late-time values during the first few hundred milliseconds, have a particularly large impact on the production. The exact treatment of the shape of the neutrino spectra is found to have a negligible effect on the  $\nu$ -process yields (model 1a vs model 1b). Replacing the time-dependent neutrino energies by a constant average neutrino energy, derived from the full time evolution of the neutrino emission, decreases the  $\nu$ -process yields slightly (model 1a vs model 2). The rather noticeable differences between the yields obtained in models 2 and 3 underline the important contributions of the neutrino burst and the accretion phases, which both correspond to relatively large neutrino energies and were neglected in previous studies (e.g. [19, 59, 61]). We note that the  $\nu$ -process presents a rather delicate competition between the time-scales for the shock passage and for the decline in neutrino energies. This competition can have opposite effects on the yields depending on where in the star the production occurs [68]. This is a strong argument why the time-dependence of the neutrino luminosities and energies should be accounted for in studies of the  $\nu$  process. Similar investigations for stars of different masses are called for.

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