

# Neutrino nucleosynthesis in core-collapse Supernova explosions

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**Abstract.** The neutrino-induced nucleosynthesis ( $\nu$  process) in supernova explosions of massive stars of solar metallicity with initial main sequence masses between 15 and 40  $M_{\odot}$  has been studied. A new extensive set of neutrino-nucleus cross-sections for all the nuclei included in the reaction network is used and the average neutrino energies are reduced to agree with modern supernova simulations. Despite these changes the  $\nu$  process is found to contribute still significantly to the production of the nuclei  ${}^7\text{Li}$ ,  ${}^{11}\text{B}$ ,  ${}^{19}\text{F}$ ,  ${}^{138}\text{La}$  and  ${}^{180}\text{Ta}$ , even though the total yields for those nuclei are reduced. Furthermore we study in detail contributions of the  $\nu$  process to the production of radioactive isotopes  ${}^{26}\text{Al}$ ,  ${}^{22}\text{Na}$  and confirm the production of  ${}^{92}\text{Nb}$  and  ${}^{98}\text{Tc}$ .

## 1. Introduction

Core-Collapse-Supernova explosions are the most energetic events known to astronomers. The conditions created by the passage of the supernova shockwave through the chemically enriched layers of massive stars allow for important nucleosynthesis processes to occur which are crucial for the enrichment of the interstellar medium and chemical evolution of the universe. A major part of the energy released by the core-collapse leaves the stellar core as neutrinos of all flavors. Those neutrinos can interact with the shock-heated material and affect the nucleosynthesis. In recent years multi-dimensional supernova simulations have given new insights concerning the neutrino radiation. Neutrinos with energies of the order of 10 MeV can lead to nuclear excitations beyond the particle separation threshold, affecting the chemical composition and density of free nucleons. Furthermore, electron neutrinos and electron antineutrinos can be captured by nuclei, leading to the inverse process of  $\beta$ -decay.

Following the approach of previous studies we choose a highly parametrized supernova model as described in reference [1] which allows a exploration of the parameter space of the neutrino properties and the explosion. The key ingredient of the explosive nucleosynthesis is the peak temperature of the shock heated material. This is estimated by an analytic expression that has been shown to agree reasonably well with hydrodynamical simulation. The decrease of temperature and density are modeled to be exponential on a density dependent timescale.



**Table 1.** Production factors relative to solar abundances from reference [8], normalized to  $^{16}\text{O}$  production. Shown are the results obtained without neutrinos, with our choice of neutrino temperatures (“Low energies”,  $T_{\nu_e} = 2.8$  MeV,  $T_{\bar{\nu}_e} = T_{\bar{\nu}_{\mu,\tau}} = T_{\nu_{\mu,\tau}} = 4.0$  MeV), and with the choice of ref. [5] (“High energies”,  $T_{\nu_e} = T_{\bar{\nu}_e} = 4.0$  MeV,  $T_{\nu_{\mu,\tau}} = T_{\bar{\nu}_{\mu,\tau}} = 6.0$  MeV) for  $25 M_{\odot}$  progenitor model.

Star	Nucleus	no $\nu$	Low energies	High energies
$25 M_{\odot}$	$^7\text{Li}$	0.0005	0.11	0.55
	$^{11}\text{B}$	0.003	0.80	2.61
	$^{15}\text{N}$	0.08	0.10	0.13
	$^{19}\text{F}$	0.06	0.24	0.43
	$^{138}\text{La}$	0.03	0.63	1.14
	$^{180}\text{Ta}$	0.14	1.80	2.81

Neutrinos are assumed to have Fermi-Dirac spectra with chemical potential  $\mu_{\nu} = 0$ , characterized by a neutrino temperature  $T_{\nu}$  related to the average energy by  $\langle E_{\nu} \rangle \approx 3.14 T_{\nu}$ . Neutrino luminosities are modeled with and exponential decrease on the timescale of 3 s. A total energy of  $10^{53}$  erg is distributed equally among the 6 neutrino flavors, leading to number fluxes according to the average energy of the prescribed to the corresponding neutrino type.

Our set of neutrino-nucleus cross-sections has been calculated for both, charged- and neutral-current reactions, based on Random Phase Approximation (RPA) [2]. Spallation products in the case of states above particle separation threshold are computed based on statistical models [3].

We use solar metallicity supernova progenitors calculated by A. Heger et al. [4], with main sequence masses ranging between 15 and  $40 M_{\odot}$ . The stellar models have been evolved up to core-collapse, providing the initial conditions and composition for the further evolution parametrized as stated above.

## 2. Canonical $\nu$ process nuclei

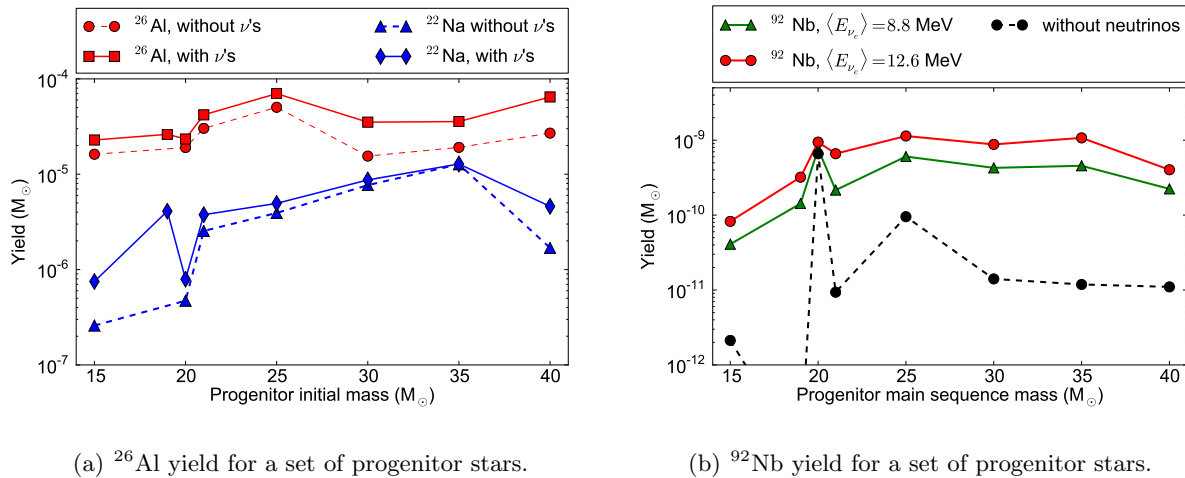
The  $\nu$  process is known to have significant effects on the production of  $^7\text{Li}$ ,  $^{11}\text{B}$ ,  $^{19}\text{F}$ ,  $^{138}\text{La}$  and  $^{180}\text{Ta}$ . Previous studies of neutrino nucleosynthesis have assumed average neutrino energies of  $\langle E_{\nu_e, \bar{\nu}_e} \rangle = 12.6$  MeV,  $\langle E_{\nu_x} \rangle = 18.8$  MeV, where  $\nu_x$  corresponds to  $\nu_{\mu}$ ,  $\bar{\nu}_{\mu}$ ,  $\nu_{\tau}$  and  $\bar{\nu}_{\tau}$  [5]. Using instead significantly reduced values of  $\langle E_{\nu_e} \rangle = 8.8$  MeV,  $\langle E_{\bar{\nu}_e, \nu_x} \rangle = 12.6$  MeV as suggested by detailed simulations e.g. in references [6, 7] we still see a significant increase in the production of  $^7\text{Li}$ ,  $^{11}\text{B}$ ,  $^{19}\text{F}$ ,  $^{138}\text{La}$  and  $^{180}\text{Ta}$  due to neutrino-induced reactions (see Table 1).

We observe, that the the  $15 M_{\odot}$  progenitor model overproduces  $^{19}\text{F}$  even without neutrinos mainly via the reaction chain  $^{18}\text{O}(p, \alpha)^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$  operating on  $^{18}\text{O}$  at the lower edge of the He-shell. Due to the stellar structure this process does not work for the more massive progenitor models and here the  $\nu$  process can make a major contribution.

A direct comparison between the present results and the results of reference [5] tends to be misleading, since differences appear due to the different treatment of hydrodynamic variables. Work to disentangle changes due to different neutrino interactions from changes due to the hydrodynamics is in progress.

## 3. Impact on radioactive nuclei

Observations of  $\gamma$ -rays allow direct access to the production of  $^{26}\text{Al}$  in the galaxy. Supernova explosions are assumed to give a significant contribution to the overall abundance of  $^{26}\text{Al}$  [9].



**Figure 1.** Shown are the results of calculations without neutrinos (dashed lines) and including neutrinos with different spectra. Electron neutrinos and anti-neutrinos are assumed have a distribution with  $T_{\nu_e} = T_{\bar{\nu}_e} = 4$  MeV.

Previous studies have already reported an enhancement of the production of  $^{26}\text{Al}$  by 30% to 50% [10] due to neutrinos. This effect is largely due to neutral-current spallation reactions that increase the abundance of free protons, enhancing capture reactions on  $^{25}\text{Mg}$  in the Oxygen-Neon shells. In our calculations we even find an increase in the production of  $^{26}\text{Al}$  of up to a factor of 2 for the 30 and 35  $M_\odot$  progenitor models. Especially in those cases the charged-current reaction  $^{26}\text{Mg}(\nu_e, e^-)^{26}\text{Al}$  is found to be the dominating channel for the increased production.

The decay of  $^{22}\text{Na}$  it is relevant for the description of supernova lightcurves [11]. In our calculations the production of  $^{22}\text{Na}$  is increased up to a factor of 3, mainly due to increased proton captures on  $^{22}\text{Ne}$  and  $^{22}\text{Ne}(\nu_e, e^-)^{22}\text{Na}$ .

In total we find also for  $^{22}\text{Na}$  an increase of the relative importance of charged-current channels, as discussed in more detail in reference [12].

We can also confirm significant contributions of the  $\nu$  process to the production of  $^{92}\text{Nb}$  and  $^{98}\text{Tc}$  due to electron neutrino absorption on the corresponding isobars, as also discussed in [13].

Furthermore, we find a significant enhancement of the production of the short-lived radioisotope  $^{36}\text{Cl}$ . The characteristic  $\gamma$ -rays from the decay of  $^{44}\text{Ti}$  and  $^{60}\text{Fe}$  are also used as tracers for active nucleosynthesis sites [9, 14]. The effect of neutrino interactions on the yields of  $^{44}\text{Ti}$  and  $^{60}\text{Fe}$  have been found to be at most 2% in the case of  $^{44}\text{Ti}$  and even less for  $^{60}\text{Fe}$ .

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