Neutrino Nucleosynthesis of radioactive nuclei in supernovae*

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Core-Collapse-Supernova explosions are the final stage of stellar nucleosynthesis and are crucial for the determination of the chemical composition of material that is ejected and enriches the interstellar medium, forming the basis for the next generation of stars. A major part of this nucleosynthesis happens as the shock front launched from the remnant of the stellar core passes through the layers of the star, increasing temperature and density and triggering nuclear processes. At the same time these layers are irradiated by neutrinos of all flavors, that are emitted as the remnant of the stellar core cools. We have performed nucleosynthesis calculations for a set of models of core-collapse supernovae including an extensive set of neutrino-nucleus interactions. Compared to previous studies of ν-nucleosynthesis, we use neutrino spectra corresponding to reduced average energies in agreement with modern core-collapse simulations [1]. For simplicity we assume, that each type $x \in \{e, \mu, \tau\}$ of neutrino follows a Fermi-Dirac distribution characterized by a corresponding temperatures T_{ν_x} with zero chemical potential. We assume $T_{\nu_e} = 2.8$ MeV, $T_{\bar{\nu}_e} = T_{\nu_{\mu,\tau}} = 4.0$ MeV

The main candidates for neutrino nucleosynthesis are ^{7}Li, ^{11}B, ^{19}F, ^{138}La and ^{180}Ta [2], all of which are observed in the solar system, but are not produced in sufficient amount by supernova simulations without including neutrino interactions. Neutrino nucleosynthesis can push the production factors of those nuclei close to the solar system values, as shown in table 1. Furthermore, reference [3] has discussed the ν-process in supernovae as a production site for the radioactive isotopes ^{92}Nb and ^{98}Tc. Our calculations confirm that charged-current neutrino interactions increase the yield of ^{92}Nb and ^{98}Tc significantly.

Observations of γ-rays allow direct access to the production of radioactive nuclei. Among the most interesting γ-ray sources that indicate active nucleosynthesis are ^{22}Na, ^{26}Al, ^{44}Ti and ^{60}Fe. Neutrinos contribute to the production of ^{26}Al during the explosive phase by two different mechanisms. First, neutrino-induced spallation reactions on the most abundant nuclei int the O/Ne shell, ^{20}Ne,^{24}Mg and ^{16}O increase the number of free protons, which enhances the reaction ^{25}Mg(p,γ), which is the main production channel also without neutrinos. Additionally, the charged-current reaction ^{26}Mg(ν_e,e$^-$) gives significant contributions. Both mechanisms contribute to a similar extent to the production and both occur in the O/Ne layer. In total we find an increase of the ^{26}Al yield by factors between 1.4 and 2.0.

Table 1: Production factors relative to solar abundances from reference [4], normalized to ^{16}O production. Shown are the results from our calculations without neutrinos, with the low energy neutrino spectra we now consider more realistic as stated above. Also shown are the results for the "high" energy neutrino spectra ($T_{\nu_e} = T_{\bar{\nu}_e} = 4.0$ MeV, $T_{\nu_{\mu,\tau}} = 6.0$ MeV) for comparison with [2].

Nucleus	no ν	Low energies	High energies
15 M$_\odot$ star			
^{7}Li	0.001	0.28	2.54
^{11}B	0.007	1.43	6.13
^{15}N	0.67	0.68	0.79
^{19}F	1.02	1.14	1.31
^{138}La	0.07	0.67	1.18
^{180}Ta	0.07	1.14	1.81
25 M$_\odot$ star			
^{7}Li	0.0005	0.11	0.55
^{11}B	0.003	0.80	2.61
^{15}N	0.08	0.10	0.13
^{19}F	0.06	0.24	0.43
^{138}La	0.03	0.63	1.14
^{180}Ta	0.14	1.80	2.81

Similarly, the production of ^{22}Na is increased on average by a factor of 3.1 , mainly due to increased proton captures on ^{22}Ne and ^{23}Na(ν_e,e$^-$ p)^{22}Na. Further contributions are provided by the neutral current neutron evaporation on ^{23}Na and the charged-current reaction ^{22}Ne(ν_e,e$^-$)^{22}Na. We find that the balance of the different production channels and the total enhancement depends

The effect of neutrino interactions on the yields of ^{44}Ti and ^{60}Fe have been found to be at most 2% in the case of ^{44}Ti and even less for ^{60}Fe.

References

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