Proc. 14th Int. Symp. on Nuclei in the Cosmos (NIC2016)
JPS Conf. Proc. **14**, 020701 (2017)
https://doi.org/10.7566/JPSCP.14.020701

Neutrino Induced Nucleosynthesis of Radioactive Nuclei in Core-Collapse Supernovae

Andre SIEVERDING[1], Gabriel MARTÍNEZ-PINEDO[1,2], Karlheinz LANGANKE[1,2] and Alexander HEGER[3]

[1] *Technical University of Darmstadt, Institute for Nuclear Physics, Schlossgartenstr. 2, 64289 Darmstadt, Germany*
[2] *GSI Helmhotz Centre for Heavy Ion Research, Planckstr. 1, 6429 Darmstadt, Germany*
[3] *Monash Centre for Astrophysics, School of Physics and Astronomy, Monash University, Victoria 3800, Australia*

E-mail: asiever@theorie.ikp.physik.tu-darmstadt.de

(Received August 17, 2016)

We study the impact of neutrino-nucleus reactions on the nucleosynthesis in shock- heated supernova ejecta. Nucleosynthesis calculations with an extensive set of neutrino-induced reactions are performed, including updated insights into expected neutrino properties in a Supernova environment. Sensitivities and mechanisms of the production of the the main ν process products ^{7}Li,^{11}B,^{19}F,^{138}La,^{180}Ta and effects on radioactive nuclei like ^{26}Al are explored.

KEYWORDS: Core-Collapse Supernovae, Neutrinos, Nucleosynthesis

1. Introduction

Neutrinos play a major role for many aspects of Core Collapse Supernovae [1]. In addition to the Collapse timescale and the shock revival neutrinos also have a direct effect on the final nucleosynthesis yields. The Supernova explosion heats and compresses the chemically enriched layers of the star and finally ejects them after a final phase of nucleosynthesis has taken place. Compared to all the hydrostatic stellar burning phases this explosive nucleosynthesis takes place on a much shorter timescale and it is accompanied by intense neutrino irradiation from the accreting and cooling core. Woosley et al. [2] have provided the first quantitative study of the effect that this ν process can have on final nucleosynthesis results. They found that high energy neutrinos can knock out particles from the abundant nuclei present in the chemically enriched layers of a massive star, contributing to the production of several rare isotopes, particularly ^{7}Li,^{11}B,^{19}F,^{138}Li,^{180}Ta. Neutrino irradiation was later included into detailed calculations of supernova nucleosynthesis [3] with some improvements of a few specific rates [4] and possible effects of neutrino oscillations have been explored [5].

2. Importance of charged-current reactions for ^{26}Al

Recent advances (e.g. [6]) in Supernova simulation provide increasingly detailed information about the neutrino properties due to a sophisticated treatment of the neutrino transport problem. As a result, it is now expected, that the average neutrino energies will be lower than the canonical estimates. Especially, the μ- and τ neutrinos and anti-neutrinos are no longer expected to be exceedingly more energetic than the electron flavor neutrinos and as a result the neutral current induced spallation reactions cannot be assumed to dominate over charged-current processes [7]. This gives reason for a more careful treatment of neutrino-absorption cross-sections which are dominated by low-lying

Gamow-Teller and Fermi transitions, in contrast to the neutral current spallation reactions which proceed mainly through collective excitations the target nucleus and rely mainly on the high energy tail of the neutrino distribution.

Since radioactive nuclei are more likely to provide detectable signatures we study the effect of the ν process on the yield of ^{26}Al in particular detail. From experimental data about GT transition strengths [8] it is possible to infer the cross-section for ^{26}Mg(ν_e,e$^-$)^{26}Al. Fig. 1 shows the cross-section for this reaction supplemented by forbidden transitions calculated with an RPA model. Also shown is the distribution of electron neutrinos which illustrates that the main part of the strength leading to the production of ^{26}Al is located at relatively low neutrino energies, for which the cross-sections can rely on experimental data. The calculated forbidden contributions are more important for excitations that decay by particle emission.

With a parametrized model for the supernova explosion following the work of [2] we have performed some dedicated studies of the ν process. The neutrino luminosity is assumed to decrease exponentially with a timescale of 3s, radiating away in total 3×10^{53} erg. Neutrinos are assumed to be follow a Fermi-Dirac distribution with average energies of

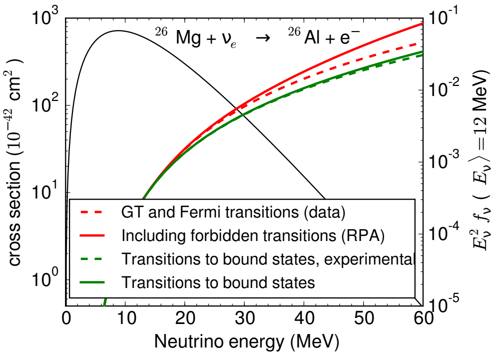

Fig. 1. Cross-section for ^{26}Mg(ν_e,e$^-$)^{26}Al and normalized neutrino distribution for a typical average energy. Transitions to bound states indicate the part of the cross-section that contributes to the production of ^{26}Al.

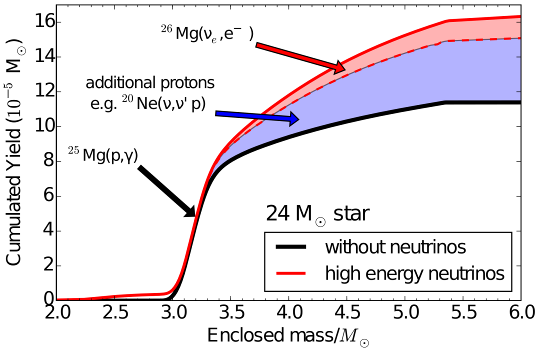

Fig. 2. Contributions of the ν process to ^{26}Al for a 24 M$_\odot$ progenitor with solar metallicity and the neutrino energies given in (1)

$$\langle E_{\nu_e} \rangle = 9\text{MeV}, \langle E_{\bar{\nu}_e} \rangle = \langle E_{\nu_{\mu,\tau}} \rangle = \langle E_{\bar{\nu}_{\mu,\tau}} \rangle = 12.5\text{MeV (low energies).} \tag{1}$$

or

$$\langle E_{\nu_e} \rangle = \langle E_{\bar{\nu}_e} \rangle = 12.5\text{MeV}, \langle E_{\nu_{\mu,\tau}} \rangle = \langle E_{\bar{\nu}_{\mu,\tau}} \rangle = 19\text{MeV (high energies).} \tag{2}$$

Fig. 2 shows a decomposition of the cumulated yield of ^{26}Al for a 24 M$_\odot$ progenitor model of solar metallicity for the case of low neutrino energies (1). Electron neutrino absorption contributes around 7% of the total yield, which is increased by 30% due to neutrinos. The main part of this enhancement is due protons provided by neutrino-induces spallation reactions, mainly on ^{20}Ne and ^{24}Mg.

Nucleosynthesis calculations have been performed for set of progenitors in the mass range between 12-30 M$_\odot$ [9]. Taking the average with an initial mass function (IMF $\propto m_*^{-1.35}$) gives the results in terms of the production factor relative ^{16}O shown in fig. 3. For the lower, but potentially more realistic neutrino energies we find a significant reduction of the yields of the light elements, but still a substantial fraction of the solar abundances can be achieved. Taking other possible sources like Cosmic ray spallation into account, the results are still consistent with observed abundances [10].

Nucleus	without neutrinos	Low energies$^{(1)}$	High energies$^{(2)}$
^{7}Li	0.001	0.29	0.79
^{11}B	0.005	0.14	0.53
^{15}N	0.06	0.09	0.13
^{19}F	0.36	0.41	0.57
^{138}La	0.07	0.63	1.39
^{180}Ta	0.43	1.20	2.07

Fig. 3. IMF averaged production factors (i.e. ratio to solar abundances normalized to^{16}O) based on progenitors in the mass range 12-30 $M_{\odot}$ with the low and high neutrino energies as defined in (1) and (2). Lower neutrino energies results in lower but non-negligible yields. The production factors for the high energies are also still lower than the results reported in [3].

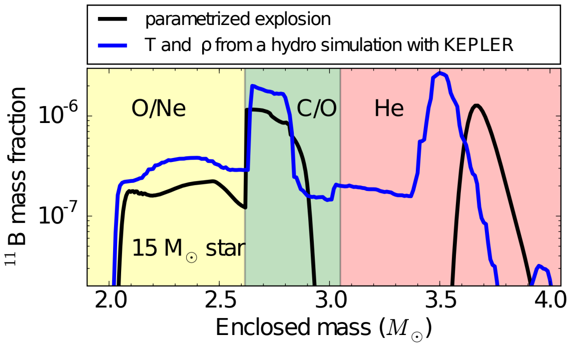

Fig. 4. The local mass fractions of ^{11}B in the SN ejecta of a 15 $M_{\odot}$ progenitor star with our parametrized explosion according to [2] compared to the results based on a piston driven explosion calculated with the hydrodynamics code KEPLER, in both cases, the same nuclear reaction network used.

3. Hydrodynamics and Radiation Transport

Fig. 4 illustrates the significant impact the hydrodynamics can have on the production of ^{11}B, indicating that the explosion dynamics can account for at least part of the differences with respect to [3]. ^{11}B is a fragile nucleosynthesis product that is destroyed by α and proton captures at the temperatures of stellar burning. It can however be produced via neutrinos in the expanding ejecta directly via ^{12}C(ν,ν' p/n) or via a reaction chains using ^{3}He and ^{3}H produced via neutrino reactions on ^{4}He in a narrow temperature window. Therefore, the final ^{11}B yield is very sensitive to the peak temperature that is reached, the time of shock arrival and the cooling timescale. Hence, it is interesting to look at the ν process in the context of supernova dynamics, ideally also including neutrino energies and even non-thermal spectra consistent with the explosion model.

This work was partly supported by the Helmholtz Association through the Nuclear Astrophysics Virtual Institute (VH- VI-417). AH was supported by an Australian Research Council (ARC) Future Fellowship (FT120100363).

References

[1] K. G. Balasi, K. Langanke, G. Martínez-Pinedo, Prog. Part. Nucl. Phys. **85** (2015) 33, .
[2] S.E. Woosley, D.H. Hartmann, R.D. Hoffman, W.C. Haxton, ApJ. **356** (1990), 272.
[3] A. Heger, E. Kolbe, W. C. Haxton, K. Langanke, G. Martínez-Pinedo, S. E. Woosley, Physics Letters B **606** (2005) 258.
[4] A. Byelikov, *et al.*, Physical Review Letters **98** (2007) (8) 082501.
[5] T. Yoshida, T. Kajino, D. H. Hartmann, Phys. Rev. Lett. **94** (2005) 231101.
[6] T. Melson, H.-T. Janka, R. Bollig, F. Hanke, A. Marek, B. Müller, ApJ. **808** L42.
[7] A. Sieverding, L. Huther, G. Martínez-Pinedo, K. Langanke, A. Heger, EPJ WoC, vol. 109 (2016), 06004.
[8] R. G. T. Zegers, *et al.*, Phys. Rev. C **74** (2006) 024309.
[9] Woosley, S. E. and Heger, A., Phys. Rep. **442** (2007) 269-283.
[10] Austin, S.,West, A.,Heger, A., Phys.Rev.Lett. **112** (2014) 111101