Neutrino Nucleosynthesis

A. Heger,1,2 E. Kolbe,3 W. C. Haxton,4 K. Langanke,5 G. Martínez-Pinedo,6,7 and S. E. Woosley4

1Department of Astronomy and Astrophysics, The University of Chicago, 5640 S. Ellis Ave, Chicago, IL 60637, USA
2Theoretical Astrophysics Group, MS B227, Los Alamos National Laboratory, Los Alamos, NM 87545, USA
3Departement für Physik, Universität Basel, Basel, Switzerland
4Institute for Nuclear Theory, University of Washington, Seattle 98195, USA
5Institut für Physik og Astronomi, Århus Universitet, DK-8000 Århus C, Denmark
6Institut d’Estudis Espacials de Catalunya, Edifici Nexus, Gran Capità 2, E-08034 Barcelona, Spain
7Institució Catalana de Recerca i Estudis Avançats, Lluis Companys 23, E-08010 Barcelona, Spain
8Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA95064, USA

(Dated: March 20, 2022)

We study neutrino process nucleosynthesis in massive stars using newly calculated cross sections, an expanded reaction network, and complete and self-consistent models of the progenitor star. We reevaluate the production of light isotopes from abundant progenitors as well as that of rare, heavy, proton-rich isotopes. In particular, new results are given for 11B, 19F, 138La, and 180Ta. The production of these isotopes places limits on neutrino spectrum and oscillations.

PACS numbers: 25.30.Pt, 26.20.+f, 26.30.+k, 26.50.+x, 97.60.-s, 97.60.Bw

Nuclei can be synthesized in the mantle of a core collapse supernova by the neutrino process ν – energetic supernova neutrinos excite nuclei above particle breakup through neutral- and charge-current reactions, creating new daughter nuclei. While typically only 1% of mantle nuclei experience inelastic neutrino reactions, certain rare nuclei, one mass unit below abundant parent nuclei such as C, O, and Ne, may nevertheless be produced dominantly by the neutrino process. The final abundance depends not only on the instantaneous yield of the daughter isotope, but also whether that isotope survives subsequent processing. In many cases the heating associated with the passage of the shock destroys the daughter isotope: the surviving nuclei may be only those produced post-shock, after the relevant shell has expanded and cooled.

Two recent developments make a re-examination of the ν-process timely. First, we now know about neutrino oscillations, which could alter certain ν-process yields by enhancing charged-current production channels. Second, new data on the abundances of B and F – two key ν-process products – have been obtained. Prochaska, Howk, and Wolfe recently observed over 25 elements in a galaxy at redshift z = 2.626, whose young age and high metallicity implies a nucleosynthetic pattern dominated by short-lived, massive stars. Their observation of a solar B/O ratio in an approximately 1/3-solar-metallicity gas argues for a primary (metal-independent) production mechanism, such as the ν-process (making 11B), rather than a secondary process, such as cosmic ray proton spallation reactions on interstellar CNO seed nuclei (making 10B and 11B). The new F abundance data of Cunha et al. showing a low F/O ratio in two ω Centauri stars argue against AGB-star production of F, and are quite consistent with ν-process models (though also with production in cores of stars sufficiently massive to be Wolf-Rayet stars at the beginning of He burning).

Until the present effort the most complete neutrino process calculations were those of , who evaluated productions in a 20 M⊙ Pop I star evolved without mass loss, including semiconvection, and using the Caughlan et al. 12C(α, γ)16O reaction rate. The nuclear chemistry of the coproduced protons and neutrons, which proved to reduce productions of important isotopes like 11B, 15N and 19F, was followed in a nuclear reaction network. The effects of shock-wave heating and post-shock neutrino process production, in shells expanding off the star and cooling, were evaluated. Later Timmes et al. extended this calculation to a full galactic model, integrating the neutrino process over a range of progenitor stars with evolving metallicity.

This letter extends this earlier work in several important ways. One is the incorporation of mass loss in the evolution of the progenitor star. Second, for the first time a reaction network is employed that includes all of the heavy elements through bismuth using updated reaction rates : the work of ranged only up to zinc. This allows us to add selected neutrino reactions – the inclusion of neutrino cross sections for the entire extended network has not yet been attempted – for products that may serve as electron-neutrino “thermometers.” These cross sections are evaluated in a model that we believe is suitable for heavy nuclei. Third, the nuclear evaporation process – emission of a proton, neutron, or α – is treated in a more sophisticated statistical model that takes into account known nuclear levels and their spins and parities. The various partial neutrino cross sections are calculated as two-step processes, as in . The charged- and neutral-current cross sections are evaluated as function of excitation energy in the final nucleus, then a statistical model is used to evaluate the subsequent decay by particle or γ emission. For the p- and sd-shell nuclei
the Gamow-Teller (GT) contributions to the \((\nu_e, e^-)\) and \((\nu, \nu')\) responses were taken from 0\(\hbar\omega\) shell model diagonalizations, as appropriate. The Cohen-Kurath \((^{14}\text{N})K\) and Brown-Wildenthal \(K\) interactions were used. For \(^{12}\text{C}\) we adopted energy and GT strength of the main GT transition, to the \(T = 1\) state at 15.11 MeV in \(^{12}\text{C}\) or its analogue in \(^{12}\text{N}\), from experiment. The double-magic nucleus \(^{16}\text{O}\) has no GT response in the 0\(\hbar\omega\) limit. All other contributions to the neutrino cross sections have been determined within the random phase approximation (RPA) considering multipoles up to \(J = 4\) and both parities. The RPA model, described in \(^{10}\), treats proton and neutron degrees of freedom separately and employs a partial occupancy formalism for non-closed-shell nuclei. The residual interaction is a zero-range Migdal force. As realistic shell-model calculations for the heavy nuclei \(^{138}\text{Ba}, ^{139}\text{La}, ^{181}\text{Ta}, ^{180}\text{Hf}\) are yet not practical, the entire response was calculated using RPA.

In the second step we use the statistical model SMOKER \(^{11}\) to calculate, for each final state with well-defined energy, angular momentum, and parity, branching ratios for \(p, n, \alpha\), and \(\gamma\) emission. SMOKER uses experimentally determined levels in the daughter nucleus, supplemented at higher energies by an appropriate level density formula \(^{11}\). If the decay leads to an excited level of the daughter nucleus above particle threshold, the subsequent decay of this level is treated similarly. The yield of a given nucleus is obtained by folding the various branching ratios, as a function of energy, with the neutrino response function.

This is qualitatively the same procedure used in \(^{4}\). There full multi-shell shell-model calculations were done through \(^{16}\text{O}\); in the \(sd\) shell, however, the first-forbidden response was taken from the simpler Goldhaber-Teller model. The \(sd\) positive-parity shell model calculations for \(^{24}\text{Mg}, ^{28}\text{Si}, \) and \(^{34}\text{S}\) were also truncated. Perhaps more important, the branching ratios were evaluated in \(^{4}\) with a statistical model that lacked the capabilities of SMOKER (e.g., experimental level densities and spin/parity selection rules). In general, the present cross sections turn out to be slightly smaller than those of \(^{4}\). Detailed partial cross sections for the heavier nuclei \((^{138}\text{Ba}, ^{139}\text{Ta}, ^{180}\text{Hf}, ^{181}\text{Ta})\) have not been previously calculated.

For the neutrino spectra we took Fermi-Dirac distributions with zero chemical potential and temperatures \(T = 6\) MeV for \(\mu\) and \(\tau\) neutrinos and their antiparticles and \(T = 4\) MeV for \(\nu_e\) and \(\bar{\nu}_e\). Very recent supernova simulations \(^{12}\) find somewhat harder \(\nu_{\mu, \tau}\) spectra with \(T = 5.9\) MeV and a degeneracy parameter \(\alpha = 1.5\), predicting slightly larger average neutrino energies and increased cross sections (for example by 13\% for \(^{20}\text{Ne}(\nu, \nu')\)). The \(\bar{\nu}_e\) energies are also found to be more energetic than what we assumed, but they have only little influence on the nuclei studied here.

Potentially important \(\nu\)-process candidates can be identified by looking at the abundances in the star during the explosion, after the passage of the shock. This includes in particular radioactive parent nuclei, existing in nuclear statistical equilibrium or produced in the passage of the shock wave. Table \(^{11}\) shows some of the candidate reactions that were identified from abundances found in our progenitor star 3.85s after core bounce, the time when the shock reaches the base of the helium shell, located at radius \(4 \times 10^{10}\) cm and mass coordinate \(6.3\, \text{M}_\odot\). The table includes an estimate of the
TABLE I: Heavy ν-process candidate reactions as derived form a 25 M⊙ stellar model 3.85 s after core bounce. \( \sigma_{\odot} \) is the cross section in 10^{-42} cm^2 that would be required for solar production of the isotope.

| product | \( \sigma_{\odot} \) | parent | process |
|---------|-----------------|--------|---------|
| 51V | 3.0 | 52Fe | \( (\nu, e^-) + p \) |
| 55Mn | 2.0 | 56Ni | \( (\nu, e^-) + n \) |
| 76Kr | 11; 29 | 80Kr | \( (\nu, e^-) + 2n \); \( (\nu, e^-) + \nu' \) |
| 84Sr | 19; 50 | 86Sr | \( (\nu, e^-) + 2n \); \( (\nu, e^-) + n \) |
| 138Ce | 33; 88 | 140Ce | \( (\nu, e^-) + 2n \); \( (\nu, e^-) + n \) |
| 180Ta | 58 | 182Hf | \( (\nu, e^-) + 2n \) |
| 196Hg | 74 | 198Pb | \( (\nu, e^-) + n \); \( (\nu, e^-) + 2n \) |

neutrino cross section \( \sigma_{\odot} \), required to produce the solar abundance of each isotope Y⊙, measured with respect to \(^{16}\)O, when averaged over all ejecta: \( \sigma_{\odot} := 4\pi Y_{\odot} M_{\text{ejecta}} n_p \int_{\text{ejecta}} Y_{\text{parent}} r^2 \, dr \). In this integration we use the progenitor radial coordinates \( r \) to locate the various shells, which would underestimate the needed cross sections for isotopes produced dominantly after shock wave passage (when the shell is expanding outward). We note the two most favorable candidates (smallest required cross sections), \(^{51}\)V and \(^{55}\)Mn, were produced at significant levels in the \( \nu \)-process work of [4]: those calculations used an interpolation method to generate neutrino cross section estimates for all nuclei in the network. (However, the \(^{51}\)V and \(^{55}\)Mn were made as \(^{51}\)Mn and \(^{55}\)Co by the neutral current reactions \( (\nu, e^-) \) of \(^{52}\)Fe and \(^{56}\)Ni, respectively, not by the charged-current reactions listed in the table.) The remaining reactions in Table I will be explored in future, once the needed neutrino cross sections are evaluated.

Our full \( \nu \)-process calculations included all dynamics, explosive and \( \gamma \)-process nucleosynthesis, and all network reactions destroying parent or daughter isotopes involved in \( \nu \)-process synthesis. Supernova calculations were done with the KEPLER code [14], starting from the 15 and 25 M⊙ models S15 and S25 of [7]. We assume a total energy of \( 5 \times 10^{52} \text{ erg} \) per species with a luminosity exponentially decaying after onset of core collapse on a time-scale of 3 s and constant neutrino temperature of 4 MeV for the \( \nu_e \) and \( \bar{\nu}_e \), and of 6 MeV for the \( \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \) and \( \bar{\nu}_\tau \), with zero degeneracy parameter (\( \alpha = 0 \)).

We evaluated neutral current reactions and two particle cascades for \(^{12}\)C, \(^{14}\)N, \(^{16,18}\)O, \(^{20,22}\)Ne, \(^{24,26}\)Mg, \(^{28,30}\)Si, \(^{138}\)La and \(^{181}\)Ta. For charged current reactions we include two particle cascades for \(^{138}\)Ba and \(^{180}\)Hf (Figure 2). Figure 2 shows that the 2n channel is important for these nuclei.

It was recently argued by Goriely et al. [15], following the suggestion first made in [4], that charged current reactions on \(^{138}\)Ba would dominate the production of \(^{138}\)La. We confirm this, finding the \( \gamma \)-process contribution is small and the neutral current reaction on \(^{138}\)La is insignificant (Figure 3). Sufficient \(^{138}\)La is made for about solar co-production with \(^{16}\)O in massive stars (Table III). The key is the enhancement of \(^{138}\)Ba by the s-process prior to the SN (Figure 3). Conversely, charge-current production of \(^{191}\)Pt is insignificant because of the destruction of the parent \(^{191}\)Ir in the s-process.

FIG. 3: Production of \(^{138}\)La in a 25 M⊙ star. We give the production of \(^{138}\)La without neutrinos, with the charged current reaction \( (\nu, e^-) \), with the neutral current reaction \( (\nu, \nu' + n) \) and with both reactions. Additionally, we show the SN shock temperature, the pre-SN density, and the neutrino energy fluence \( F_{\nu,e} \) assuming a total neutrino energy of \( 3 \times 10^{53} \text{ erg} \).

TABLE II: Production factor relative to solar normalized to \(^{16}\)O production as a function of \( T_e \) (for charged current only) and using 6 MeV for the \( \mu \) and \( \tau \) neutrinos.

| star | product | (no \( \nu \)) | (no \( \nu_\tau \)) | 4 MeV | 6 MeV | 8 MeV |
|------|---------|--------------|----------------|---------|---------|---------|
| 15 B | 0.111 | 1.509 | 1.899 | 3.291 | —— | —— |
| 15 N | 0.396 | 0.480 | 0.486 | 0.530 | —— | —— |
| 15 M⊙ | 19 F | 0.375 | 0.577 | 0.643 | 0.914 | —— | —— |
| 138 La | 0.190 | 0.279 | 0.974 | 1.734 | 2.456 | —— |
| 180 Ta | 0.599 | 1.016 | 2.751 | 4.628 | 6.026 | —— | —— |
| 15 B | 0.004 | 0.828 | 1.170 | 2.384 | —— | —— |
| 15 N | 0.039 | 0.112 | 0.118 | 0.157 | —— | —— |
| 25 M⊙ | 19 F | 0.105 | 0.300 | 0.366 | 0.643 | —— | —— |
| 138 La | 0.106 | 0.192 | 0.901 | 1.604 | 2.244 | —— | —— |
| 180 Ta | 1.382 | 2.360 | 4.238 | 6.238 | 7.102 | —— | —— |
FIG. 4: Production of $^{138}$La in a 25 $M_\odot$ star and its neutrino process progenitor nuclei, $^{139}$La (neutral current) and $^{138}$Ba (charged current). The mass fraction of these isotopes as a function of the enclosed mass is shown before (gray) and after (black) the supernova explosion.

TABLE III: Production factor relative to solar normalized to $^{16}$O production as a function of $\mu$ and $\tau$ neutrino temperature (neutral current) and using 4 MeV for the electron (ani-)neutrinos (for charged current only). “Hax” are the results from [4] using Haxton’s $\nu$ cross sections and “Kol” for the new rates of this paper by Kolbe.

| product | $15 M_\odot$ | $25 M_\odot$ |
|---------|-------------|-------------|
|         | $6$ MeV    | $8$ MeV    | $6$ MeV    | $8$ MeV    |
| $^{11}$B | 1.65       | 3.26       | 1.05       | 1.36       |
| $^{19}$F | 0.83       | 0.82       | 0.56       | 0.83       |
| $^{15}$N | 0.46       | 0.58       | 0.11       | 0.19       |
| $^{138}$La | 0.97       | 1.10       | 0.90       | 1.03       |
| $^{180}$Ta | 2.75       | 3.07       | 4.24       | 5.24       |

AH, KL, GMP, and EK thank the INT for support during the 2002 workshop “nucleosynthesis”. This research has been supported by the NSF (AST 02-06111), the SciDAC Program of the DOE (DE-FG02-01ER41176), the DOE ASCI Program (B347885), and by NASA (NAGW-12036). AH is supported in part by the DOE under grant B341495 to the FLASH Center at the University of Chicago and acknowledges supported by a Fermi Fellowship of the Enrico Fermi Institute at The University of Chicago. GMP is supported by the Spanish MCYT under contracts AYA2002-04094-C03-02 and AYA2003-06128.

The $\gamma$-process and neutral-current $\nu$-process each account for about 25% of $^{180}$Ta, with the remainder coming from the charged current $\nu$ process. It is somewhat overproduced. However, our calculations do not distinguish production in the $9^-$ excited state from production in the $1^+$ ground state, while only the former is long lived. Estimates indicated thermal freeze-out should leave 30-50% in the isomeric state. A significant part of what is made by neutrino process from low-spin parent nuclei, however, might preferentially cascade down to the $1^+$ state as the $\nu$ interaction is dominated by low multipoles (A. Hayes, priv. com.). This could account for the apparent overproduction.

The $^{11}$B yield is somewhat higher than $^{14}$N (Table II), but we note that this may also vary by up to a factor 2 when modifying the $^{12}$C($\alpha$,,$\gamma$) rate within its current 30% range of uncertainty [16]. $^{19}$F is typically 50% lower (Table II due to the reduced cross section. The neutral current cross section is uncertain as it depends sensitively on the strong quenching of the GT strength as predicted by the shell model and what fraction of the GT strength resides above the particle threshold; experimental guidance is needed. The neutrino contribution to $^{15}$N is increased by about 50% using our new rates, but the total yield remains low.

The $^{138}$La and $^{180}$Ta yields are very sensitive to the $\nu_e$ temperature, with $^{138}$La the better thermometer as it is made almost exclusively in this channel (Tables II and III). Such a thermometer is potentially quite important because of the role of the as yet unmeasured neutrino mixing angle $\theta_{13}$. This parameter, crucial to proposed terrestrial long-baseline neutrino searches for CP violation, will generate matter-enhanced $\nu_e \leftrightarrow \nu_x$ oscillations at a density corresponding to the atmospheric $\delta m^2$. Naively this corresponds roughly to the base of the carbon zone. Such an oscillation would in turn “heat” the $\nu_\mu$s (assuming a normal rather than inverted mass hierarchy), thus enhancing charged current rates. As most of surviving $^{138}$La is produced at higher densities, in the outer half of the neon zone, one might conclude that its production does not probe this interesting physics. However, it has been recently noted that $\nu - \nu$ scattering may push the MSW resonance toward higher densities, thus into the neon zone [17]. This is clearly an interesting question deserving further study.

[1] G.V. Domogatskii, D.K. Nadyozhin, Sov. Astr. 22, 297 (1978); S.E. Woosley, W.C. Haxton, Nat. 334, 45 (1988)
[2] J.X. Prochaska, J.C. Howk, A.M. Wolfe, Nat. 423, 57 (2003)
[3] K. Cunha, V.V. Smith, D.L. Lambert, K.H. Hinkle, astro-ph/0305303
[4] S.E. Woosley, D.H. Hartmann, R.D. Hoffman, W.C. Haxton, AJ 356, 272 (1990)
[5] G.R. Caughlan, W.A. Fowler, M.J. Harris, B.A. Zimmerman, ADNDT 32, 197 (1985)
[6] F.X. Timmes, S.E. Woosley, T.A. Weaver, ApJS 98, 617 (1995)
[7] T. Rauscher, A. Heger, R.D. Hoffman, S.E. Woosley, ApJ 576, 323 (2002)
[8] S. Cohen, D. Kurath, Nucl. Phys. 73, 1 (1965)
[9] B.A. Brown, B.H. Wildenthal, Annu. Rev. Nucl. Part. Sci. 38, 29 (1988)
[10] E. Kolbe, K. Langanke, P. Vogel, Phys. Rev. C50, 2576 (1994); Nucl. Phys. A652, 91 (1999)
[11] J.J. Cowan, F.-K. Thielemann, J.W. Truran, Phys. Rep. 208, 267 (1991)
[12] M.Th. Keil, G. Raffelt, H.-Th. Janka, ApJ 590, 971 (2003)
[13] J. Audouze, A&A 8, 436 (1970)
[14] T.A. Weaver, G.B. Zimmerman, S.E. Woosley, ApJ 225 (1978) 1021
[15] S. Goriely, M. Arnould, I. Borzov, M. Rayet, A&A 375, 35 (2001)
[16] R. Kunz et al., ApJ 567, 643 (2002)
[17] G.M. Fuller, W.C. Haxton, in preparation.