

# NEUTRINO EFFECTS IN NUCLEOSYNTHESIS

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The nucleosynthesis within a Type II supernova occurs in an intense neutrino flux. I discuss some of the effects associated with neutrino interactions, including direct synthesis in the neutrino process, the role of neutrinos in controlling the r-process path and in postprocessing r-process products, and neutrino oscillation connections.

It is a great pleasure to attend this meeting in honor of a long-time friend, Frank Avignone, and dedicated to his favorite subject, neutrino physics. In contrast to the rare neutrino events that Frank has measured in the laboratory, I will talk about an environment where neutrino reactions are so frequent that they determine much of the chemistry of the matter. That environment is the progenitor star's envelope in the first seconds after a core-collapse supernova. Here the neutrinos directly synthesize new nuclei, and help to eject that matter into the interstellar medium, where it is incorporated into stars like our sun. The neutrinos also control the isospin of the nucleon soup that is the likely site of the r-process. It follows that there is an intimate connection between the properties of neutrinos, including phenomena like neutrino oscillations, and supernova nucleosynthesis.

## 1 Core-Collapse Supernovae

In the infall stage of a core-collapse supernova <sup>1</sup> neutrinos are trapped by their neutral current interactions once a density of  $\rho \sim 10^{12}$  g/cm<sup>3</sup> is reached. Trapped in this sense means that the neutrino diffusion time becomes longer than the time needed to complete the collapse, thereby guaranteeing that the energy liberated by the matter falling into the gravitational potential,  $\sim 3 \times 10^{53}$  ergs, is contained within the protoneutron star. A small portion of this energy is later apparent in the kinetic energy of the ejected shells and in the accompanying optical display. But the vast majority,  $\sim 99\%$ , is radiated in neutrinos over the  $\sim 3$  second cooling time of the core, following core bounce.

Throughout most of their outward diffusion, the various neutrino flavors remain in equilibrium

$$\nu_e + \bar{\nu}_e \leftrightarrow \nu_\mu + \bar{\nu}_\mu \quad (1)$$

thereby ensuring that the energy is shared equally by the three flavors. However, when they reach the “neutrinosphere” at  $\sim 10^{12}$  g/cm<sup>3</sup>, their decoupling is flavor dependent due to the reactions



The first reaction for  $\nu_e$ s is about six times that for heavy flavors, while the second and third affect only electron neutrinos. As a result the heavy-flavor neutrinos decouple at a higher density, and thus temperature, than the electron neutrinos. The result is a characteristic temperature hierarchy

$$\begin{aligned}T_{\nu_\mu, \nu_\tau} &\sim 8\text{MeV} \\ T_{\bar{\nu}_e} &\sim 4.5\text{MeV} \\ T_{\nu_e} &\sim 3.5\text{MeV}\end{aligned}\tag{3}$$

where the  $\nu_e - \bar{\nu}_e$  temperature difference results from the matter near the neutrinosphere being neutron rich (having experienced significant electron capture). As the energy is divided approximately equally among the flavors, it follows that the electron neutrino flux is about twice that of the heavy flavors.

Supernovae are important engines driving galactic evolution, producing and ejecting the metals that enrich the galaxy. Elements produced in the hydrostatic evolution of the presupernova star (C, O, Ne, ...) are abundant in the ejecta of the explosion. The shock wave resulting from core bounce produces peak temperatures of  $\sim (1-3) \cdot 10^9$  K as it traverses the silicon, oxygen, and neon shells. This shock wave heating induces proton and  $\alpha$  reactions like  $(\gamma, \alpha) \leftrightarrow (\alpha, \gamma)$  which generate a mass flow toward highly bound nuclei, resulting in the synthesis of iron peak elements as well as less abundant odd-A species. Rapid neutron-capture reactions are thought to take place in the high-entropy atmosphere just above the mass cut, producing about half of the heavy elements above  $A \sim 80$ . Finally, the neutrinos themselves transmute certain nuclei within the mantle, producing rare isotopes like <sup>11</sup>B and <sup>19</sup>F in the neutrino process.

## 2 The Neutrino Process

The neutrino process was described independently by Domagatsky *et al.*<sup>2</sup> and by Woosley, Haxton, *et al.*<sup>3</sup> Probably the simplest example occurs in the neon shell in a supernova. Because of the first-forbidden contributions, the cross section for inelastic neutrino scattering to the giant resonances in Ne is

$\sim 3 \cdot 10^{-41}$  cm<sup>2</sup>/flavor for the more energetic heavy-flavor neutrinos. This reaction

$$\nu + A \rightarrow \nu' + A^* \quad (4)$$

transfers an energy typical of giant resonances,  $\sim 20$  MeV. A supernova energy release of  $3 \times 10^{53}$  ergs converts to about  $4 \times 10^{57}$  heavy flavor neutrinos. The Ne shell in a  $20 M_{\odot}$  star has at a radius  $\sim 20,000$  km. Thus the neutrino fluence through the Ne shell is

$$\phi \sim \frac{4 \cdot 10^{57}}{4\pi(20,000\text{km})^2} \sim 10^{38}/\text{cm}^2. \quad (5)$$

Thus folding the fluence and cross section, one concludes that approximately 1/300th of the Ne nuclei interact, often breaking up to form  $^{19}\text{F}$ .

This is quite interesting since the astrophysical origin of  $^{19}\text{F}$  had not been understood. The only stable isotope of fluorine,  $^{19}\text{F}$  has an abundance

$$\frac{^{19}\text{F}}{^{20}\text{Ne}} \sim \frac{1}{3100}. \quad (6)$$

This leads to the conclusion that the fluorine found in toothpaste was created by neutral current neutrino reactions deep inside some ancient supernova.

The calculation of the  $^{19}\text{F}/^{20}\text{Ne}$  ratio is somewhat more complicated than a folding of the cross section and fluence:

- When Ne is excited by  $\sim 20$  MeV through inelastic neutrino scattering, it breaks up in two ways

$$\begin{aligned} ^{20}\text{Ne}(\nu, \nu')^{20}\text{Ne}^* &\rightarrow ^{19}\text{Ne} + \text{n} \rightarrow ^{19}\text{F} + \text{e}^+ + \nu_{\text{e}} + \text{n} \\ ^{20}\text{Ne}(\nu, \nu')^{20}\text{Ne}^* &\rightarrow ^{19}\text{F} + \text{p} \end{aligned} \quad (7)$$

with the first reaction occurring half as frequently as the second. The sum of these two channels is the 1/300 yield mentioned above.

- The subsequent nuclear processing determines whether the  $^{19}\text{F}$  survives. In the first  $10^{-8}$  seconds the coproduced neutrons in the first reaction react via

$$^{15}\text{O}(\text{n}, \text{p})^{15}\text{N} \quad ^{19}\text{Ne}(\text{n}, \alpha)^{16}\text{O} \quad ^{20}\text{Ne}(\text{n}, \gamma)^{21}\text{Ne} \quad ^{19}\text{Ne}(\text{n}, \text{p})^{19}\text{F} \quad (8)$$

with the result that about 70% of the  $^{19}\text{F}$  produced via spallation of neutrons is then immediately destroyed, primarily by the  $(\text{n}, \alpha)$  reaction above. In the next  $10^{-6}$  seconds the coproduced protons are also processed

$$^{15}\text{N}(\text{p}, \alpha)^{12}\text{C} \quad ^{19}\text{F}(\text{p}, \alpha)^{16}\text{O} \quad ^{23}\text{Na}(\text{p}, \alpha)^{20}\text{Ne} \quad (9)$$

with the latter two reactions competing as the primary proton poisons. This makes an important prediction: stars with high Na abundances should make more F, as the  $^{23}\text{Na}$  acts as a proton poison to preserve the produced F.

- A final destruction mechanism is the heating associated with the passage of the shock wave. Fluorine produced prior to shock wave passage can survive if it is in the outside half of the Ne shell. The reaction



destroys F for peak explosion temperatures exceeding  $1.7 \cdot 10^9 \text{K}$ . Such a temperature is produced at the inner edge of the Ne shell by the shock wave heating, but not at the outer edge.

If all of this physics is handled is a network code that includes the shock wave heating and F production both before and after shock wave passage, one finds<sup>3</sup>

$\frac{[^{19}\text{F}/^{20}\text{Ne}]}{[^{19}\text{F}/^{20}\text{Ne}]_{\odot}}$	$T_{\text{heavy } \nu}(\text{MeV})$
0.14	4
0.6	6
1.2	8
1.1	10
1.1	12

for a progenitor star of solar metallicity. One sees that the attribution of F to the neutrino process argues that the heavy flavor  $\nu$  temperature must be greater than 6 MeV, a result theory favors. One also sees that F cannot be overproduced by this mechanism: although the instantaneous production of F continues to grow rapidly with the neutrino temperature, too much F results in its destruction through the  $(p, \alpha)$  reaction, given a solar abundance of the competing proton poison  $^{23}\text{Na}$ . Indeed, this illustrates an odd quirk: although in most cases the neutrino process is a primary mechanism, one needs  $^{23}\text{Na}$  present to produce significant F. Thus in this case the neutrino process is a secondary mechanism.

While there are other significant neutrino process products ( $^7\text{Li}$ ,  $^{138}\text{La}$ ,  $^{180}\text{Ta}$ ,  $^{15}\text{N}$  ...), the most important is  $^{11}\text{B}$ , produced by spallation off carbon. A calculation by Timmes *et al.*<sup>4</sup> found that the combination of the neutrino process, cosmic ray spallation and big-bang nucleosynthesis together can explain the evolution of the light elements. The neutrino process, which produces a great deal of  $^{11}\text{B}$  but relatively little  $^{10}\text{B}$ , combines with the cosmic ray spallation mechanism to yield the observed isotope ratio. Again, one prediction of this picture is that early stars should be  $^{11}\text{B}$  rich, as the neutrino process is primary and operates early in our galaxy's history; the cosmic ray production

of  $^{10}\text{B}$  is more recent. (We return to this point below.) There is hope that abundance studies will soon be able to discriminate between  $^{10}\text{B}$  and  $^{11}\text{B}$ : as yet this has not been done.

### 3 The r-process

Beyond the iron peak nuclear Coulomb barriers become so high that charged particle reactions become ineffective, leaving neutron capture as the mechanism responsible for producing the heaviest nuclei. If the neutron abundance is modest, this capture occurs in such a way that each newly synthesized nucleus has the opportunity to  $\beta$  decay, if it is energetically favorable to do so. Thus weak equilibrium is maintained within the nucleus, so that synthesis is along the path of stable nuclei. This is called the s- or slow-process. However a plot of the s-process in the (N,Z) plane reveals that this path misses many stable, neutron-rich nuclei that are known to exist in nature. This suggests that another mechanism is at work, too. Furthermore, the abundance peaks found near masses  $A \sim 130$  and  $A \sim 190$ , which mark the closed neutron shells where neutron capture rates and  $\beta$  decay rates are slower, each split into two subpeaks. One set of subpeaks corresponds to the closed-neutron-shell numbers  $N \sim 82$  and  $N \sim 126$ , and is clearly associated with the s-process. The other set is shifted to smaller N,  $\sim 76$  and  $\sim 116$ , respectively, and is suggestive of a much more explosive environment where neutron capture is rapid.

This second process is the r- or rapid-process, characterized by:

- The neutron capture is fast compared to  $\beta$  decay rates.
- The equilibrium maintained within a nucleus is established by  $(n, \gamma) \leftrightarrow (\gamma, n)$ : neutron capture fills up the available bound levels in the nucleus until this equilibrium sets in. The new Fermi level depends on the temperature and the relative  $n/\gamma$  abundance.
- The nucleosynthesis rate is thus controlled by the  $\beta$  decay rate: each  $\beta^-$  capture converting  $n \rightarrow p$  opens up a hole in the neutron Fermi sea, allowing another neutron to be captured.
- The nucleosynthesis path is along exotic, neutron-rich nuclei that would be highly unstable under normal laboratory conditions.
- As the nucleosynthesis rate is controlled by the  $\beta$  decay, mass will build up at nuclei where the  $\beta$  decay rates are slow. It follows, if the neutron flux is reasonably steady over time so that equilibrated mass flow is reached, that the resulting abundances should be inversely proportional to these  $\beta$  decay rates. Thus large abundances are expected at the shell closures, the “waiting point” nuclei where several  $\beta$  decays must occur before the shell gap inhibiting further

neutron capture can be overcome.

The r-process requires exceptionally explosive conditions: neutron densities in excess of  $\sim 10^{20}/\text{cm}^3$ , temperatures of  $(1-3) \times 10^9 \text{K}$ , and times on the order of one to a few seconds. Evaluating the  $(n, \gamma) \leftrightarrow (\gamma, n)$  equilibrium for typical conditions yields neutron binding energies on the order of  $\sim 30 \text{ kT}$ , or about 2-3 MeV below the neutron drip line. After the r-process finishes (the neutron exposure ends) the nuclei decay back to the valley of stability by  $\beta$  decay. This can involve some neutron spallation ( $\beta$ -delayed neutrons) that shift the mass number  $A$  to a lower value. But it certainly involves conversion of neutrons into protons, which moves the r-process peaks at  $N \sim 82$  and  $126$  to lower  $N$ , clearly. This shifted r-process peak combines with the s-process peak to produce the double-hump distributions near neutron shell closures found in nature. It is believed that the r-process can proceed to very heavy nuclei ( $A \sim 270$ ) where it is finally ended by  $\beta$ -delayed and n-induced fission, which feeds matter back into the process at an  $A \sim A_{max}/2$ . Thus there may be important cycling effects in the upper half of the r-process distribution.

What is the site(s) of the r-process? This has been debated many years and still remains a controversial subject. Both primary (requiring no preexisting metals) and secondary (enriched in s-process elements) sites have been proposed. Some of the suggested primary sites include the neutronized atmosphere above the proto-neutron star in a Type II supernova, neutron-rich jets produced in supernova explosions or in neutron star mergers, and inhomogeneous big bangs. Secondary sites, where successful synthesis can result for lower  $\rho(n)$ , include the He and C zones in Type II supernovae and the red giant He flash.

The balance of evidence favors a primary site, so one requiring no pre-enrichment of heavy s-process metals. In particular, recent abundance studies<sup>5</sup> of very metal-poor stars ( $[\text{Fe}/\text{H}] \sim -1.7$  to  $-3.12$ ) have yielded r-process distributions very much like that of our sun (at least for  $Z \gtrsim 56$ ) (see Fig. 1). In these stars the iron content is variable. This suggests that the “time resolution” inherent in these old stars is short compared to galactic mixing times (otherwise Fe would be more constant). The conclusion is that the r-process material in these stars is most likely from one or a few local supernovae. The fact that the distributions match the solar r-process strongly suggests that there is some kind of unique site for the r-process: the solar r-process distribution did not come from averaging over many different kinds of r-process events. Clearly the fact that these old stars are enriched in r-process metals also strongly argues for a primary process: the r-process works quite well in an environment where there are few initial s-process metals.

It may be that these and similar data make certain primary r-process

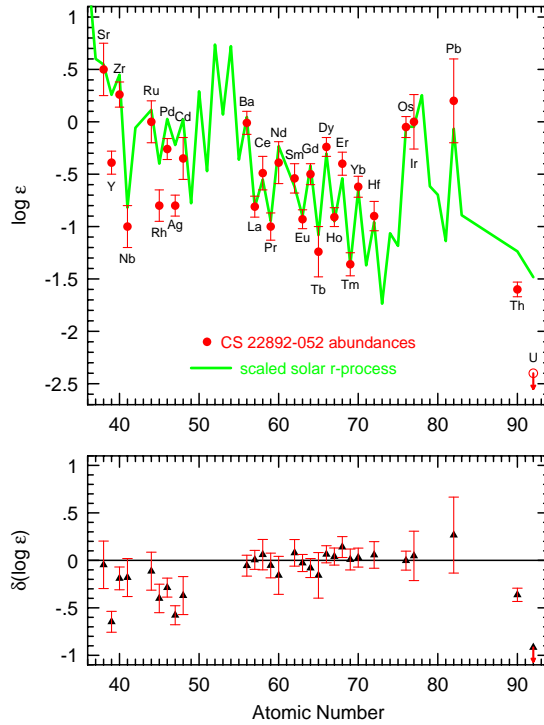


Figure 1: Neutron-capture abundances in the ultra-metal-poor ( $[\text{Fe}/\text{H}] = -3.1$ ) halo field giant star CS 22892-052 are plotted as filled circles with error bars, along with a scaled solar system r-process abundance curve (solid line). In the bottom panel, a differential comparison between individual elements and the scaled solar system r-process abundance distribution shows excellent agreement above  $Z = 56$ , but some deviations for lighter elements. From Ref. 5.

sites, such as neutron star mergers, less probable. The reasoning rests on the expected infrequency of neutron star mergers (no more than 1/100th the rate of galactic supernovae), and thus on the larger nucleosynthetic output required from such r-process sites<sup>6</sup>. Since the ejecta of neutron star mergers and supernovae are expected to mix over similarly sized regions, the former should produce a larger scatter of enrichments in metal-poor stars.

These and other arguments have led many to suspect that core-collapse supernova may be the correct site. There is good theoretical support for this conclusion. First, galactic chemical evolution studies indicate that the growth of r-process elements in the galaxy is consistent with low-mass Type II super-

novae in rate and distribution. More convincing is the fact that modelers<sup>7</sup> have shown that the conditions needed for an r-process (very high neutron densities, temperatures of 1-3 billion degrees) might be realized in a supernova. The identified location is the last material blown off the supernova, the material just above the mass cut. When this material is initial at small  $r$ , it is a very hot, neutron-rich, radiation-dominated gas containing neutrons and protons, with neutrons dominating. As it expands off the star and cools, the material first goes through a freezeout to  $\alpha$  particles, a step that essentially locks up all the protons in this way. Then the  $\alpha$ s interact through reactions like



to start forming heavier nuclei. Unlike the big bang, the density is sufficiently high to allow such three-body interactions to bridge the mass gaps at  $A = 5, 8$ . The  $\alpha$  capture continues up to  $A \sim 80$  in network calculations. The result is a small number of “seed” nuclei, a large number of  $\alpha$ s, and excess neutrons. These neutrons preferentially capture on the heavy seeds to produce an r-process. Of course, what is necessary is to have  $\sim 100$  excess neutrons per seed in order to successfully synthesize heavy mass nuclei. While some calculations come close to achieving this, the entropies tend to fall short of what is needed. An attractive aspect of this site is the amount of matter ejected, about  $10^{-5} - 10^{-6}$  solar masses, enough to produce the present galactic r-process metallicity for a reasonable supernova rate.

It is clear that neutrino physics is an intimate part of the r-process. The supernova scenario described above is usually attributed to material ejected by the proton-neutron star’s neutrino wind. This wind is also responsible for regulating the essential proton/neutron chemistry of this material: the reactions  $\nu_e + n \leftrightarrow e^- + p$  and  $\bar{\nu}_e + p \leftrightarrow e^+ + n$  control this physics. Nonstandard neutrino physics could be critical to the r-process. An oscillation of the type  $\nu_e \rightarrow \nu_{\text{sterile}}$  can alter the n/p ratio, as it turns off the  $\nu_e$ s that destroy neutrons by charged-current reactions.

The nuclear physics of the r-process tells us that the synthesis occurs when the nucleon soup is in the temperature range of  $(3-1) \cdot 10^9\text{K}$ , which, in the hot bubble r-process described above, corresponds to a freezeout radius of (600-1000) km and a time  $\sim 10$  seconds after core collapse. The neutrino fluence after freezeout (when the temperature has dropped below  $10^9\text{K}$  and the r-process stops) is then  $\sim (0.045-0.015) \cdot 10^{51}$  ergs/(100km)<sup>2</sup>. Thus, after completion of the r-process, the newly synthesized material experiences an intense flux of neutrinos. This brings up the question of whether the neutrino flux could have any effect on the r-process.



## 4 Neutrinos and the r-process

Rather than describe the exotic effects of neutrino oscillations on the r-process, mentioned briefly above, we will examine standard-model effects that are nevertheless quite interesting. The nuclear physics of this section – neutrino-induced neutron spallation reactions – is also relevant to recently proposed supernova neutrino observatories such as OMNIS and LAND. In contrast to our first discussion of the  $\nu$ -process in producing  $^{19}\text{F}$  and  $^{11}\text{B}$ , it is apparent that neutrino effects could be much larger in the hot bubble r-process: the synthesis occurs *much* closer to the star than our Ne radius of 20,000 km. The r-process is completed in about 10 seconds (when the temperature drops to about one billion degrees), but the neutrino flux is still significant as the r-process freezes out. The net result is that the “post-processing” neutrino fluence - the fluence that can alter the nuclear distribution after the r-process is completed - is about 100 times larger than that responsible for fluorine production in the Ne zone. Recalling that 1/300 of the nuclei in the Ne zone interacted with neutrinos, and noting that the relevant neutrino-nucleus cross sections scale as  $A$  (a consequence of the sum rules governing first-forbidden neutrino cross sections), one quickly sees that the probability of a r-process nucleus interacting with the neutrino flux is approximately unity.

Because the hydrodynamic conditions of the r-process are highly uncertain, one way to attack this problem is to work backward in time<sup>8</sup>. We know the final r-process distribution (what nature gives us) and we can calculate neutrino-nucleus interactions relatively well. Thus from the observed r-process distribution (including neutrino postprocessing) we can deduce what the r-process distribution looked like at the point of freezeout. In Figs. 2 and 3, the “real” r-process distribution - that produced at freezeout - is given by the dashed lines, while the solid lines show the effects of the neutrino postprocessing for a particular choice of fluence.

One important aspect of the figures is that the mass shift is significant. This has to do with the fact that a 20 MeV excitation of a neutron-rich, weakly bound nucleus allows multiple neutrons ( $\sim 5$ ) to be emitted. The relative contribution of the neutrino process is particularly important in the “valleys” beneath the mass peaks: the reason is that the parents on the mass peak are abundant, and the valley daughters rare. In fact, it follows from this that the neutrino process effects can be dominant for precisely seven isotopes (Te, Re, etc.) lying in these valleys. Furthermore if an appropriate neutrino fluence is picked, these isotope abundances are produced perfectly (given the abundance errors). The fluences are

$$N = 82 \text{ peak : } 0.031 \cdot 10^{51} \text{ ergs}/(100\text{km})^2/\text{flavor}$$

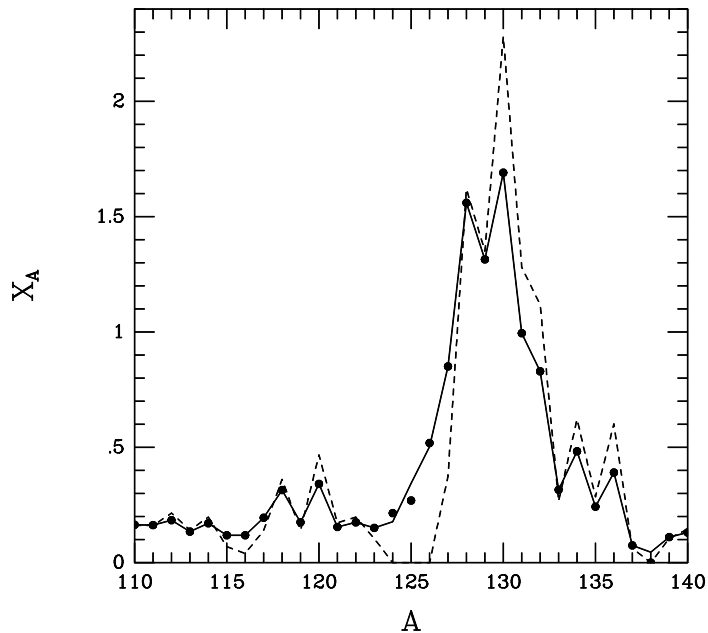


Figure 2: Comparison of the r-process distribution that would result from the freezeout abundances near the  $A \sim 130$  mass peak (dashed line) to that where the effects of neutrino postprocessing have been include (solid line). The fluence has been fixed by assuming that the  $A = 124-126$  abundances are entirely due to the  $\nu$ -process.

$$N = 126 \text{ peak} : \quad 0.015 \cdot 10^{51} \text{ergs}/(100\text{km})^2/\text{flavor} \quad (12)$$

values in fine agreement with those that would be found in a hot bubble r-process. So this is circumstantial but significant evidence that the material near the mass cut of a Type II supernova is the site of the r-process: there is a neutrino fingerprint.

## 5 Neutrino Oscillations and Supernova Nucleosynthesis

There are some intriguing connections between supernova nucleosynthesis, the explosion mechanism, and neutrino oscillations. Several of these have to do with the distinctive temperature hierarchy of supernova neutrinos mentioned earlier. In contrast to solar neutrinos, where detailed nuclear physics determines the neutrino spectrum, the supernova neutrino temperature dependence

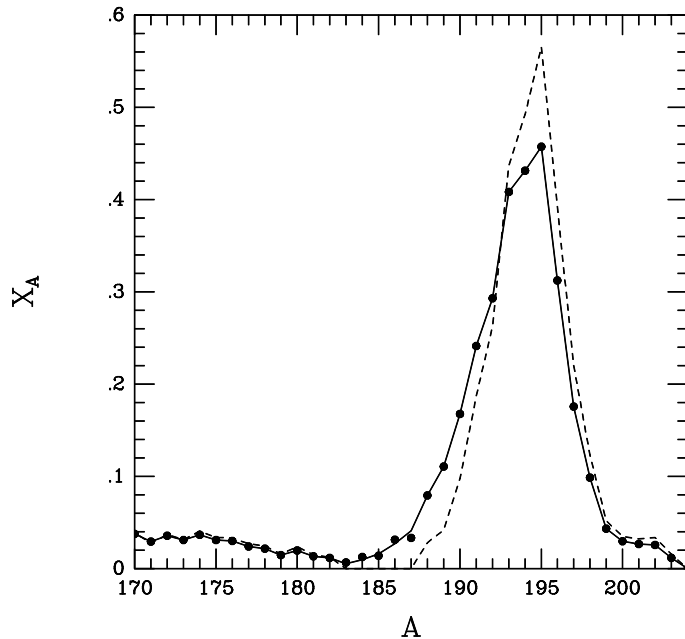


Figure 3: As in Fig. 5, but for the  $A \sim 195$  mass peak. The  $A = 183-187$  abundances are entirely attributed to the  $\nu$ -process.

on flavor is governed by very general arguments having to do with neutrino couplings to matter, as we have noted. While modelers differ somewhat in their estimates of neutrino temperatures, there is agreement that the heavy flavor neutrino mean energy is higher than that of the electron neutrinos, and that the  $\nu_e$  temperature is lower than that of the  $\bar{\nu}_e$ s. One consequence is that neutrino oscillation signals in terrestrial detectors could be quite obvious at the time of the next galactic supernova. For example, if  $\nu_e$  events prove to be substantially more energetic than  $\bar{\nu}_e$  events, the natural interpretation would be oscillations between heavy-flavor and  $\nu_e$  neutrinos, leading to an anomalously hot  $\nu_e$  spectrum.

One important aspect of supernova neutrino oscillations is their potential to probe the MSW mechanism over greatly extended parameter ranges. The neutrinos have fixed spectra after they decouple at the neutrinosphere,  $\sim 10^{12}$  g/cm<sup>3</sup>, a density ten orders of magnitude greater than that at the core of the sun. It follows that neutrinos with masses in excess of 100 eV (thus  $\delta m^2$  in

excess of  $(100 \text{ eV})^2$ ) will experience an MSW crossing. These crossings remain adiabatic – that is, capable of converting neutrino flavor – for mixing angles as small as  $10^{-5}$ , depending on the  $\delta m^2$  value. It follows that oscillations unobservable by any other means could be revealed in supernovae.

Relevant to the present talk is the possibility that we will not need to wait for the next supernova: oscillation effects might be deduced from their effects on nucleosynthesis. For example, we have noted that a MSW oscillation between heavy and electron flavors would lead to an unusually hot  $\nu_e$  spectrum. The proton/neutron chemistry of the hot nucleon soup blown off the protoneutron star is governed by the competition between the reactions

$$\begin{aligned}\nu_e + n &\rightarrow e^- + p \\ \bar{\nu}_e + p &\rightarrow e^+ + n.\end{aligned}\tag{13}$$

As the oscillation leads to a hotter  $\nu_e$  spectrum but does not affect the  $\bar{\nu}_e$ s (which, for the usual mass hierarchy, do not experience an MSW crossing), the first reaction is enhanced while the second is unchanged. The matter is thus driven proton-rich, destroying any possibility of an r-process. Thus, as Fuller has argued<sup>9</sup>, a demonstration that the supernova “hot bubble” is the site of the r-process would impose very stringent constraints on  $\nu_e \leftrightarrow \nu_\mu/\nu_\tau$  oscillations. The constraints address the entire range of cosmologically interesting  $\nu_\tau$  masses.

Another r-process connection arose from efforts to explain the LSND, atmospheric, and solar neutrino results in four-neutrino schemes (three active and one approximately sterile). One such scheme involves a  $\nu_\tau/\nu_\mu$  doublet at about 2 eV, split in order to reproduce the atmospheric  $\delta m^2$ , and a light  $\nu_e/\nu_{sterile}$  doublet, split to reproduce the solar  $\delta m^2$ . Such a scheme can have a salutary effect on the r-process because of successive MSW crossings<sup>10</sup>. First the  $\nu_\mu/\nu_\tau$  flux is removed by an oscillation with  $\nu_{sterile}$ ; then a  $\nu_e \rightarrow \nu_\mu/\nu_\tau$  oscillation can take place without a corresponding back reaction. With the  $\nu_e$  flux reduced but the  $\bar{\nu}_e$  unaffected, the matter can be driven neutron rich. This occurs at a radius where the increase in available neutrons helps the r-process to succeed in producing the  $A \sim 190$  mass peak.

Oscillations could also influence our interpretation of the abundances of the rare isotopes  $^{10,11}\text{B}$ ,  $^9\text{Be}$ , and  $^{6,7}\text{Li}$ . The neutrino process on  $^{12}\text{C}$  appears to produce a great deal of  $^{11}\text{B}$ , consistent with its abundance. It also produces significant  $^7\text{Li}$ , but very little  $^{10}\text{B}$ ,  $^9\text{Be}$ , and  $^6\text{Li}$ : neutral current neutrino reactions generally do not impart sufficient energy to  $^{12}\text{C}$  to populate the higher threshold channels corresponding to these products. The neutrino process produces a  $^{10}\text{B}/^{11}\text{B}$  ratio of  $\sim 0.05$ , while the true abundance ratio is  $\sim 0.25$ .

As a primary process, it predicts a linear growth of boron with metallicity (e.g., Fe).

However, the textbook explanation for the synthesis of these elements is the interaction of cosmic ray protons with  $^{12}\text{C}$  and  $^{16}\text{O}$  in the interstellar medium<sup>11</sup>. As the reactions involve high-energy protons,  $^{10}\text{B}$  and  $^6\text{Li}$  are readily produced: the  $^{10}\text{B}/^{11}\text{B}$  ratio is  $\sim 0.5$ , about twice that observed. The cosmic ray mechanism becomes more effective as the interstellar medium is enriched in  $^{12}\text{C}$  and  $^{16}\text{O}$  and thus, as a secondary process, produces a quadratic growth in B with metallicity. It is very possible that nature uses a mixture of these two mechanisms. If each contributed about 50% of the  $^{11}\text{B}$ , the correct  $^{10}\text{B}/^{11}\text{B}$  ratio would result.

However recent studies of metal-poor stars show that the boron grows linearly with Fe<sup>12</sup>: the production appears to be primary. This has encouraged several efforts to reformulate the cosmic ray mechanism as a primary process, e.g., by accelerating  $^{12}\text{C}$  and  $^{16}\text{O}$  off a supernova on to target protons in the interstellar medium. (I believe the tasking of estimating the production resulting from such a scenario is highly uncertain, however.) Surprising quantities of  $^9\text{Be}$  have also been observed in metal-poor halo stars.

Since the  $\nu$  process is a primary process, one could consider whether the calculated productions of  $^{10}\text{B}$  and other high-threshold products might have been underestimated. It is clear that the nuclear physics uncertainties affecting these channels are much greater than in the case of  $^{11}\text{B}$ . But another possibility that has not been explored is neutrino oscillations. In fact, if the neutrino masses have a standard seesaw pattern, the atmospheric neutrino results suggest a  $\delta m_{13}^2$  somewhat below  $0.01 \text{ eV}^2$ , producing a  $\nu_e \leftrightarrow \nu_\tau$  MSW crossing near  $10^5 \text{ g/cm}^3$ . This is outside the r-process region, thus leaving that synthesis unaffected, but before the carbon zone at  $\rho \sim 8 \cdot 10^2 - 5 \cdot 10^3 \text{ g/cm}^3$ . The hot  $\nu_e$  flux leads to enhanced production of  $^{10}\text{B}$  through  $^{12}\text{C}(\nu_e, e^-)$ , as well as increased  $^7\text{Li}$  through the burnup reaction  $^{10}\text{B}(p, \alpha)^7\text{Be}$ . Numerical results will be published soon<sup>14</sup>.

## 6 Summary

The connections between neutrino nucleosynthesis and the supernova mechanism are rather remarkable. We have seen that neutrinos are directly responsible for important synthesis. In turn this synthesis can be exploited as a diagnostic of the explosion, e.g., as a monitor of yet unmeasured heavy-flavor temperatures in the  $\nu$  process, and as a constraint on the explosion dynamics in the case of the r-process. (The neutrino fluence derived from the  $\nu$  post-processing “fingerprint” on the r-process constrains a product of the freezeout

radius and the expansion rate.)

If one adds new neutrino physics to the equation, the occurrence of a supernova “hot bubble” r-process places important new constraints on the entire range of  $\delta m^2$  relevant cosmologically. Four-neutrino scenarios postulated to account for the LSND, atmospheric, and solar neutrino results can enhance r-process production in the vicinity of the  $A \sim 190$  peak, and thus could account for current underproductions in this region. Finally, the relative mix of cosmic ray and  $\nu$  process synthesis of Li/Be/B would be affected by mixings of the  $\nu_e$  governed by  $\delta m^2$  near the atmospheric neutrino value.

The most interesting aspect of all of this is the impact new abundances observations are having. It gives one hope that new  $\nu$  physics might be learned from supernovae even before the next flux of supernova  $\nu$ s hits the earth.

### Acknowledgements

I thank Scott Burles for providing, on behalf of the authors of Ref. 5, Fig. 1. This work was supported in part by the US Department of Energy.

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