

Neutrino-Induced Nucleosynthesis and the Site of the r Process

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If the r process occurs deep within a type II supernova, probably the most popular of the proposed sites, abundances of r -process elements may be altered by the intense neutrino flux. We point out that the effects would be especially pronounced for eight isotopes that can be efficiently synthesized by the neutrino reactions following r -process freeze-out. We show that the observed abundances of these isotopes are entirely consistent with neutrino-induced nucleosynthesis, strongly arguing for a supernova r -process site. The deduced neutrino fluences place stringent constraints on the freeze-out radius and dynamic time scale of the r process. [S0031-9007(97)02846-9]

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It is known that approximately half of the heavy elements with mass number $A > 70$ and all of the transuranics are formed by the process of rapid neutron capture, the r process. The astrophysical site where the required conditions occur—neutron number densities in excess of $\sim 10^{20} \text{ cm}^{-3}$ and temperatures of $\sim 10^9 \text{ K}$ lasting for on the order of 1 s [1]—has been a matter of speculation for almost four decades. The suggested sites [1] include the neutronized atmospheres just above the supernova core, neutron-rich jets from supernovae or neutron star coalescence, and an inhomogeneous big bang. In addition to these so-called primary sites, there are also secondary r -process models which can succeed with somewhat lower neutron number densities and temperatures, but require preexisting heavy nuclei to act as seeds for the neutron capture. Proposed secondary sites vary from the He and C shells during explosive burning in type II supernovae to the core He flash in low-mass red giants.

In recent years a number of observational and theoretical arguments have strengthened the case for a primary r process in type II supernovae. The discovery of very metal-poor halo stars enriched in r -process elements with relative abundance distributions characteristic of the solar system argues that the r process is primary, already operating early in the history of the Galaxy [2]. Studies of galactic chemical evolution [1] have found that the growth of r -process material is consistent with low-mass type II supernovae being the r -process site. Finally, the suggestion made long ago that the r process might be associated with expansion and cooling of neutron-rich matter from the vicinity of the mass cut in supernovae [3] has been modeled much more convincingly. It has been shown in Ref. [4] that an expanding neutron-rich nucleon gas can undergo an α -particle freeze-out, in which effectively all of the protons are consumed, followed by an α process in which seed nuclei near $A \sim 100$ are produced. The r process then takes place through the capture of the excess neutrons on these seed nuclei. Unfortunately, this specific model has some shortcomings,

especially the need for very high entropies which might be hard to obtain [5,6]. However, it has demonstrated that a supernova “hot bubble” r process can produce both a reasonable elemental abundance distribution and an appropriate amount of r -process ejecta. The goal of the present work is to identify the features of this r process that are especially sensitive to neutrino physics and, at the same time, are largely independent of the detailed supernova model.

If the r process indeed occurs in supernovae, the synthesis and subsequent ejection of the r -process products take place in an intense flux of neutrinos of all flavors emitted by the cooling protoneutron star. As it is known that neutrinos are capable of inducing important nucleosynthesis in the C and O shells in type II supernovae [7], this neutrino fluence could also have consequences for the r process. In fact, as we show below, the conclusions of the present work depend only on the neutrino fluence. Furthermore, the relevant values of this fluence we identify are in accord with various supernova models.

Neutrino reactions can affect the r process in two ways, by altering the path or pace of the nuclear flow during the synthesis, or by modifying (postprocessing) the abundance pattern after freeze-out. The former possibility has been suggested and/or discussed in several papers (see references given in Ref. [8]), including the recent work where the effects of neutrinos on the charge flow were shown, under certain conditions, to improve the agreement with inferred abundances [9]. Much less work has been done on neutrino postprocessing. In a recent, more technical paper [8] we reexamined many of the neutrino physics issues affecting both the r process itself and the subsequent postprocessing. The purpose of this Letter is to highlight one result with broad implications, that the site of the r process might be deduced from certain specific neutrino postprocessing signatures.

A cooling protoneutron star emits about 3×10^{53} erg in neutrinos, with the energy roughly equipartitioned among all species. The rate of neutrino reactions at radius r from

the center of the neutron star is

$$\lambda_\nu \approx 4.97 \left[\frac{L_\nu(t)}{10^{51} \text{ erg s}^{-1}} \right] \left(\frac{\text{MeV}}{\langle E_\nu \rangle} \right) \left(\frac{100 \text{ km}}{r} \right)^2 \times \left(\frac{\langle \sigma_\nu \rangle}{10^{-41} \text{ cm}^2} \right) \text{s}^{-1}, \quad (1)$$

where $L_\nu(t)$ and $\langle E_\nu \rangle$ are the luminosity and average energy, respectively, of the neutrino species responsible for the reaction, and $\langle \sigma_\nu \rangle$ is the corresponding cross section averaged over the neutrino spectrum. The neutrino luminosity is expected to evolve with time as $\exp(-t/\tau_\nu)$, with $\tau_\nu \sim 3$ s. The spectrum-averaged neutrino reaction cross section sums over all final nuclear states. The neutrino spectrum is taken to be a modified Fermi-Dirac distribution with the corresponding average neutrino energies $\langle E_{\nu_e} \rangle \approx 11$ MeV, $\langle E_{\bar{\nu}_e} \rangle \approx 16$ MeV, and $\langle E_{\nu_{\mu(\tau)}} \rangle \approx \langle E_{\bar{\nu}_{\mu(\tau)}} \rangle \approx 25$ MeV.

The important reactions in Eq. (1) are the charged-current (ν_e, e^-) reaction and the neutral-current heavy-flavor (ν, ν') reaction: charged-current $\bar{\nu}_e$ reactions are Pauli blocked for the very neutron-rich heavy nuclei in the r process, while the lower average energies of ν_e and $\bar{\nu}_e$ lead to smaller neutral-current cross sections. Our evaluation of these cross sections, described in much more detail in Ref. [8], was based on extrapolating known nuclear responses to the neutron-rich nuclei of present interest, guided by explicit shell model and continuum random phase approximation (CRPA) calculations for certain nuclei of interest. The (ν_e, e^-) cross sections were treated in the allowed approximation, with the Fermi strength $|M_F|^2 = N - Z$ carried by the isobaric analog state and the Gamow-Teller (GT) strength $|M_{GT}|^2 \sim 3(N - Z)$ carried by a broad resonance whose position and shape were determined from nuclear systematics. The GT strength can be equated to the Ikeda sum rule result because the ($\bar{\nu}_e, e^+$) channel is effectively blocked. Similar studies of the charged-current (ν_e, e^-) reactions on heavy nuclei have been carried out in Ref. [10]. The corresponding neutral-current calculation is more complicated as, in addition to the allowed GT transition, forbidden transitions become important due to the higher average heavy-flavor neutrino energies. The neutral-current results used here were taken from the CRPA calculations of Ref. [8].

The charged-current and forbidden neutral-current reactions typically produce a nucleus excited well into the continuum. The nucleus then emits one or more neutrons. This is the process that alters the r -process abundance distribution. The average number of spallation neutrons, $\langle n \rangle$, is obtained by folding the neutrino-induced excitation spectrum with the neutron-evaporation spectrum determined from the statistical model [11]. The total rates of charged-current and neutral-current reactions on an average nucleus in the $A \sim 80, 130,$ and 195 regions are $\sim 9, 15,$ and 20 s^{-1} (with $\langle n \rangle \sim 2, 2,$ and 3), respectively, for $r = 100 \text{ km}$ and $L_\nu = 10^{51} \text{ erg s}^{-1}$ per species.

The r process freezes out when the neutron number density drops below a critical level. The resulting r -process

progenitor nuclei would, in the absence of neutrino post-processing, decay back to the valley of β stability, producing the abundance pattern found in nature. However, if this freeze-out occurs in an intense neutrino flux, both charged-current and neutral-current reactions take place on the progenitor nuclei (and their daughters), modifying the final r -process abundance distribution in a characteristic way. We make three approximations in evaluating these effects. First, we exploit the fact [8] that neutrino rates and neutron spallation yields do not vary excessively (e.g., by more than about $\pm 40\%$) over an abundance peak. (Variations between peaks are more significant.) Thus it is a reasonable approximation to assign average rates and neutron emission probabilities to each abundance peak. Second, we employ these mean progenitor rates and neutron emission probabilities throughout the postprocessing phase, even as $N - Z$ is evolving due to β -decay and neutrino reactions. This is a good assumption for neutral-current reactions, where rates are tied to sum rules [8] that are only weakly dependent on $N - Z$, but more dangerous for charged-current reactions, where the direct dependence of rates on $N - Z$ could generate important corrections if the number of β -decay or neutrino reactions is large during postprocessing. However, for the fluences we consider below, the mean number of postprocessing neutrino reactions is less than unity. Third, we do not account for the subsequent processing of neutrons liberated in the spallation. Because the effects of reabsorption are spread over a broad range of r -process nuclei, they are of minor importance to the eight special “window nuclei” we discuss below.

With these approximations, the neutrino postprocessing effects for a given abundance peak can be evaluated without reference to the details of the r -process freeze-out pattern or of the decay back to the valley of β stability. These effects depend only on the total neutrino fluence through the r -process ejecta following freeze-out. Our results will be given in terms of the dimensionless parameter \mathcal{F} , the fluence in units of $10^{47} \text{ erg km}^{-2}$, and can be immediately applied to any hydrodynamic r -process scenario for which the neutrino postprocessing fluence is known. Clearly, \mathcal{F} depends on the radius r_{FO} and neutrino luminosity $L_{\nu, \text{FO}}$ at freeze-out, and the time over which a significant neutrino irradiation continues, which in turn depends on both the outflow velocity v of the ejecta and the neutron star cooling history. For example, in a neutrino-driven wind scenario [6] the outflow can be described by a constant dynamic time scale $\tau_{\text{dyn}} = r/v$, i.e., $r \propto \exp(t/\tau_{\text{dyn}})$. With $L_\nu \propto \exp(-t/\tau_\nu)$, we have

$$\mathcal{F} = \left(\frac{L_{\nu, \text{FO}}}{10^{51} \text{ erg s}^{-1}} \right) \left(\frac{100 \text{ km}}{r_{\text{FO}}} \right)^2 \left(\frac{\tau_{\text{dyn}}/(2 \text{ s})}{1 + \tau_{\text{dyn}}/(2\tau_\nu)} \right). \quad (2)$$

The remaining calculations involve rather straightforward combinatorics, described in more detail in Ref. [8]. One first determines $\bar{N}(n)$, the mean number of neutrino events (including both charged-current and neutral-current reactions, which prove to be of comparable

importance) producing exactly n neutrons in the subsequent spallation after freeze-out. Each $\bar{N}(n)$ is proportional to the fluence \mathcal{F} . Under the assumptions enumerated above, the rates and neutron emission probabilities in the vicinity of each abundance peak are not affected by the prior history of the target nucleus. Thus the distribution of neutrino events that produce exactly n spallation neutrons is governed by a Poisson distribution with parameter $\bar{N}(n)$. The overall probability for a given nucleus to emit, for example, two neutrons can then be evaluated by listing the ways this can be done (e.g., two neutrons can be produced by one interaction that knocks out two neutrons, or by two interactions each of which knocks out one), and folding the Poisson probabilities for each type of event in the product. The probability P_n for an average nucleus in the $A \sim 195$ region to emit a total of n neutrons after freeze-out is illustrated in Fig. 1 for three different values of \mathcal{F} . The bumps in the probability distributions at $n = 4$ and 5 in Fig. 1 are due to the charged-current (ν_e, e^-) reactions, which tend to knock out more neutrons after each reaction.

The most straightforward use of these probabilities would be to include them in a standard r -process network calculation. However, there is an alternative and very instructive use of these results that does not require a baseline r -process freeze-out pattern from theory: begin with the r -process abundance distribution observed in nature and, for a given neutrino fluence, invert this distribution to determine the initial distribution that must have existed prior to the neutrino postprocessing. This initial distribution would be the one conventional theory should strive to match, if indeed we have picked the correct \mathcal{F} . The

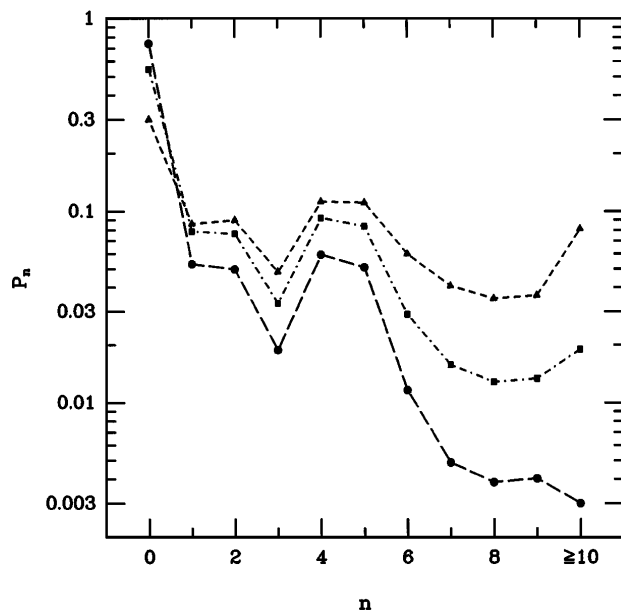


FIG. 1. Postprocessing neutron emission probabilities for an average nucleus in the $A \sim 195$ region. The points connected by the long-dashed, dot-dashed, and short-dashed lines are for $\mathcal{F} = 0.015, 0.030, \text{ and } 0.060$, respectively.

appeal of this procedure is that the final r -process abundances are rather tightly constrained by observation and the neutrino physics is relatively simple, compared with other aspects of the r process. Thus we can derive the unpostprocessed distribution with some confidence. The inversion is easily carried out iteratively, as described in Ref. [8]. (Note that this procedure is valid even in the presence of β -delayed neutron emission given the approximations detailed above.)

The dominant features of the observed r -process abundance distribution are the abundance peaks at $A \sim 130$ and 195 , corresponding to the progenitor nuclei with $N = 82$ and 126 closed neutron shells. Independent of the exact value of the neutrino fluence, the most important result of the inversion described above is the discovery that eight nuclei, lying in the windows $A = 124\text{--}126$ and $183\text{--}187$, are unusually sensitive to the neutrino postprocessing. These nuclei sit in the valleys immediately below the abundance peaks which can be readily filled by spallation off the abundant isotopes in the peaks. This situation is entirely analogous to other cases where the neutrino-induced synthesis is known to be important [7].

This observation allows us to place upper bounds on the fluence \mathcal{F} characterizing the freeze-out of the abundance peaks. This is done by requiring that the neutrino-induced synthesis by itself not overproduce these nuclei. For the $A \sim 130$ peak, we find $\mathcal{F} \leq 0.045$. The limiting fluence would overproduce all three isotopes ^{124}Sn , ^{125}Te , and ^{126}Te (see Fig. 2), with the discrepancy for ^{125}Te being particularly severe (4σ).

In deriving this limit, a rather surprising observation was made: a fluence slightly below this limiting value would produce abundances in good agreement with observation. To test the hypothesis that these three isotopes might be neutrino postprocessing products, we repeated the inversion with the constraint of zero freeze-out abundances. The postprocessed abundance distributions in the $A = 124\text{--}126$ window are shown in Fig. 2 for $\mathcal{F} = 0.020, 0.031, \text{ and } 0.045$. For the choice $\mathcal{F} = 0.031$, all three nuclei are produced within $\sim 1\sigma$ of the observed abundances. Therefore, if a realistic r -process network calculation gives a characteristic freeze-out pattern with severely underabundant nuclei in the window, the observed abundances of these nuclei would strongly favor an r -process site with a neutrino fluence close to $\mathcal{F} = 0.031$ after the freeze-out of the $A \sim 130$ peak. Furthermore, the unpostprocessed abundance distribution outside the window derived by the inversion necessarily depends on \mathcal{F} . Thus, in principle, the comparison of this distribution with the one calculated by the r -process theory could provide a consistency check on whether we have picked the correct \mathcal{F} .

The existence of a second set of postprocessing-sensitive nuclei, those residing in the $A = 183\text{--}187$ valley just below the $A \sim 195$ peak, provides an important additional test of the hypothesis that neutrino postprocessing has modified the r -process abundance distribution. This

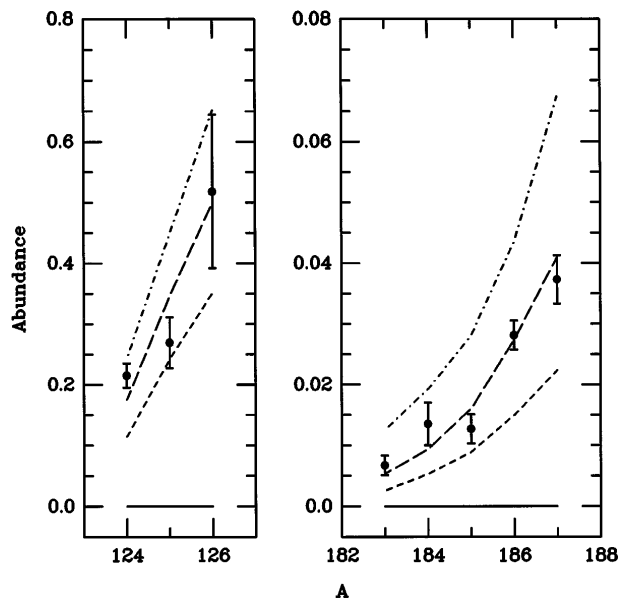


FIG. 2. Postprocessed abundance distributions in the $A = 124-126$ and $183-187$ windows. The short-dashed, long-dashed, and dot-dashed lines correspond to $\mathcal{F} = 0.020$ (0.007), 0.031 (0.015), and 0.045 (0.030), respectively, for the $A = 124-126$ ($183-187$) window. The observed abundances [12] are plotted as filled circles with error bars. The unpostprocessed abundances in the windows were set to zero (solid lines).

second window corresponds to the stable nuclei ^{183}W , ^{184}W , ^{185}Re , ^{186}W , and ^{187}Re . As in the case of the $A \sim 130$ peak we first establish a conservative upper bound on the neutrino fluence, $\mathcal{F} \lesssim 0.030$, by finding the unpostprocessed conditions under which all of these nuclei are overproduced by the postprocessing alone. A fluence saturating this bound overproduces all five species, with the deviations being $\geq 3\sigma$ in four cases [and with the disagreement for ^{187}Re being particularly large (7σ)]. Next, we again test the ansatz that these special nuclei might be the exclusive products of neutrino-induced synthesis. The postprocessed abundance distributions of these nuclei are also shown in Fig. 2 for $\mathcal{F} = 0.007$, 0.015, and 0.030. The choice $\mathcal{F} = 0.015$ yields an excellent fit, again agreeing with observation within $\sim 1\sigma$.

It is remarkable that the eight isotopes we initially identified as having great sensitivity to neutrino postprocessing prove to have abundances fully consistent with neutrino-induced synthesis during postprocessing. We consider this as strong evidence suggesting that the r process does occur in an intense neutrino fluence, and thus that the interior region of a type II supernova is the site of the r process. The best-fit fluences derived, $\mathcal{F} = 0.031$ and 0.015, are typical of such sites. For example, the r -process model in Ref. [4] is characterized by $L_{\nu, \text{FO}} \sim 10^{51} \text{ erg s}^{-1}$, $r_{\text{FO}} \sim 600-1000 \text{ km}$, and $\tau_{\text{dyn}} \sim \tau_{\nu} \sim 3 \text{ s}$, yielding $\mathcal{F} \sim 0.01-0.03$.

If this conclusion is correct, neutrino-induced synthesis places stringent new constraints on models of the r process. The product of the neutrino flux and dynamic time scale at freeze-out for each abundance peak is now determined, and would appear to require either fairly large freeze-out radii, as in Ref. [4], or fairly short dynamic time scales, as deduced in Ref. [6]. Our results also suggest that the $A \sim 195$ peak freezes out either at a smaller neutrino luminosity corresponding to a later time, consistent with Ref. [4], or at a larger radius and a larger neutrino luminosity corresponding to a shorter dynamic time scale, as in the wind scenario of Ref. [6], than the $A \sim 130$ peak. The possibility of deriving strong constraints on the dynamics of the r process should provide adequate motivation for fully incorporating neutrino interactions into the networks modeling the r process and the subsequent decay-back to the valley of β stability.

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