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EVIDENCE FOR AN INTENSE NEUTRINO FLUX DURING *r*-PROCESS NUCLEOSYNTHESIS?

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ABSTRACT

We investigate the possibility that neutrino capture on heavy nuclei competes with beta decay in the environment where the *r*-process elements are synthesized. We find that such neutrino capture is not excluded by existing abundance determinations. We show that inclusion of significant neutrino capture on the neutron number $N = 82$ waiting-point nuclei can allow the inferred abundances of these species to provide a good fit to steady weak (beta decay plus neutrino capture) flow equilibrium. In fact, for particular choices of neutrino flux conditions, this fit is an improvement over the case in which nuclei change their charge by beta decay alone. However, this improved fit can be realized only if neutrino capture plays a negligible role in nuclear decay back toward stability. We discuss the implications of these considerations for currently proposed sites and models of *r*-process nucleosynthesis.

Subject headings: elementary particles — nuclear reactions, nucleosynthesis, abundances — supernovae: general

1. INTRODUCTION

Many elements heavier than the iron peak, and about half of all nuclei heavier than mass $A > 100$, are believed to be synthesized in the *r*-process, or rapid neutron capture process (Burbridge et al. 1957; Cameron 1957; for a recent review, see Meyer 1994). The *r*-process is thought to take place in conditions of $(n, \gamma) \rightleftharpoons (\gamma, n)$ equilibrium (see Kratz et al. 1988, 1993). Measurements of abundances of *r*-process nuclei show that peaks exist near the closed neutron shells, which occur at neutron numbers $N = 50$, 82, and 126. In particular, the relative abundances of the *r*-process progenitor elements can be determined to accuracies of ~20% in the vicinity of the $N = 82$ (nuclear mass number $A \approx 130$) abundance peak (Kratz et al. 1988). This determination involves first subtracting the predicted *s*-process contribution from the measured solar abundance for each stable nuclide. The *r*-process progenitor abundances then are inferred from beta-decay lifetimes and the estimated probabilities for beta-delayed neutron emission along the decay path back to stability.

In $(n, \gamma) \rightleftharpoons (\gamma, n)$ equilibrium, the abundance distribution along an isotopic chain often can be strongly peaked at one or a few nuclear species around the closed neutron shells. We define $Y(Z)$ to be the abundance of the nuclide at the abundance peak for an isotopic chain Z. In the limit in which $Y(Z)$ is approximately equal to the total abundance along isotopic chain Z, the dominant source of leakage from isotopic chain Z to chain $Z + 1$ will occur through the beta decay of this nucleus at the abundance peak. We define the beta-decay rate of this nuclide to be $\lambda_\beta(Z)$. Usually, such a "waiting point" nucleus will have a closed neutron shell. Conditions of locally steady nuclear flow (time-independent abundances) would correspond to a constant value of the product $Y(Z)\lambda_\beta(Z)$ over some range of nuclear charges. This is sometimes termed steady beta flow equilibrium (see Cameron, Cowan, & Truran 1983). We can define the beta flow ratio $R_\beta(Z, Z')$ for isotopic chains Z and Z' to be

$$R_\beta(Z, Z') \equiv \frac{Y(Z)\lambda_\beta(Z)}{Y(Z')\lambda_\beta(Z')} . \qquad (1)$$

If Z and Z' are within the range of nuclear charges in which a locally steady beta flow obtains, then we would expect $R_\beta(Z, Z') = 1$. Obviously, these considerations for defining steady beta flow have to be modified if there are two or more isotopes that are significantly populated in a given isotopic chain.

Conditions of steady beta flow and $(n, \gamma) \rightleftharpoons (\gamma, n)$ equilibrium could occur in many of the diverse environments that have been suggested as possible sites of origin for *r*-process nucleosynthesis (for reviews, see Mathews & Cowan 1990; Cowan, Thielemann, & Truran 1991; Meyer 1994; and references therein). However, two proposed *r*-process sites could occur in intense neutrino fluxes: decompression of cold neutron matter from neutron star mergers or neutron star/black hole mergers (see Meyer 1989; Lattimer et al. 1977) and neutrino-heated supernova ejecta (see Woosley & Hoffman 1992; Meyer et al. 1992; Woosley et al. 1994; Takahashi, Witti, & Janka 1994). The processes of neutrino and antineutrino capture on heavy nuclei,

$$\nu_e + A(Z, N) \rightarrow A(Z + 1, N - 1) + e^- , \qquad (2a)$$

$$\bar{\nu}_e + A(Z, N) \rightarrow A(Z - 1, N + 1) + e^+ , \qquad (2b)$$

produce the same nuclear charge–changing effect as beta decay (positron capture) and positron decay (electron capture), respectively, though the nuclear dynamics and energetics of these processes can be very different (see Fuller & Meyer 1995, hereafter FM95; McLaughlin & Fuller 1995, hereafter MF). For the neutron-rich nuclei that are of interest in the *r*-process and for the neutrino and antineutrino energy spectra expected from hot nuclear matter, probably only neutrino capture (eq. [2a]) could play an important role (FM95; MF). If the rates of neutrino capture on the waiting-point nuclei in the *r*-process compete favorably with the corresponding beta-decay rates, then we could expect significant alterations of our picture of steady flow equilibrium (FM95; Nadyozhin & Panov 1993).

Neutrino capture on heavy nuclei could be important if the neutrino flux is large or if the neutrinos have high energies. The neutrino capture rate, λ_ν, depends both on nuclear physics and on the properties of the neutrino flux. For example, assuming that the neutrino flux originates from a

TABLE 1

$N = 82$ Nuclei

Parameter	^{130}Cd	^{129}Ag	^{128}Pd	^{127}Rh
λ_β (s^{-1})	3.47[a]	4.88[b]	6.03[b]	10.35[b]
$\lambda_\nu r_7^2$ (s^{-1}).......	4.01	4.25	4.49	4.75
$\lambda_\nu r_7^2/\lambda_\beta$	1.15	0.87	0.75	0.46
Y	2.28[c]	2.05[c]	1.76[c]	1.24[c]

[a] Beta decay rate known experimentally from Tuli 1990.

[b] Beta decay rate calculated by Kratz et al. 1988.

[c] Progenitor abundance from Kratz et al. 1988.

spherical, hot proto–neutron star, the following rough dependence holds (FM95; MF):

$$\lambda_\nu \propto L_\nu T_\nu r_7^{-2} \, |M|^2 P \, . \tag{3}$$

Here L_ν is the energy luminosity of the neutrinos, T_ν is the temperature of the electron neutrino distribution function (assuming that the neutrino chemical potential is $\mu_\nu \approx 0$), and r_7 is the distance from the center of the neutron star in units of 10^7 cm. The characteristic nuclear matrix element is $|M|^2$, and P is a characteristic phase-space factor. Given a sufficiently energetic neutrino distribution function, we expect neutrino capture to be dominated by transitions to the Fermi and Gamow-Teller resonance states (FM95; MF). We caution the reader that the dependence of λ_ν on the various ingredient quantities in equation (3) is highly dependent upon the particular geometry of our example. Alternatively, if we were to consider outflow from merging neutron stars, then we could obtain similar values of λ_ν and, hence, similar *r*-process effects from neutrino capture, though the dependence on the geometry and neutrino distribution function parameters could be significantly different than in the supernova case. The neutrino fluxes and mass-outflow geometries of merging neutron stars are poorly understood at present (see Wilson & Mathews 1995; Ruffert, Janka, & Schäfer 1995).

2. STEADY BETA FLOW VERSUS STEADY WEAK FLOW

We have calculated the ratios R_β for elements in the $N = 82$ peak. The beta-decay rates (s^{-1})we used (Kratz et al. 1988; Tuli 1990) are shown in Table 1. In general, the heavier elements tend to have slower beta-decay rates since they also have larger Z and thus are closer to stability. The abundances used (Kratz et al. 1988) are also shown in Table 1. The resulting values of R_β are shown in Table 2. The R_β ratios have been calculated with the heavier (more stable) element always in the numerator and the lighter element always in the denominator. These values fall systematically below unity. This systematic trend has not been pointed out before. However, the R_β-values in Table 2 usually are taken as evidence of steady beta flow in the *r*-process since the characteristic abundance errors are believed to be of order 15%–20% and the R_β-values differ from unity by roughly that amount. Unless there are systematic, non-Gaussian normal errors in the abundance determinations, it is difficult to understand why these R_β ratios are systematically low. Although most of the elements in the abundance peak are concentrated in the $N = 82$ isotopes, a small component in another isotope would cause a deviation of the ratios R_β from unity. Below we will argue that ν-capture could explain this result; however, F.-K. Thielemann (1996, private communication) has suggested that a superposition of several distinct neutron exposure conditions could account for the systematic trend evident in Table 2. There remains the question of whether the particular temperature, density, and Y_e (electron fraction) tracks proposed in, for example, the Woosley et al. (1994) or the Qian & Woosley (1996) ejection trajectories provide the requisite superposition of conditions to explain the trend. Note that we have employed ground-state beta-decay rates in Tables 1 and 2. If the *r*-process is occurring in high-temperature environments, then there may be an acceleration of the beta-decay rates resulting from thermal population of excited nuclear parent states.

TABLE 2

R_β-Values[a]

Nucleus	^{129}Ag	^{128}Pd	^{127}Rh
^{130}Cd	0.79	0.74	0.62
^{129}Ag	⋯	0.92	0.77
^{128}Pd	⋯	⋯	0.82

[a] These ratios always contain the heavier nucleus's abundance and beta-decay rate in the numerator and the lighter nucleus's abundance and beta-decay rate in the denominator.

However, we note that a modicum of neutrino exposure can lead to an interesting interpretation of the trends in Table 2. To take account of the possibility that neutrino capture, as well as beta decay, contributes to the rate of weak leakage from one isotopic chain to the next, we define

$$R_{\beta+\nu}(Z, Z') \equiv \frac{Y(Z)[\lambda_\beta(Z) + \lambda_\nu(Z)]}{Y(Z')[\lambda_\beta(Z') + \lambda_\nu(Z')]} \, , \tag{4}$$

where $\lambda_\nu(Z)$ and $\lambda_\nu(Z')$ are the neutrino capture rates on the waiting-point nuclei of charge Z and Z', respectively, while the other notation is as in equation (1). Clearly $R_{\beta+\nu} = 1$ if steady flow equilibrium prevails over the region of the abundance peak that includes Z and Z'. We term this condition steady *weak* flow equilibrium.

The evaluation of $R_{\beta+\nu}(Z, Z')$ is more difficult than the calculation of $R_\beta(Z, Z')$. The neutrino capture rate will vary according to the properties of the neutrino flux and distance from the neutron star or other neutrino source. In addition, the rate will vary between nuclei as a result of differences in characteristic matrix elements and the excitation energy of the Fermi and Gamow-Teller resonances. Our calculations of the neutrino capture rates (s^{-1}) for the $N = 82$ waiting-point nuclei are tabulated in Table 1. These computations conform to the method of FM95 and MF, except that we include here a full numerical calculation of the energy-dependent phase-space factors and Coulomb wave correction factors (see McLaughlin & Fuller 1996). For the rates in Table 1, a neutrino luminosity of $L_\nu = 10^{51}$ ergs s^{-1} and a ν_e neutrino sphere temperature of $T_\nu = 3.1$ MeV is assumed. These conditions are consistent with those obtained at late time ($t_{\rm pb} \approx 7$ s), when most of the $N = 82$ nuclei are made in the Woosley et al. (1994) calculations of *r*-process nucleosynthesis. Using these conditions, and a distance of $r_7 = 0.8$, we find that the ratio $R_{\beta+\nu} \approx 1$ in all cases. The $R_{\beta+\nu}$ ratios for $r_7 = 0.8$ are shown in Table 3. These results demonstrate that significant neutrino capture could be tolerated in some models of *r*-process nucleosynthesis. Note that the neutrino flux parameters and the distance to the neutron star may be varied as long as the value $L_\nu T_\nu r_7^{-2}$ remains the same, at least in the context of the model of *r*-process nucleosynthesis from supernova

TABLE 3

$R_{\beta+\nu}$-VALUES[a]

Nucleus	^{129}Ag	^{128}Pd	^{127}Rh
^{130}Cd	0.93	0.95	1.0
^{129}Ag	⋯	1.0	1.1
^{128}Pd	⋯	⋯	1.0

[a] Neutrino fluxes evaluated at $T_\nu = 3.1$ MeV, $L_\nu = 10^{51}$ ergs s^{-1}, and $r_7 = 0.8$.

outflow. If the radius is increased by a factor of 2, the luminosity or temperature must increase by a factor of 4. Other possible alterations to the capture rates are discussed in § 3.

Additional variance in neutrino capture rates between nuclei could arise from differences in the placement and width of the Gamow-Teller strength. The excitation energy distribution of this strength is uncertain (FM95, MF). The Gamow-Teller strength distribution width in the $N = 82$ nuclei may be varied to effect an increase in the neutrino capture rate in these species by a factor of ~2. The neutrino capture rate calculations presented in Table 1 are based on the assumption that the Gamow-Teller resonance was located at the same excitation energy as the Fermi strength. If the Gamow-Teller strength centroid was pushed upward by ~4 MeV in excitation energy, then the neutrino capture rate could decrease by as much as a factor of ~2. Such effects could cause significant rate variations between nuclei. In the case of the nuclei examined in Tables 2 and 3, all $R_{\beta+\nu}$ ratios are close to unity when calculated with the given neutrino flux parameters. If the capture rate for one nucleus were to change (e.g., from a change in the width or centroid of the Gamow-Teller strength), then all the ratios $R_{\beta+\nu}$ would be driven further from unity when an attempt was made to find a new concordant r_7-value.

3. DISCUSSION

First, we must note that in the particular environment of the post–core-bounce Type II supernova, an *r*-process at $r_7 \sim 1$ is in conflict with the models based on the high-entropy bubble in the Wilson and Mayle supernova calculations. At the high entropy per baryon $s/k \approx 400$ obtained in these models, the *r*-process goes on at, or above, ~600–1000 km (Woosley et al. 1994; Meyer et al. 1992). However, if the entropy at this time were lower, $s/k \approx 100$, then heavy-element nucleosynthesis $[(n, \gamma) \rightleftharpoons (\gamma, n)$ equilibrium$]$ could conceivably occur much closer to the neutron star, with $r_7 \sim 1$ not out of the question (see, e.g., the calculations in Qian & Woosley 1996, where it is argued that the entropy must be less than $s/k \approx 200$). Production of *r*-process elements in this scenario requires further investigation into the velocity field and electron fraction of the outflowing material. Other numerical models of supernovae seem to obtain such low entropies (e.g., the models on which the Takahashi et al. 1994 calculations are based; see also Burrows, Hayes, & Fryxell 1995). Note however that models with entropies $s/k \lesssim 200$ would require very neutron-rich conditions, $Y_e \lesssim 0.26$, if *r*-process nucleosynthesis is to take place (Meyer, Brown, & Luo 1991; Hoffman et al. 1996). In any case, it is not obvious that any of the existing *r*-process models based on neutrino-heated supernova ejecta could yield $(n, \gamma) \rightleftharpoons (\gamma, n)$ equilibrium freezeout for the $N = 82$ nuclei at $r_7 \sim 1$ with the requisite electron fraction. This implies that either (1) the trend seen in Table 2 does not arise from neutrino capture, (2) models of the *r*-process from supernova ejecta need to be altered, or (3) the *r*-process originates in some other site.

In Woosley et al.'s (1994) calculations, mass elements (trajectories, in their terminology) that leave the neutron star at progressively later times tend to be responsible for the production of progressively heavier *r*-process nuclear mass ranges. It is clear that neutrino capture can dominate over beta decay throughout the stage of the *r*-process leading up to the establishment of $(n, \gamma) \rightleftharpoons (\gamma, n)$ equilibrium. Indeed, this can accelerate the *r*-process (Nadyozhin & Panov 1993) and perhaps explain how the "scale height" of models could be reduced. However, neutrino capture must be comparable or subdominant to the beta-decay rates of the waiting-point species when freezeout from $(n, \gamma) \rightleftharpoons (\gamma, n)$ equilibrium occurs.

It would be desirable to examine steady weak flow in the $N = 50$ peak nuclei in a manner similar to our treatment of the $N = 82$ nuclei. Unfortunately, because of difficulties in extracting the *r*-process component of the measured abundances for these species, the inferred progenitor abundances (e.g., ^{80}Zn) are more uncertain than those inferred for the $N = 82$ abundance peak (Kratz et al. 1988). This makes analysis of the weak flow in this region difficult. Fuller & Meyer (1995, 1996) considered the ratio of ^{80}Zn to ^{79}Cu. They found that if steady beta flow is assumed ($R_\beta = 1$, to within 20%), then a significant rate of neutrino capture on heavy nuclei is not tolerable. In fact, they employed their calculations to place a limit of $r_7 > 4$ on the location of $(n, \gamma) \rightleftharpoons (\gamma, n)$ equilibrium freezeout for the $N = 50$ nuclei. This limiting value of radius depends sensitively on the value of R_β. Therefore, it would be desirable to know a more precise value of the progenitor abundances in order to make a determination of the prospects for significant neutrino capture contributions to steady weak flow in this case. Furthermore, in models of neutrino-heated supernova ejecta, the $N = 50$ nuclei are primarily made much earlier than are the $N = 82$ species. The neutrino-heating history, outflow velocity, and other parameters could be different at this earlier epoch. Therefore, it is conceivable that Fuller & Meyer's (1995, 1996) limit on the location of the $N = 50$ freezeout could be consistent with significant neutrino capture in the $N = 82$ species, at least within the context of the *r*-process originating in supernova ejecta.

If neutrino capture can affect steady weak flow equilibrium, then would it not also play a role during the decay back toward stability? Neutrino capture–induced neutron emission would be greatly enhanced over beta-delayed neutron emission, since neutrino capture could access the considerable Gamow-Teller and Fermi strength that resides at daughter-nucleus excitation energies above the neutron separation energy for the *r*-process progenitor species (FM95). Indeed, populating the region of excitation energy near the isobaric analog state or Gamow-Teller peak could result in multiple-neutron emission. Clearly, if such processes operate during decay back toward stability in the *r*-process, then the inference of the progenitor abundances from the measured stable species abundances could be quite significantly different from the results of Kratz et al. (1988, 1993). In this event, our discussion of neutrino capture contributions to weak steady flow based on Kratz et al.'s progenitor abundances would be specious, and the remarkable results of Table 3 merely an accident. For this scenario, perhaps

Thielemann's suggestion for explaining the trends in Table 2 will prove to be correct, in which case neutrino capture will serve to drive the $R_{\beta+\nu}$ ratios further from unity. Such an effect could allow for very useful and stringent constraints on the location of the $(n,\ \gamma) \rightleftharpoons (\gamma,\ n)$ equilibrium freezeout in various models of the *r*-process.

However, the rapid outflow of material inherent in some models of the *r*-process suggests an alternative resolution to the inconsistency of significant neutrino capture in both weak steady flow and during decay back toward stability. As a working example, consider models of the *r*-process inspired by the rapidly outflowing, neutrino-driven wind in the post–core-bounce supernova environment. Here we would expect neutrino capture and decay back toward stability to be occurring in material that is moving away from the source of the neutrino flux. If indeed neutrino capture is as significant in steady weak flow as Table 3 suggests, then we know that the neutrino flux must be high enough to yield the neutrino capture rates in Table 1 for the $N = 82$ species when this material freezes out of $(n,\ \gamma) \rightleftharpoons (\gamma,\ n)$ equilibrium. The condition $R_{\beta+\nu} \approx 1$ in Table 3 suggests that the $N = 82$ nuclei experience this freezeout at $r_7 \approx 0.8$. If neutrino capture is to play a negligible role in decay back toward stability, then, conservatively, the mean neutrino capture rates should be less than $\sim\frac{1}{10}$ the beta-decay rates. So, for example, for ^{127}Rh, $\lambda_\nu \approx 7.4\ \mathrm{s}^{-1}$ at $r_7 = 0.8$ while $\lambda_\beta \approx 10.35\ \mathrm{s}^{-1}$. A characteristic outflow velocity of $10^8\ \mathrm{cm\ s}^{-1}$ will take the material at the $(n,\ \gamma) \rightleftharpoons (\gamma,\ n)$ freezeout point at $r_7 \approx 0.8$ to $r_7 \approx 2$ in one neutrino capture time. At $r_7 \approx 2$, we will have $\lambda_\nu \ll \lambda_\beta$. An outflow velocity $\geq 10^8\ \mathrm{cm\ s}^{-1}$ is just what is expected in recent models. Therefore, the rapid outflow of the material could allow significant neutrino capture influence on steady flow equilibrium yet minimize neutrino-induced processing during decay back to stability.

Neutrino capture conceivably could populate highly excited states in the daughter nucleus that lie above the fission barrier. Such neutrino capture–induced fission would be most likely for heavier nuclei, including the $A \approx 195$ peak nuclei and, especially, the actinides (Fuller, McLaughlin, & Meyer 1996).

Could neutrino capture–induced fissioning of heavy nuclei halt the *r*-process flow before the actinides were synthesized? Again, rapid outflow could allow lower mass nuclei to experience significant neutrino flux exposure while the heavier species that are synthesized later experienced insignificant neutrino processing. Although this is plausible, it remains to be seen whether detailed models of the *r*-process in neutrino-heated outflows can avoid problems related to neutrino capture–induced fission or neutrino processing on the decay back to stability.

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REFERENCES

Burbridge, E. M., Burbridge, G. R., Fowler, W. A., & Hoyle, F. 1957, Rev. Mod. Phys., 29, 694
Burrows, A., Hayes, J., & Fryxell, B. A. 1995, ApJ, 450, 830
Cameron, A. G. W. 1957, Stellar Evolution, Nuclear Astrophysics, and Nucleogenesis (Chalk River Rep. CRL-41) (2d ed.; Chalk River, Ontario: At. Energy Canada Ltd.)
Cameron, A. G. W., Cowan, J. J., & Truran, J. W. 1983, Ap&SS, 91, 235
Cowan, J. J., Thielemann, F.-K., & Truran, J. W. 1991, Phys. Rep., 208, 267
Fuller, G. M., McLaughlin, G. C., & Meyer, B. S. 1996, in preparation
Fuller, G. M., & Meyer, B. S. 1995, ApJ, 453, 792 (FM95)
———. 1996, ApJ, 464, 521 (erratum to FM95)
Hoffman, R. D., Woosley, S. E., Qian, Y.-Z., & Fuller, G. M. 1996, in preparation
Kratz, K.-L., Bitouzet, J.-P., Thielemann, F.-K., Möller, P., & Pfeiffer, B. 1993, ApJ, 403, 216
Kratz, K.-L., Thielemann, F.-K., Hillebrandt, W., Möller, P., Härms, V., Wöhr, A., & Truran, J. W. 1988, J. Phys. G, 24, S331
Lattimer, J. M., Mackie, F., Ravenhall, D. G., & Schramm, D. N. 1977, ApJ, 213, 225
Mathews, G. J., & Cowan, J. J. 1990, Nature, 345, 491
McLaughlin, G. C., & Fuller, G. M. 1995, ApJ, 455, 202 (MF)
———. 1996, ApJ, in press (erratum to MF)
Meyer, B. S. 1989, ApJ, 343, 254
———. 1994, ARA&A, 32, 153
Meyer, B. S., Brown, J. S., & Luo, N. 1996, preprint
Meyer, B. S., Mathews, G. J., Howard, W. M., Woosley, S. E., & Hoffman, R. 1992, ApJ, 399, 656
Nadyozhin, D. K., & Panov, I. V. 1993, in Proc. 3d Int. Symp. on Weak and Electromagnetic Interactions in Nuclei (WEIN-92), ed. Ts. D. Vylov (Singapore: World Sci.), 479
Ruffert, M., Janka, H. T., & Schäfer, G. 1995, A&A, 231, 423
Takahashi, K., Witti, J., & Janka, H. T. 1994, A&A, 286, 857
Tuli, J. K. 1990, Nuclear Wallet Cards (4th ed.; Upton, NY: Brookhaven Natl. Lab.)
Qian, Y.-Z., & Woosley, S. E. 1996, ApJ, submitted
Wilson, J. R., & Mathews, G. J. 1995, Phys. Rev. Lett., 75, 4161
Woosley, S. E., & Hoffman, R. D. 1992, ApJ, 395, 202
Woosley, S. E., Wilson, J. R., Mathews, G. J., Hoffman, R. D., & Meyer, B. S. 1994, ApJ, 433, 229