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WEAK CHARGE-CHANGING FLOW IN EXPANDING *r*-PROCESS ENVIRONMENTS

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ABSTRACT

We assess the prospects for attaining steady nuclear-flow equilibrium in expanding *r*-process environments where beta decay and/or neutrino capture determine the nuclear charge-changing rates. For very rapid expansions, we find that weak steady flow equilibrium normally cannot be attained. However, even when neutron-capture processes freeze out in such nonequilibrium conditions, abundance ratios of nuclear species in the *r*-process peaks might still *mimic* those attained in weak steady flow. This result suggests that the *r*-process yield in a regime of rapid expansion can be calculated reliably only when all neutron-capture, photodisintegration, and weak interaction processes are fully coupled in a dynamical calculation. We discuss the implications of these results for models of the *r*-process sited in rapidly expanding neutrino-heated ejecta.

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

1. INTRODUCTION

In this paper we study the influence of weak, charge-changing nuclear reactions (beta decay and neutrino capture) on neutron-capture nucleosynthesis in rapidly expanding (decompressing) media. The astrophysical site of origin of *r*-process nucleosynthesis (or rapid neutron-capture nucleosynthesis; Burbidge et al. 1957; Cameron 1957) is not known with certainty (see Mathews & Cowan 1990). Recently, however, there has been a resurgence of interest in *r*-process nucleosynthesis. This interest stems from new observations of heavy elements in low-metallicity halo stars (Sneden et al. 1996) and the possibility that the *r*-process may be situated in neutrino-heated supernova ejecta (Meyer et al. 1992; Woosley & Hoffman 1992; Takahashi, Witti, & Janka 1994; Woosley et al. 1994). These considerations could have implications for particle physics and cosmology, since, if we understand the abundance yields of decompressing neutrino-heated material, it becomes possible to probe the basic properties of neutrinos (Fuller et al. 1992; Qian et al. 1993; Qian & Fuller 1995).

Although models of *r*-process nucleosynthesis from neutrino-heated ejecta are promising, they suffer from a number of flaws. For example, it is not understood how the neutron/seed nucleus ratio in neutrino-heated supernova ejecta can become high enough to produce an abundance pattern yield that will match that of the solar system (see, e.g., Hoffman, Woosley, & Qian 1996; Meyer, Brown, & Luo 1996). Yet it may be required that at least *some* supernovae produce a solar *r*-process distribution, as there may be direct observational evidence that even the earliest *r*-process events in the galaxy produced an abundance pattern consistent with that observed in the solar system (see, e.g., Sneden et al. 1996). An alternative *r*-process site that may not suffer from the neutron/seed nucleus problem is the decompression of "cold" neutron matter from neutron star collisions (Lattimer et al. 1977; Meyer 1989).

Despite problems with these models, it may be *necessary* to consider *r*-process environments situated in an intense neutrino flux. It has been argued that the observed solar system *r*-process abundance pattern itself may contain clues that point to *r*-process nucleosynthesis occurring in an intense neutrino flux (McLaughlin & Fuller 1996) or requiring a significant neutrino fluence (Qian et al. 1997; Haxton et al. 1997). Neutrino postprocessing effects were also discussed in Meyer et al. (1992). The neutrino-heated supernova ejecta environment and the neutron star merger site would each suggest that rapid neutron-capture nucleosynthesis takes place in an expanding medium and in an intense neutrino flux.

In this paper we concentrate on how the nuclear flows in a rapid neutron-capture environment can be influenced by the interplay of weak charge-changing reactions and rapid material outflow. Our study is meant to extend the evaluations of the "waiting point" assumption (that neutron captures are balanced against photodisintegrations along an isotopic [constant Z] chain; see, e.g., Cameron, Cowan, & Truran 1983; Cowan, Thielemann, & Truran 1991) to the unique conditions of rapid outflow and intense neutrino flux that may characterize neutrino-heated supernova ejecta or decompressing neutron star matter.

The intense neutrino flux provides a new wrinkle for *r*-process calculations: in addition to the usual beta decay processes, electron neutrino ν_e captures on nuclei can change nuclear charge (Nadyozhin & Panov 1993; Fuller & Meyer 1995; McLaughlin & Fuller 1995, 1996; Qian 1996; Qian et al. 1997). Further complicating matters, neutrino-capture rates can be position (time) dependent, unlike beta decay rates. In the comoving frame of a fluid element rapidly receding from a neutrino source, the neutrino-capture rate on heavy nuclei will fall sharply with time. Indeed, it has been suggested that rapid outflow may allow neutrino capture to dominate over beta decay at the onset of the neutron-capture epoch, yet allow beta decays to dominate weak flows after neutron capture ceases in the regime where neutron-rich nuclei "decay back" toward the valley of beta stability (McLaughlin & Fuller 1996; Qian 1996; Qian et al. 1997).

Weak nuclear flows help determine the final abundance ratios of nuclear species in the abundance peaks. It has been argued that the solar system data provide evidence that these ratios are within 20% of the predictions of calculations based on weak steady flow (Kratz et al. 1988, 1993). In weak steady flow, all abundances remain constant in time: neutron capture/photodisintegration or (n, γ)-(γ, n)

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equilibrium obtains for the species along an isotopic Z chain, and weak flows couple the abundances of adjacent isotopic chains.

We can identify three regimes that characterize weak flows in r-process nucleosynthesis in a rapidly expanding medium. These are (1) the case where the expansion timescale (or, more precisely, the time available for neutron capture) for the medium is long compared to the weak charge-changing timescale (given by the inverse of the sum of the typical neutrino-capture and beta decay rates); (2) the case where the expansion timescale is short compared to the weak charge-changing timescale; and (3) the case where these timescales are comparable. We will show that weak steady flow equilibrium can only be guaranteed in case 1, is impossible in case 2, and doubtful in case 3.

In § 2 we consider these cases and discuss the prospects for attaining weak steady flow. We explicitly integrate the differential equations for the abundances of the nuclear species in the neutron number $N = 82$ peak under several restrictive assumptions, including that of instantaneous (n, γ)-(γ, n) equilibrium. In § 3 we employ these calculations to produce a plot suggesting which regions of expansion timescale and neutrino flux parameter space might be conducive to either attaining weak steady flow equilibrium or abundance ratios that mimic those derived from weak steady flow. In § 4 we assess the implications of these results for models of r-process nucleosynthesis from neutrino-heated ejecta in general and wind models of the post–core-bounce supernova environment in particular.

2. WEAK FLOW

Here we outline a method for evaluating the effect of the weak charge-changing flow in a potential r-process environment. To start, we write down the general set of equations governing the flow of nuclei in a medium that contains neutrons and heavy nuclei and that is set in a flux of neutrinos of all six species. For a nucleus of charge Z, mass number A, and neutron number $N = A - Z$, the rate of change of its abundance $Y(Z, A)$ [or, alternatively, $Y(Z, N)$] will be

$$\begin{aligned}\frac{dY(Z,A)}{dt} &= \sum_{n=0}^{\infty}[Y(Z-1,A+n)(\lambda_{\beta n}^{Z-1,A+n}+\lambda_{\nu n}^{Z-1,A+n})]\\ &\quad - Y(Z,A)\sum_{n=0}^{A-Z}(\lambda_{\beta n}^{Z,A}+\lambda_{\nu n}^{Z,A})\\ &\quad + \sum_{n=0}^{\infty}[Y(Z,A+n)\lambda_{\nu n}^{\rm NC}(Z,A+n)]\\ &\quad - Y(Z,A)\sum_{n=0}^{A-Z}\lambda_{\nu n}^{\rm NC}(Z,A)\\ &\quad + [Y(Z,A-1)\lambda_{n\gamma}(Z,A-1)-Y(Z,A)\lambda_{\gamma n}(Z,A)]\\ &\quad + [Y(Z,A+1)\lambda_{\gamma n}(Z,A+1)-Y(Z,A)\lambda_{n\gamma}(Z,A)]\,. \qquad (1)\end{aligned}$$

In this equation the rates for charged current electron neutrino-capture and beta decay processes followed by the emission of n neutrons proceeding on, for example, nucleus (Z, A), are $\lambda_{\nu n}^{Z,A}$ and $\lambda_{\beta n}^{Z,A}$, respectively. The rate of neutral current neutrino scattering on, for example, nucleus (Z, A), accompanied by the spallation (emission) of n neutrons is $\lambda_{\nu n}^{\rm NC}(Z, A)$. The neutron-capture rate (photodisintegration rate) on nucleus (Z, A), for example, is labeled as $\lambda_{n\gamma}(Z, A)$ $[\lambda_{\gamma n}(Z, A)]$. Here we have ignored charged particle nuclear reactions, and we take photodisintegration rates to include the effects of charged particle–induced Coulomb excitation followed by neutron emission. The first two lines of this equation represent the effects of charged current weak processes, and the third and fourth lines give the effects of neutral current neutrino scattering–induced neutron spallation. The fifth and sixth lines of this equation show the effects of (n, γ) and (γ, n) reactions. In general all of the above terms need to be included in the calculation of $dY(Z, A)/dt$. However, in some conditions certain simplifying assumptions can be made.

For example, at sufficiently high temperature and density ($T_9 \gtrsim 1$, $n_n \gtrsim 10^{20}$ cm^{-3}, where T_9 is the temperature in units of 10^9 K and n_n is the neutron number density; see Meyer et al. 1992), (n, γ)-(γ, n) equilibrium obtains. In this equilibrium situation, the rate of photodissociation reactions is balanced by the rate of neutron captures for a given set of nuclei. This often occurs in conditions when the weak charge-changing rates are much slower than the neutron-capture rates, so that the waiting-point approximation is valid (Cameron et al. 1983). If (n, γ)-(γ, n) equilibrium is assumed to be established on a rapid timescale compared to that of any of the weak processes, then we can ignore neutral current neutrino scattering–induced neutron spallation and, further, rewrite the above equation in terms of *inclusive*, or total weak charged current rates, e.g., $\lambda_\beta(Z, N) \equiv \sum_{n=0}^{A-Z} \lambda_{\beta n}^{Z,A}$, and $\lambda_\nu(Z, N) \equiv \sum_{n=0}^{A-Z} \lambda_{\nu n}^{Z,A}$. Of course, under the general assumption of (n, γ)-(γ, n) equilibrium, neutron-capture reaction rates will be equal and opposite to corresponding photodisintegration rates, so that we can drop these terms in equation (1) to obtain

$$\begin{aligned}\frac{dY(Z,N)}{dt} &= -[\lambda_\beta(Z,N)+\lambda_\nu(Z,N)]Y(Z,N)\\ &\quad + [\lambda_\beta(Z-1,N+1)+\lambda_\nu(Z-1,N+1)]\\ &\quad \times Y(Z-1,N+1)\,. \qquad (2)\end{aligned}$$

The reactions governing the abundances of a set of nuclei can be described as a series of coupled differential equations, of the form of equation (1). In regions where the waiting-point approximation is valid, this set may be reduced to equations of the form of equation (2). The nuclei that comprise the peaks in the r-process abundance distribution *may* be an example of such a set.

Sometimes it is also possible to make the steady flow approximation. Steady beta flow has been invoked to explain the measured solar system r-process abundance peaks (see Kratz et al. 1988). The definition of steady flow equilibrium is as follows: if the input to a system of nuclei, such as the nuclei that comprise the r-process peaks, at the nucleus of lowest Z, is equal to the output at the nucleus of highest Z, then steady flow equilibrium obtains. As a consequence of steady beta flow equilibrium in an environment with no neutrinos, the ratio of abundances of progenitor r-process nuclei in the peaks will be the inverse ratio of the beta decay rates. More generally with neutrinos, the ratio of these abundances will reflect the inverse ratio of the neutrino-capture plus beta decay rates when steady *weak* flow equilibrium obtains.

We wish to evaluate the prospects for attaining weak steady flow equilibrium in an expanding outflow such as that of the post–core-bounce supernova. To this end, we write the formal solution of equation (2) for a particular $Y(Z, N)$:

$$\begin{aligned} Y(Z, N, t_f) &= \left[Y(Z, N, t_i) - \frac{\lambda_{\beta+\nu}(Z-1, N+1, t_i) Y(Z-1, N+1, t_i)}{\lambda_{\beta+\nu}(Z, N, t_i)} \right] \\ &\times f(t_i, t_f) + \left[\frac{\lambda_{\beta+\nu}(Z-1, N+1, t_f) Y(Z-1, N+1, t_f)}{\lambda_{\beta+\nu}(Z, N, t_f)} \right] \\ &- \int_{t_i}^{t_f} \frac{d}{dt} \left[\frac{\lambda_{\beta+\nu}(Z-1, N+1, t) Y(Z-1, N+1, t)}{\lambda_{\beta+\nu}(Z, N, t)} \right] \\ &\times f(t_f, t) dt , \end{aligned} \quad (3)$$

$$f(a, b) = \exp\left[- \int_a^b \lambda_{\beta+\nu}(Z, N, t')dt' \right] .$$

Here the time dependence of the rates and the abundances has been explicitly included and the solution is evaluated at the final time, t_f. Note that equation (3), after integration by parts, is a standard solution of a first-order linear differential equation in the form $dy/dt - f(t)y = g(t)$, where $f(t)$ and $g(t)$ are continuous functions on the interval $t_i < t < t_f$. The first line in equation (3) shows the dependence of the solution on the initial conditions (time t_i). For compactness of notation we have denoted the sum $\lambda_\beta(Z, N) + \lambda_\nu(Z, N, t)$ as $\lambda_{\beta+\nu}(Z, N, t)$. The beta decay rates are independent of time, while the time dependence of the neutrino-capture rates is linked to the outflow rate of the material. In equation (3) the initial time corresponds to the onset of (n, γ)-(γ, n) equilibrium and the final time corresponds to freezeout from (n, γ)-(γ, n) equilibrium. It is apparent from equation (3) that the comparison between the total time spent in (n, γ)-(γ, n) equilibrium and the lifetime of a nucleus against beta decay and neutrino capture is an important factor in determining the abundances. We divide the solutions into three categories based on this comparison.

The first category is composed of the solutions for which $\lambda_\beta(Z, N, t_f) + \lambda_\nu(Z, N, t_f) \gg 1/(t_f - t_i)$. Here the term in the first line and the beginning of the second line in the above equation is very small, due to the large negative factor in the exponent, so that the effect of the initial conditions has been erased. In addition, the exponent in the last term is very small, except for the last time interval $\delta t \sim 1/[\lambda_\beta(Z, N, t) + \lambda_\nu(Z, N, t)]$. As long as the rates are large, the range of integration where the integrand is nonnegligible is very small, rendering the last term approximately equal to zero. Therefore the ratio of abundances of $Y(Z, N)$ to $Y(Z-1, N+1)$ is approximately the inverse ratio of the rates, and steady weak flow is obtained. This is the regime of applicability of the analysis of constraints on or contributions from the neutrino flux as employed by Fuller & Meyer (1995) and McLaughlin & Fuller (1996).

The second category is the situation where $\lambda_\beta(Z, N, t_f) + \lambda_\nu(Z, N, t_f) \ll 1/(t_f - t_i)$. In this case, the solution is governed mostly by the initial conditions, since there is very little time to move nuclei around with weak charge-changing reactions. In this case, the *r*-process cannot take place, since the nuclei will not be able to move up the proton number ladder fast enough to produce the peaks seen in the *r*-process abundance measurements.

The third category is the intermediate regime, where the solution is not entirely governed by the initial conditions, yet steady flow has not been attained. There is a fairly wide range of conditions around $\lambda_\beta(Z, N, t_f) + \lambda_\nu(Z, N, t_f) \sim 1/(t_f - t_i)$, which fall into this category. In this case all the terms in equation (3) must be included in order to predict the abundance of element $Y(Z, N)$ at the time of freezeout from (n, γ)-(γ, n) equilibrium. Despite the fact that steady weak flow has not been attained, it is possible in some cases to mimic the ratios expected in steady beta flow conditions, as discussed later in this section.

In order to give an example of the third intermediate case, we present the solution for the $N = 82$ peak for a particular set of conditions. We integrate forward four coupled differential equations of the type of equation (2), corresponding to each of the nuclei ^{127}Rh, ^{128}Pd, ^{129}Ag, and ^{130}Cd. The beta decay rates and neutrino-capture rates are taken from Table 1 of McLaughlin & Fuller (1996). The neutrino-capture rates scale as $1/r^2$, where r is the distance from the neutrino sphere. Therefore, rapidly outflowing environments will produce rapidly changing neutrino-capture rates. We take the distance coordinate r to vary as $r \propto \exp(t/\tau_e)$, where τ_e is the expansion timescale. We make the simplifying assumption that there is a constant input at the bottom of the ladder (at ^{127}Rh). Note that in the true *r*-process environment, it may be necessary to describe the input as a more complicated function of time. In fact, the initial distribution of seed nuclei in the (N, Z)-plane at the onset of neutron capture, and the time dependence of the thermodynamic conditions, can influence nuclear flow. Thus our calculations are quite schematic and are designed only to illustrate salient physical effects. We take the abundances of all the nuclei to be zero at the beginning of our calculation. In addition, we begin the integration at a time when the material is close to the neutrino sphere, so that the neutrino-capture rates are roughly 10 times the beta decay rates at the onset of (n, γ)-(γ, n) equilibrium

The solution is plotted in Figure 1 as the ratio of ^{130}Cd to ^{127}Rh against time. This lower curve at first rises rapidly, since the fast neutrino-capture rates cause the nuclei to climb the ladder to ^{130}Cd. However, after a few tenths of a second the curve turns over, due to the rapidly falling neutrino-capture rates. The abundance ratios cannot keep pace with the changing neutrino-capture rates, and nuclei begin to pile up at the bottom of the ladder. After a little more than a second, the curve turns upward again. This signals the point at which the beta decay rates become comparable to the neutrino-capture rates. The solution then asymptotes to the steady beta flow value. Note that in an environment where the neutrino-capture rates are small, the solution would begin at zero and slowly asymptote to the steady beta flow value (i.e., there would be no spike and subsequent turnover at the early time).

For comparison, the inverse ratio of the weak rates is also plotted against time (*upper curve*) in this figure. When the calculation begins, neutrino captures dominate over beta decays and the ratio of the rates is high. This is because of the small variation of neutrino-capture rates between nuclei of similar neutron and proton number (Fuller & Meyer 1995; McLaughlin & Fuller 1995). At late times, beta decays dominate over neutrino captures. Since beta decay rates show larger variation between nuclei, the ratio is significantly different from unity at late times.

It is clear from the figure that, for this choice of conditions, steady flow is not attained until a few seconds have elapsed. In order to determine the abundance ratios it is necessary to locate the time of freezeout from of (n, γ)-(γ, n)

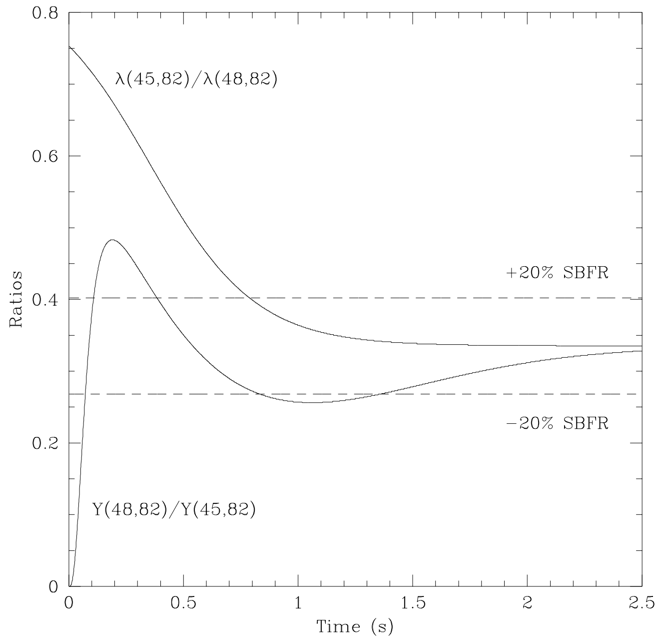

FIG. 1.—Abundance ratio of ^{130}Cd to ^{127}Rh plotted against time. Also shown for comparison is the inverse ratio of the weak rates (beta decay plus neutrino capture) for these nuclei. If at any time the two curves took on the same or a similar value, then weak steady flow would obtain. In this plot, the distance from the neutrino sphere r depends on time t as $r \propto \exp(t/\tau_e)$. For illustrative purposes we have taken the expansion time τ_e to be 0.5 s. When the abundance ratio enters the region between the two dashed lines, then the abundance ratio is within 20% of the value it would take on in conditions of steady beta flow.

equilibrium on Figure 1. For example, in the wind model discussed by Qian et al. (1997), freezeout is at $1.1\tau_e$. For our example parameters, that occurs at 0.55 s. At this time, the value of the abundance ratios is within 20% of the steady beta flow values, despite the fact that steady beta flow has not been attained. In fact, the abundance ratio is determined by the expansion timescale and the overall magnitude of the neutrino-capture rates and has very little to do with the values of the beta decay rates for these nuclei. This example serves to demonstrate that it is possible to mimic steady beta flow ratios when the neutrino-capture rates are dominant or at least comparable to the beta decay rates. Such a scenario is highly model dependent and, due to the large contribution from neutrino capture, will usually necessitate significant neutrino postprocessing effects. Our simple calculation cannot, of course, obtain the details of r-process nucleosynthesis. It can suggest only where it will be necessary to perform fully coupled calculations that do not rely on equilibrium assumptions.

3. WEAK FLOW IN WINDLIKE MODELS

In this section we explore the range of neutrino flux conditions and expansion timescales that may produce steady weak flow, steady beta flow, or abundances that mimic steady weak flow in a rapidly expanding environment. We show the link between these parameters and get an estimate of the degree to which the r-process progenitor abundances will experience neutrino postprocessing. In order to investigate the available parameter space, it is necessary to adopt a model that relates the timescale over which significant neutron capture occurs to the material expansion timescale. In the context of the simple model employed above, the time during which neutron capture occurs will be taken to be the time over which (n, γ)-(γ, n) equilibrium obtains. Ideally, an analysis of weak flow should be conducted with a sophisticated multidimensional hydrodynamic model for the post–core-bounce supernova outflow or the neutron star collision scenario that makes no recourse to equilibrium assumptions. Although understanding of multidimensional Type II supernova models has greatly improved recently, it does not yet give a definitive picture of the late time outflow conditions during which r-process nucleosynthesis may take place (Herant, Benz, & Colgate 1992; Herant at al. 1994; Miller, Wilson, & Mayle 1993; Burrows, Hayes, & Fryxell 1995; Janka & Müller 1996; Mezzacappa et al. 1996). In light of this, we will employ the simplistic (n, γ)-(γ, n) equilibrium calculation of § 2 in the context of one-dimensional steady state wind models. This will facilitate exploration of the weak flow parameter space and elucidate important physics issues for r-process nucleosynthesis. Neutrino-driven wind models have in the past proved useful for studying other aspects of the post–core-bounce environment such as the neutron-to-seed ratio and neutrino-induced neutron spallation during postprocessing (Qian & Woosley 1996; Hoffman et al. 1996; Qian et al. 1997).

Figure 2 shows a plot, specific to the wind model, of possible solutions to the set of coupled differential equations that govern weak flow in the $N = 82$ peak. The verti-

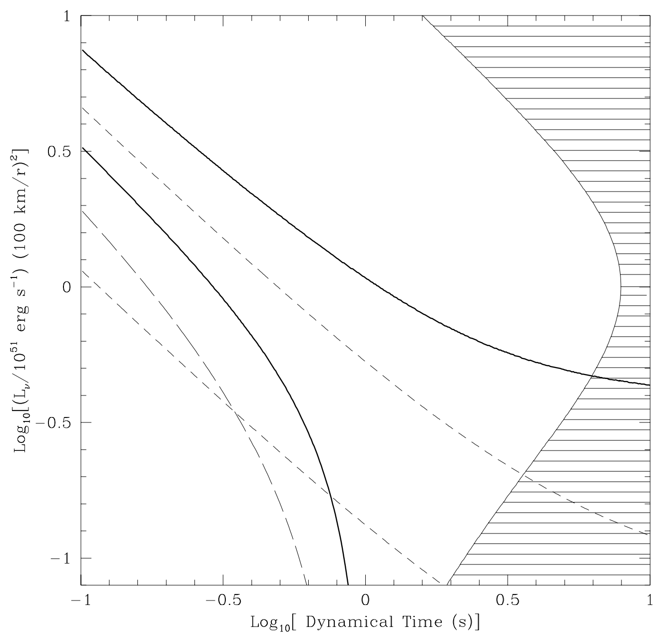

FIG. 2.—Plot delineating the parameter space available in the wind model. The quantity $(L_\nu/10^{51}\ \mathrm{ergs\ s^{-1}})(100\ \mathrm{km}/r)^2$ evaluated at (n, γ)-(γ, n) equilibrium freezeout is plotted against dynamical time. Steady weak flow (neutrino capture plus beta decay) obtains in the shaded region on the right-hand side of the graph. In the lower part of the shaded region, beta decay dominates over neutrino capture at (n, γ)-(γ, n) freezeout. In the upper region, neutrino capture dominates over beta decay at freezeout. The beta decay rates and neutrino-capture rates are approximately comparable at the time of (n, γ)-(γ, n) freezeout when $\log_{10}[(L_\nu/10^{51}\mathrm{ergs\ s^{-1}})(100\ \mathrm{km}/r)^2] \sim 0$. In the unshaded region between the dark solid lines, the abundance ratios mimic steady beta flow values. In the region below the long-dashed line, there is not enough time for a nucleus to change sufficient charge to traverse the $N = 82$ peak. In the region above the upper short-dashed line, there is more than one postprocessing neutrino capture per nucleus. In the region above the lower short-dashed line, more than 25% of the nuclei experience a postprocessing neutrino capture.

cal axis is $(L_\nu/10^{51}$ ergs$)(100$ km$/r)^2$ evaluated at freezeout from (n, γ)-(γ, n) equilibrium. Here L_ν is the neutrino luminosity and r is the distance from the neutrino sphere. The horizontal axis is the expansion timescale (i.e., the dynamical time τ_D in the wind model). The abundance ratios for each solution were evaluated at the time of (n, γ)-(γ, n) freezeout and compared to those that should obtain in steady weak flow and steady beta flow. Note that the neutrino-capture rates are roughly comparable to the beta decay rates when $\log_{10}[(L_\nu/10^{51}$ ergs$)(100$ km$/r)^2] \sim 0$.

The first question we wish to answer is, for what range of parameters does steady weak flow obtain? We choose the criterion for defining steady weak flow to be when the output from the top of the $N = 82$ peak chain is with 10% of the input at the bottom of the chain, evaluated at the time of (n, γ)-(γ, n) freezeout. The region of parameter space where steady weak flow obtains is the shaded region on the graph. Toward the top of this region the neutrino-capture rates are fast and the expansion timescale is slow, so that steady weak equilibrium is established quickly. Toward the bottom of this region steady beta flow obtains, a limiting case of steady weak flow. Here, the neutrino-capture rates are small enough that they have very little impact on the solution. It is interesting to note that a very large or very small neutrino flux assists in creating steady weak flow, although a moderate amount can prevent its establishment in a "windlike" exponential expansion. In fact, it is most difficult to obtain steady weak flow equilibrium when the neutrino-capture rates are comparable to the beta decay rates. This is because of the inability of the abundance ratios to keep pace with the rapidly changing neutrino-capture rates. It is evident from Figure 2 that steady weak flow is not a good approximation for describing the weak charge-changing flow in a fast expansion wind model. Indeed, in some senses the most natural wind models have dynamical times of 0.1–0.2 s (Qian & Woosley 1996; Duncan, Shapiro, & Wasserman 1986). For these conditions and a neutron capture timescale of $1.1\tau_D$ (see Quian et al. 1997), steady flow equilibrium is clearly a bad approximation. Finally, it can be seen from this figure that for a sufficiently long timescale $[\lambda_\beta(Z, N, t_f) + \lambda_\nu(Z, N, t_f) \gg 1/(t_f - t_i)]$, steady weak flow will be obtained for any combination of neutrino capture and beta decay.

The second question involves the mimicry of steady beta flow abundance ratios. As mentioned in § 2, the abundance ratios may be close to their steady beta flow values, despite the fact that the system is not in steady beta flow or even the more general steady weak flow. In Figure 2 the unshaded region between the thick solid lines is the region where all of the abundance ratios in the $N = 82$ peak at neutron-capture freezeout in our simplistic calculations will be within 20% of the values that would obtain if the system were in steady beta flow.

We have also placed a charge-changing constraint line on this plot for comparison. If there are roughly four charge-changing reactions that must take place in order for a nucleus to travel up the proton number ladder in the $N = 82$ peak, then this places a constraint on the expansion timescales (see, for example, Qian 1996). On the figure, above the long-dashed line, a nucleus at the bottom of the $N = 82$ peak will experience more than four charge-changing reactions before (n, γ)-(γ, n) freezeout.

Since the region of steady beta flow mimicry occurs when there is a significant or even dominant neutrino capture component to the total charge-changing rate at (n, γ)-(γ, n) freezeout, it behooves us to ask how much neutrino postprocessing will occur in this range of parameters. Several neutrons will be emitted after a neutrino-capture reaction, since such a reaction leaves the daughter nucleus in a highly excited state. If a significant percentage of nuclei are experiencing such interactions, then the decay back to the valley of beta stability after (n, γ)-(γ, n) freezeout will be significantly altered from the traditional picture. In fact, if all the nuclei experience one or more neutrino captures, the peak will be shifted toward a region with lower total nucleon number. It is possible to integrate the weak charge-changing rates to determine the percentage of nuclei that will experience a neutrino capture (Qian et al. 1997). Here for illustration we only include the contribution of the charged current processes; neutral spallation processes would give an additional (possibly comparable) contribution. In order to illustrate the postprocessing effects, we assume that the expansion timescale remains the *same* throughout the period of (n, γ)-(γ, n) equilibrium and the neutrino postprocessing epoch. With a timescale of a tenth of a second, which is a value typically discussed for the wind model, the region of mimicry occurs at a sufficiently high neutrino flux that almost all nuclei will experience one postprocessing charged current neutrino interaction. Although a detailed calculation is necessary to determine the exact abundances that would be produced by this model, it is clearly unlikely that the observed r-process distribution can be reproduced with a single wind expansion timescale of a tenth of a second.

In Figure 2, the region where nuclei will experience less than one neutrino capture per nucleus is shown as the area below the upper short-dashed line. The region where less than 25% of the nuclei will experience a neutrino capture is below the lower short-dashed line. There is only a very small region in the single expansion timescale wind model where postprocessing effects are small and steady beta flow effects might be mimicked. Steady beta flow effects are mimicked between the thick solid lines. But the region where this mimicry *and* postprocessing effects less than 25% occur is in the small unshaded triangle at the base of the horizontal axis, marked by the short-dashed line and the heavy solid line. This is probably the best scenario for reproducing the r-process abundances with a single-timescale exponentially expanding wind model. Only a detailed network calculation employing the full machinery of equation 1 could resolve this conjecture. Even so, this scenario employs an expansion timescale of 1 s. This timescale is considerably larger than that usually discussed for the wind model, but could be obtained conceivably given uncertainties in the neutrino emission and hydrodynamics in the post–core-bounce supernova environment.

4. CONCLUSIONS

In this paper we have presented a guide for analyzing the weak charge-changing flow in a potential r-process environment. We have identified three different regimes for the weak flow, which depend on the neutrino flux and the expansion timescale. Steady weak flow occurs when the time spent in (n, γ)-(γ, n) equilibrium is very long compared with the inverse charge-changing rate.

In order to assess the impact of these weak flow considerations on the nucleosynthesis yield in a potential r-process site, in § 3 we applied the weak flow analysis to a model with an exponential outflow. We concentrated on the $N = 82$ peak, although the same analysis may also be applied to other regions such as the $N = 126$ peak. (Clearly, the favored parameter space of expansion timescale and neutrino flux will be somewhat different for the material that makes the $A = 195$ material at the conclusion of neutron capture.) We find that the material is only in weak steady flow equilibrium when the expansion timescale is very long, a few seconds, for example. At the much shorter times, such as a tenth of a second, favored in the wind model, the *r*-process abundances still can conceivably mimic those of steady beta flow. However, these probably finely tuned scenarios might necessitate neutrino-induced neutron spallation postprocessing during the decay back to beta stability at a level that could be intolerable. We note that for rapid expansions, neutron capture may continue past (n, γ)-(γ, n) equilibrium freezeout. This would reduce the impact of neutrino postprocessing, as well as extend the time available for establishing weak equilibrium. A full network calculation carried through the period of decay back to beta stability would be necessary, however, to answer these questions definitively.

From our analysis of steady weak flow, we can infer the sort of conditions that would be conducive to producing the peaks in the *r*-process abundance distribution. One possibility is that neutrino capture has a limited impact during the neutron-capture phase. Then the potential environments are restricted to those where steady beta flow obtains or nearly obtains. One option might be a slightly altered version (altered to produce the correct neutron-to-seed ratio) of the slow one-dimensional post–core-bounce outflow produced in the Type II supernova model of Mayle & Wilson (as employed in the Meyer et al. 1992 and Woosley et al. 1994 *r*-process calculations). Another possibility is that the neutrino captures play a major role in accelerating the weak charge-changing flow during the neutron-capture phase, but the expansion rate takes on a more complicated time dependence than the single-timescale exponential wind model employed here. An example of such a scenario occurs when the expansion rate is fast during alpha-rich freezeout so that the neutron-to-seed ratio is acceptable (e.g., Hoffman et al. 1996), slow during the period of (n, γ)-(γ, n) equilibrium (neutron-capture epoch) so that steady weak flow can obtain, and then relatively fast during the postprocessing phase so that the amount of neutron spallation is restricted. Such a "fast-slow-fast" scenario sounds excessively convoluted in the one-dimensional post–core-bounce outflow models, but it remains to be seen whether three-dimensional convective models could produce such conditions (envision initially rapidly outflowing material that is caught in a convective eddy during the epoch of neutron capture and then later is reaccelerated and ejected). A third possibility is that the site of *r*-process nucleosynthesis is not the post–core-bounce supernova environment. We caution, however, that decompression of cold neutron matter from neutron star mergers/collisions could well experience the same parameter space "squeeze" we describe here for wind models of neutrino-heated supernova ejecta.

The method we have presented demonstrates the qualitative behavior of the weak charge-changing flow. It can be applied to any set of potential *r*-process conditions to give an indication of whether such conditions are likely to reproduce the measured *r*-process abundance pattern. We emphasize, however, that only a full network calculation, including the neutron-capture period and the postprocessing period, can predict definitively the nucleosynthesis yield that results from a rapidly expanding environment.

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