Neutrino capture by *r*-process waiting-point nuclei

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(Received 29 April 1998)

We use the quasiparticle random-phase approximation to include the effects of low-lying Gamow-Teller and first forbidden strength in neutrino capture by very neutron-rich nuclei with $N=50$, 82, or 126. For electron neutrinos in what is currently considered the most likely *r*-process site the capture cross sections are two or more times previous estimates. We briefly discuss the reliability of our calculations and their implications for nucleosynthesis. [S0556-2813(98)02410-8]

PACS number(s): 25.30.Pt, 26.30.+k

The *r* process, which is responsible for the formation of half of all elements with $A>70$, is thought by many to take place in the ''hot bubble'' that expands off a protoneutron star during a type-II supernova [1]. If that is the case the nuclei involved are subject to an intense neutrino flux while they are made. This fact has been used to argue both that the *r* process occurs far from the neutron star so that neutrinos cannot overly disturb it [2], and that it occurs closer in and is therefore accelerated by neutrino interactions [3].

Serious investigation of these and related issues will require knowledge of cross sections for neutrino capture by the very neutron-rich nuclei that lie along the *r*-process path. Although several groups have recently estimated the cross sections [2,4,5], none has tried to be very precise, for two reasons. First, precision is difficult unless one focuses on a few nuclei, and the *r* process involves a huge number of neutron-rich isotopes. Second, conditions in the hot bubble are so uncertain that precise estimates are not really warranted. Here, nonetheless, we attempt to calculate charge-changing neutrino-nucleus scattering rates[1] a little more carefully than before in particularly important ''waiting-point'' isotopes at neutron closed shells. The reason is not so much to be precise as it is to investigate effects that systematically increase cross sections above current estimates.

Using the neutrino-nucleus scattering formalism presented in Ref. [6], we examine two kinds of nuclear transitions not yet considered in this context that can be prompted by neutrinos and therefore add to the cross section: Gamow-Teller (GT) and first-forbidden transitions to *low-lying* excited states. Since most of the GT transition strength, induced by the operator $\vec{\sigma}\tau_+$, lies in a single broad resonance the low-energy strength has usually been neglected; Ref. [5], for example, approximates the entire distribution by a Gaussian of width 5 MeV. But the energy of the GT resonance in very neutron-rich nuclei is probably high enough to prevent excitation by most hot-bubble neutrinos, the average energy of which is only about 11 MeV or less [7,8]. The same is true of the isobar analog (IA) resonance, which is excited even less because $J=0$ states have only a single M substate. The low-lying GT strength may therefore contribute nearly as much to cross sections as the resonances, even though it is small in comparison.

Forbidden transitions induced by the operators $\vec{r}\tau_+$ and $[\vec{r}\vec{\sigma}]^{J=0,1,2}\tau_+$ have not been considered either, except briefly and without definite conclusion in Ref. [4], because in most stable nuclei they too are concentrated in high-lying (dipole-like) resonances and, moreover, are further suppressed by a factor of $(qR)^2$, where R is the nuclear radius. But in very neutron-rich nuclei, including the well-studied stable nucleus ^{208}Pb [9,10] some forbidden strength lies low. The reason is that the forbidden operators, which change parity and ordinarily must create a proton one oscillator shell (roughly speaking) above the neutron they destroy, can actually create a proton in an oscillator shell below the destroyed neutron if there are many more neutrons than protons. The diagram in Fig. 1 shows that in the unstable nuclei with $N=82$, for example, operators with $J^\pi=1^-$ and 2^- can transform a neutron near its Fermi surface to a proton close to its Fermi surface. As a result, some forbidden strength may lie low enough to overcome the $(qR)^2$ suppression (which is really not so great in heavy nuclei) and contribute significantly to the neutrino-nucleus cross sections. The size of this unusual contribution, and of that due to low-lying GT strength, is what we examine here.

Assessing the effects of states outside a giant resonance requires a calculation sophisticated enough to represent the competition between single-particle structure, which is responsible for the existence of low-lying strength, and the residual nucleon-nucleon interaction, which gathers strength into the higher-lying resonance. At the same time, and for reasons mentioned above, it is probably not worthwhile to aim for high precision. We therefore use a relatively simple microscopic description based on the neutron-proton quasiparticle random-phase approximation (QRPA) [11,12]. We restrict ourselves to nuclei with closed neutron shells ($N=50,82,126$) in part to avoid dealing with deformation but also because the closed-shell nuclei form ''bottlenecks'' in the *r*-process flow and thus determine the time scale of nucleosynthesis. The nuclear-structure effects that are significant here probably play a role in deformed nuclei as well.

Our calculations work as follows: We obtain single-particle energies from the parametrized Wood-Saxon potential in Ref. [13]. Where possible we include all neutron and

[1]The corresponding antineutrino rates are suppressed in neutron-rich nuclei and will not be considered here.

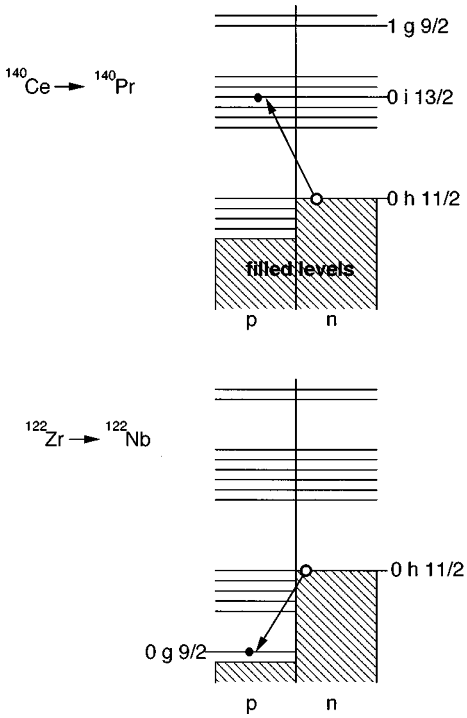

FIG. 1. Single-particle picture of forbidden charge-changing (neutron→proton) transitions in a stable nucleus and a neutron-rich nucleus, both with $N=82$. The change in parity restricts neutrons to move up an oscillator shell as they become protons in the stable nucleus, but in the neutron-rich nucleus they can move down an oscillator shell as well.

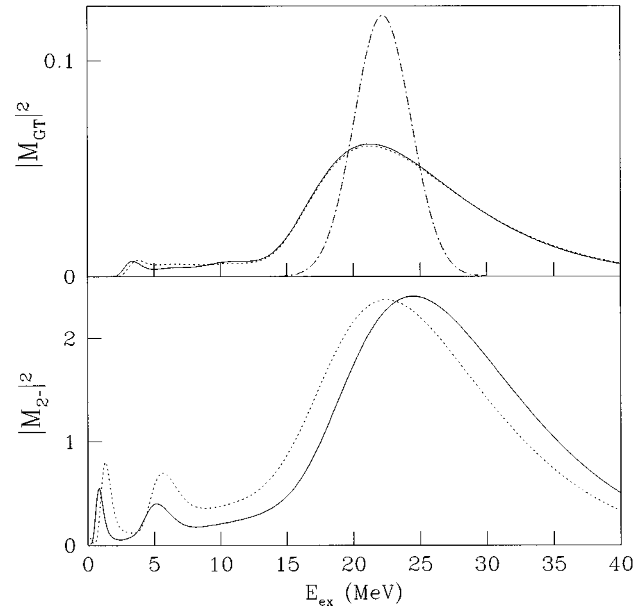

FIG. 2. Calculated GT (a) and forbidden 2^- (b) strength distributions for ^{124}Mo. The solid lines come from the δ-function interaction and the dashed lines from the *G*-matrix based interaction. The dot-dashed line in (a) is from a Gaussian GT resonance centered at the energy of the isobar analog state and with a width of 5 MeV, normalized to give the correct total strength.

proton levels that participate with reasonable probability in transitions induced by the Gamow-Teller and forbidden operators. Those that are unbound we take to be resonances; to obtain their wave functions we neglect the Coulomb interaction, making them bound. (We include Coulomb effects in perturbation theory when calculating their energies.) This procedure results in single-particle spaces of up to 20 levels for each kind of particle. Within these large spaces we use two different residual two-body interactions in the QRPA. The first is a δ function with independent strengths in the particle-hole and particle-particle channels as described in Ref. [14], and the second a combination of seven Yukawa potentials fit in Ref. [15] to a Paris-potential *G* matrix.

To reproduce systematics in stable nuclei and extrapolate to neutron-rich isotopes we modify both forces. First we adjust the strength of each interaction in the pairing channel to obtain pairing gaps $\Delta_p=\Delta_n=12/\sqrt{A}$ MeV [16] from the BCS equations. In the RPA we then adjust two parameters, the strengths of the particle-hole interactions in the 0^+ and 1^+ channels, so as to place the IA and GT resonances at appropriate energies. Unfortunately, although the energy $E_{\rm IA}$ of the analog state follows from the Coulomb energy difference between parent and daughter nuclei, the appropriate value of $E_{\rm GT}$ in very neutron-rich nuclei is less certain. (It is also more important, since the GT resonance contributes more to the cross section.) The usual way to estimate $E_{\rm GT}$ is through a relation of the form $E_{\rm GT}=E_{\rm IA}+\delta$, where, δ has a linear dependence on neutron excess. Though one can fit this parameter to data in the valley of stability [17], it is not obvious how best to extend it to unstable nuclei. Fuller and Meyer [2] take δ to be 0 for $Z/A<0.377$, while Qian *et al.* [5] extrapolate the fit from Ref. [17], $\delta=26A^{-1/3}-18.5(N-Z)A^{-1}$ MeV, with the result that $E_{\rm GT}<E_{\rm IA}$ far from stability. Here we try both prescriptions. We also use $g_A=1$ for the GT transitions to account for missing strength.

As is apparent from the top half of Fig. 2, which displays calculated strength for the *r*-process nuclide ^{124}Mo, the δ-function and *G*-matrix-based interactions produce very similar GT distributions.[2] Both in particular predict significant amounts of low-lying strength (though less than in stable nuclei for $N=82$ and 126), which will make a noticeable contribution to the neutrino cross section. The agreement between the two interactions, once they have been modified/fit as described above, is not surprising. The reason we have used two different interactions is really the uncertainty in the location of the forbidden strength, which is harder to measure, decompose, and fit than allowed strength. Instead of relying on the sketchy systematics that do exist [19], we use the two forces without further modification to get a handle on forbidden transitions. For the δ-function interaction, the strengths in the IA and GT channels determine the strengths of the $S=0$ and $S=1$ parts of the force, and we fix these once they have been fit to the allowed resonances. For the *G*-matrix-based interaction, we use the original negative-parity proton-neutron matrix elements. The two now quite different prescriptions give results that are similar, though less so than in the allowed channels. In ^{208}Pb, where

[2]The large resonance widths are due to a prescription for spreading taken from Ref. [18]; they may not be realistic but altering them has little effect on the neutrino cross sections because equal amounts of strength are spread up and down.

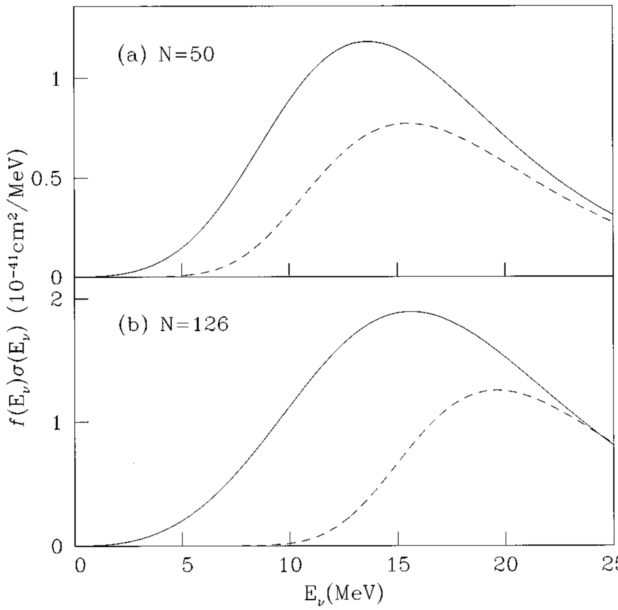

FIG. 3. GT contribution to spectrum-averaged capture cross sections as a function of neutrino energy (the average energy is 11 MeV) for (a) ^{78}Ni and (b) ^{190}Gd. The solid line is the full GT contribution calculated here and the dashed line the contribution of the Gaussian GT distribution.

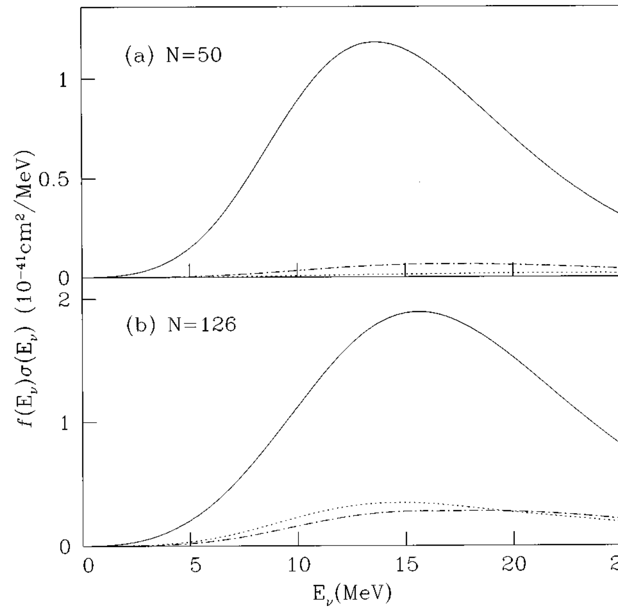

FIG. 4. Contributions to spectrum-averaged capture cross sections as a function of neutrino energy (the average energy is 11 MeV) for (a) ^{78}Ni and (b) ^{190}Gd. The solid line is the GT contribution and the dashed and dot-dashed lines are the 1^- and 2^- first-forbidden contributions.

some (p,n) measurements have been made, the δ-function (G-matrix) interaction places about 15% (20%) of the 2^- strength at low energies outside the giant resonance. These numbers are in good agreement with the rough experimental analysis of Refs. [9,10] and the calculations of Ref. [20]. Our predictions for the distribution of 2^- strength in ^{124}Mo appear in the bottom of Fig. 2. A significant portion survives at low energies. As a result forbidden transitions as well as GT transitions to low-lying states will change the neutrino reaction rates noticeably.

To quantify this remark, we use the (approximate) spectrum of supernova electron neutrinos [5],

$$f(E_\nu)=\frac{1}{F_2(\eta_\nu)T_\nu^3}\frac{E_\nu^2}{\exp[(E_\nu/T_\nu)-\eta_\nu]+1}, \qquad (1)$$

where T is the temperature, η_ν is the chemical potential, and F_2 is a normalizing factor, to obtain spectrum-averaged neutrino cross sections

$$\langle\sigma_\nu\rangle=\int f(E_\nu)\sigma(E_\nu)dE_\nu. \qquad (2)$$

The capture rates are directly proportional to $\langle\sigma_\nu\rangle$. Several values for the chemical potential η_ν appear in the literature, but while changes in that parameter affect the overall rates, they do not change the relative importance of low-lying strength with respect to the resonant strength considered previously. We therefore simply use $\eta_\nu=3$ and adjust T (for the figures and tables to follow) so that the average neutrino energy is about 11 MeV. Reference [8] proposes models with lower temperatures that would increase the relative size of the effects explored here by amounts that we discuss briefly at the end of the paper.

Contributions of the low-lying GT and forbidden strength to the spectrum-averaged cross sections (at 11 MeV) for two representative nuclei appear in Figs. 3 and 4. These particular plots result from the δ-function interaction and the prescription $E_{\rm GT}=E_{\rm IA}$, but the notable features are always the same. Figure 3 shows the contribution of low-lying GT strength in ^{78}Ni and ^{190}Gd to $f(E_\nu)\sigma(E_\nu)$ as a function of neutrino energy. The solid line represents the cross sections obtained with the full QRPA GT strength distribution calculated here, while the dashed line represents those calculated as in earlier work, with a Gaussian GT strength distribution centered at the energy of the isobar analog state and having a width of 5 MeV (the GT distributions themselves are compared in Fig. 2). The low-lying strength increases the cross

TABLE I. Comparison of total spectrum-averaged ν_e cross sections as calculated in this work, $\langle\sigma_\nu\rangle_{\rm total}$, to allowed-only cross sections, $\langle\sigma_\nu\rangle_0$, calculated with the Gaussian GT strength distribution (see text). All cross sections are in units of 10^{-41} cm^2 and the neutrinos have an average energy of 11 MeV.

Z	N	A	$\langle\sigma_\nu\rangle_{\rm total}/\langle\sigma_\nu\rangle_0$
26	50	76	1.6
28	50	78	1.6
30	50	80	1.6
40	82	122	1.8
42	82	124	1.8
46	82	128	1.8
48	82	130	1.7
62	126	188	2.3
64	126	190	2.2
66	126	192	2.2
68	126	194	2.1

TABLE II. Total spectrum-averaged ν_e cross sections for three representative nuclei, with two different forces and two prescriptions for the position of the GT centroid. All cross sections are in units of 10^{-41} cm^2 and the neutrinos have an average energy of 11 MeV.

Z	N	A	Prescription	Force	$\langle\sigma_\nu\rangle_0$	$\langle\sigma_\nu\rangle_{\rm allowed}$	$\langle\sigma_\nu\rangle_{\rm forbidden}$	$\langle\sigma_\nu\rangle_{\rm total}$
28	50	78	$E_{\rm GT}=E_{\rm IA}$	δ function	13.6	19.9	1.5	21.4
				G matrix	13.6	22.4	1.4	23.8
			$E_{\rm GT}=E_{\rm IA}+\delta$	δ function	16.1	24.1	1.8	25.9
				G matrix	16.1	26.6	1.4	28.0
42	82	124	$E_{\rm GT}=E_{\rm IA}$	δ function	19.6	29.4	4.9	34.3
				G matrix	19.6	30.1	7.0	37.1
			$E_{\rm GT}=E_{\rm IA}+\delta$	δ function	29.7	41.3	6.3	47.6
				G matrix	29.7	42.0	7.0	49.0
64	126	190	$E_{\rm GT}=E_{\rm IA}$	δ function	20.6	34.3	11.9	46.2
				G matrix	20.6	38.9	21.3	60.2
			$E_{\rm GT}=E_{\rm IA}+\delta$	δ function	35.0	49.0	14.7	63.7
				G matrix	35.0	49.4	21.3	70.7

sections for neutrinos below 15 MeV substantially, especially when the neutron excess is very large. We may even be underestimating the extent of the increase. The GT distribution shown in Fig. 1 has considerably less low-lying strength than do most stable nuclei. The reason is that near the drip line the resonance is higher in energy and particle-hole force must therefore be stronger, with the side effect that more GT strength is pulled into the resonance. If the GT distributions at $N=82$ and 126 looked more like those in stable nuclei the allowed contribution to neutrino rates would go up even further.

Figure 4 shows the role played by forbidden transitions in the same two nuclei; it compares the total GT contribution to $f(E_\nu)\sigma(E_\nu)$ just discussed with the contributions of the 1^- and 2^- transitions. The low-lying forbidden strength ought to increase with neutron excess and, indeed, Fig. 4 shows that the forbidden portion of the cross section in ^{190}Gd is clearly larger than that in ^{78}Ni. In general, the unusual low-lying forbidden strength provides about 5–10 % of the total spectrum-averaged cross section when $N=50$, 10–20 % when $N=82$, and 20–35 % when $N=126$.

Table I compares $\langle\sigma_\nu\rangle_{\rm total}$, our total cross section, with $\langle\sigma_\nu\rangle_0$, that calculated under the assumption that only the IA state and GT resonance (with width 5 MeV) contribute, in several nuclei. The factors in the table are calculated with $E_{\rm GT}=E_{\rm IA}$; rates with $E_{\rm GT}<E_{\rm IA}$ are all of course larger, but the ratio of $\langle\sigma_\nu\rangle_{\rm total}$ to $\langle\sigma_\nu\rangle_0$ remains roughly constant for the $N=50$ and $N=82$ nuclei. (For the $N=126$ nuclei, it drops by 10–20 % because the parameter δ, which lowers the GT resonance, grows rapidly with neutron excess for large A). More detailed results for three representative nuclei and the several prescriptions described above appear in Table II, where $\langle\sigma_\nu\rangle_{\rm total}$ is broken up into its allowed and forbidden parts. In the heaviest nuclei our estimates, which we believe more likely to be too small than too large, are more than twice those made before. Finally, if the average neutrino energy is about 8 MeV, as in Ref. [8] at a distance of 150 km from the center of the neutron star, the relative role of low-lying strength is even larger. Though all cross sections shrink as the neutrino energy falls, the high-lying resonances are most affected and the average of the ratios $\langle\sigma_\nu\rangle_{\rm total}$ to $\langle\sigma_\nu\rangle_0$ in Table II changes from 1.6 to 2.2 for $N=50$, from 1.8 to 3.0 for $N=82$, and from 2.2 to 5.1 for $N=126$.

To sum up, we find that low-lying GT and first forbidden strength increases the rate of neutrino scattering from very neutron-rich nuclei, usually by a factor of at least 2 and in some instances by a factor of 5. Our cross sections are still uncertain, in part because of our relatively poor understanding of nuclei far from stability. More careful and accurate calculations are possible even without more data, but in our view the effort is not yet required because of the still quite large uncertainty in, e.g., the flux of hot-bubble neutrinos. No matter what the sources and amounts of uncertainty, however, our results point to a significant increase in capture rates over previous estimates. Any serious calculation must include the effects we describe, and neutrino capture will play a larger role in the *r* process than one would otherwise believe.

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