Importance of (n,p) reactions for stellar beta decay rates

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Recent (n,p) experiments on ^{54}Fe, ^{56}Fe, ^{58}Ni, and ^{59}Co have measured Gamow-Teller resonances which are crucial for determining stellar beta decay rates in ^{54}Mn, ^{56}Mn, ^{58}Co, and ^{59}Fe, respectively. These nuclei are important players in the iron-core URCA process, which is a dynamic balancing of electron capture and beta decay rates during the final stage of nuclear burning in massive stars. We find that three of the nuclei, after calibration from (n,p) measurements, have significantly stronger decay rates than currently expected. These stronger rates will cause a more vigorous URCA process, resulting in presupernova cores which are cooler and less neutron rich than is presently used in core collapse calculations. [S0556-2813(96)00706-6]

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In the last 15 years, intermediate energy charge-exchange reactions have become a useful tool for probing the Gamow-Teller strength in nuclei. For neutrons or protons with incident energies between roughly 100 MeV and 800 MeV, the cross section for direct reactions contains large terms proportional to the Fermi and Gamow-Teller (GT) operators [1,2]. While these terms are not the only ones which contribute to the cross section, and it is often difficult to unambiguously determine the Fermi and GT matrix elements, such reactions often are the only available probes of the GT strength. Recent tests of (p,n) reactions as probes of GT strength in ^{37}Cl [3–6] and ^{38}Ar [7] have found that these reactions are fairly effective at extracting the GT strength, except for weak transitions, where $\ell=2$ excitations can contribute strongly to the cross section, leading to overestimates of weak transitions [8]. Also, near the Fermi resonance, it is difficult to determine the GT strength, which is typically weaker than the Fermi resonance. Nonetheless, these reactions allow a probe of the GT strength over a broad range of excitation energy.

In the last ten years, (n,p) reactions have been developed as a probe of the GT_+ strength (''in the electron capture direction'') [9]. Although this technique requires an initial (p,n) reaction, and hence is very limited in its resolution, it is possible to see GT resonances and to test the GT sum rule for strengths below approximately 15 MeV in the daughter nuclei. For ironlike nuclei, most of the GT_+ strength is found in a single broad GT resonance located 1–10 MeV above the daughter ground state.

This resonance is particularly important for astrophysics. In the core of a presupernova star, nuclear statistical equilibrium obtains, resulting in ironlike nuclei being abundant. Because of the high densities ($\rho \geqslant 10^7$ g/cm^3), the electrons are highly degenerate and are able to induce captures into these resonances. This effect makes the stellar electron capture rates orders of magnitude stronger than terrestrial ones and results in a larger neutronization rate, as was described first by Bethe *et al.* [10] and calculated systematically by Fuller, Fowler, and Newman (FFN) [11–14].

These resonances also can affect beta decay rates. Because the cores of massive stars are hot ($T_9 > 3$), it is possible to thermally populate these resonances which can then beta decay back to the corresponding GT parent state. Despite the Boltzmann factor which reduces the probability of thermally exciting these ''back resonances,'' the transitions can be very strong for two reasons. First, the matrix elements in this resonance are 10–100 times stronger than the standard $\ln ft = 5–7$ values seen in low energy transitions (even after detailed balance is used). Second, the Q value for the reaction final state is large and positive, leading to a large phase space integral. For some range of excitations, this large Q value can overcome the Boltzmann factor. In fact, it has recently been found [15,16] that these beta decays are able to compete with the electron captures, leading to a dynamic balancing of the rates of electron creation and destruction, known as the URCA process [17]. This new site for the URCA process (presupernova iron cores) has never been proposed before, to our knowledge.

Because both the decay and capture rates are exponentially sensitive to the location of the GT_+ resonance, any experimental measurements of them are of extreme interest. Recently, El-Kateb *et al.* [18] have reported (n,p) measurements on the nuclei ^{55}Mn, ^{56}Fe, and ^{58}Ni. In addition, similar measurements have been made on ^{51}V [19], ^{54}Fe [20], and ^{59}Co [19] (similar experiments have been done on other nuclei, but they are not relevant for this study). Only one of these nuclei, ^{59}Co, is abundant enough to be relevant for electron capture in presupernova cores. Thus, while these results are useful for calibrating shell model estimates of GT resonances, they only directly calibrate one important electron capture nucleus.

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However, the daughter nuclei of the (n,p) reactions on the above nuclei are more neutron rich and thus more abundant in presupernova conditions. In fact, four of these daughter nuclei, ^{54}Mn, ^{56}Mn, ^{58}Co, and ^{59}Fe, are among the ten most important beta decay nuclei during presupernova evolution (see Table 26 of Aufderheide *et al.* [16]). Thus, the (n,p) experiments leading to these nuclei have measured the back resonance which is so crucial to the stellar beta decay rates. Ironically, these experiments may yield more direct information about beta decay rates than electron capture rates.

An (n,p) experiment on a nucleus (Z,A) shows where in $(Z-1,A)$ the GT resonance corresponding to the ground state of (Z,A) resides. But each excited state of (Z,A) has its own GT$_+$ resonance in $(Z-1,A)$ and all of these resonances must be included in the stellar rates. Lacking the ability to measure these resonances, we are forced to use shell model methods, calibrated by ground state measurements, to provide the required information. This calibration takes two forms. The location of the resonance typically is not predicted accurately by shell model techniques unless calibrated. Neither the simple techniques of FFN [12] nor the truncated model spaces used here and in the past by us [21,5] and others [19,18], nor even the full model space Monte Carlo techniques of Dean *et al.* [22], are able to reliably match the location of GT strength, unless shifts of single particle energies are used. In previous work [5], we were able to discover systematic shifts, which depended on $N-Z$, for the FPVH interaction [23,24]. We have not yet tested this technique on the nuclei measured by El-Kateb *et al.*, since the nuclei of interest here can be directly calibrated. The other type of required calibration is ''quenching'' of the shell model GT strength. It has long been known [25–29] that shell model techniques predict more GT strength than is measured experimentally. For shell models with the limited spaces which we have used, roughly 3 times more strength is calculated than observed [5]. The Monte Carlo techniques reported by Dean *et al.* [22], which use full $0\hbar\omega$ model spaces, see less drastic quenching. The location of the GT resonance affects the stellar rates exponentially, while the amount of strength enters linearly.

For the rates reported here, we have used the interactions of Richter *et al.* [30]. The results can be summarized simply. Neither the FPD6 nor FPM13 interactions [30] provided satisfactory fits to the observed GT resonances from ^{54}Fe, ^{56}Fe, ^{58}Ni, and ^{59}Co. For shell model calculations of a parent nucleus with model space $(1f_{7/2})^n(2p_{3/2}1f_{5/2}2p_{1/2})^{\ell}$ the daughter space $(1f_{7/2})^{n-1}(2p_{3/2}1f_{5/2}2p_{1/2})^{\ell+1}$ was used (where $\ell+n=A-40$), to ensure that the GT sum rule was satisfied. For ^{54}Fe and ^{58}Ni, $(1f_{7/2})^{13}(2p_{3/2}1f_{5/2}2p_{1/2})^1$ and $(1f_{7/2})^{15}(2p_{3/2}1f_{5/2}2p_{1/2})^3$ were used for parent model spaces, respectively. For ^{56}Fe and ^{59}Co, $(1f_{7/2})^{14}(2p_{3/2}1f_{5/2}2p_{1/2})^2$ and $(1f_{7/2})^{15}(2p_{3/2}1f_{5/2}2p_{1/2})^4$ were used as model spaces, respectively. In future work we will consider the next order of excitations for ^{56}Fe and ^{59}Co, but they will not alter the conclusions here.

It was found that the FPD6 interaction of Richter *et al.* gave a slightly better fit to the (n,p) resonances, and so it was used for the rate calculations. In each nucleus the $1f_{5/2}$ single particle energy was shifted from its nominal value of -1.8966 MeV, so that the shell model resonance matched

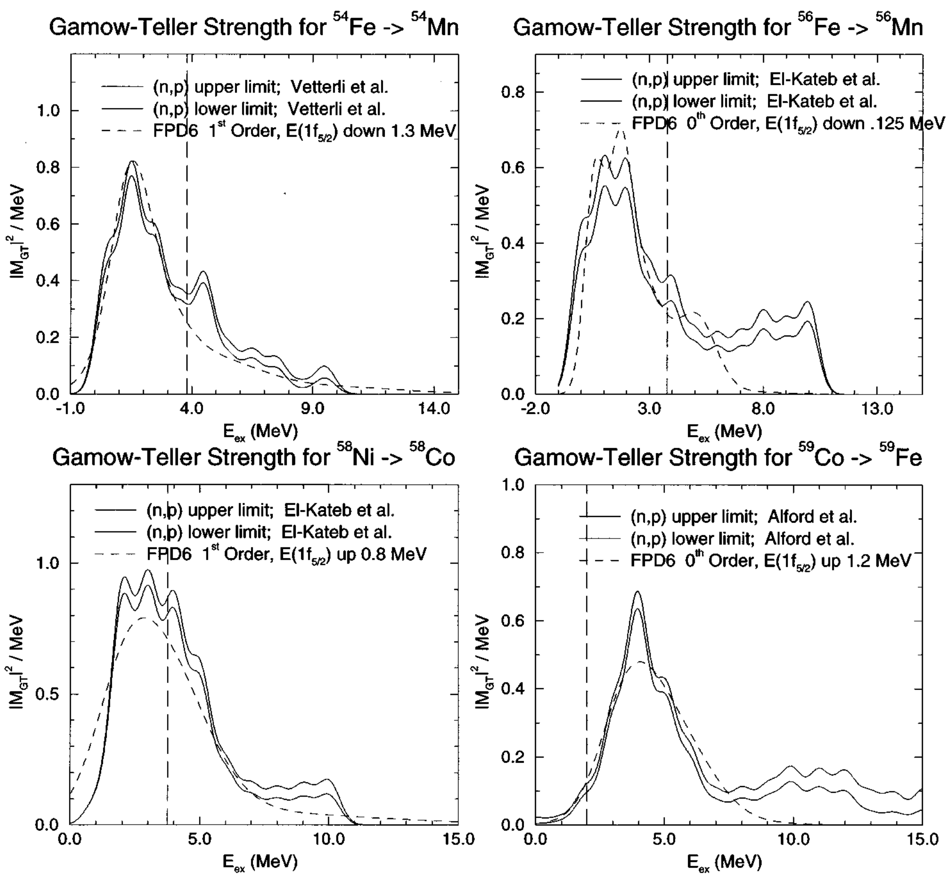

FIG. 1. Comparison of measured and calculated Gamow-Teller resonances in the nuclei of interest. The upper and lower (n,p) limits are statistical only. The vertical line in each plot shows the location of the Fuller-Fowler-Newman resonances.

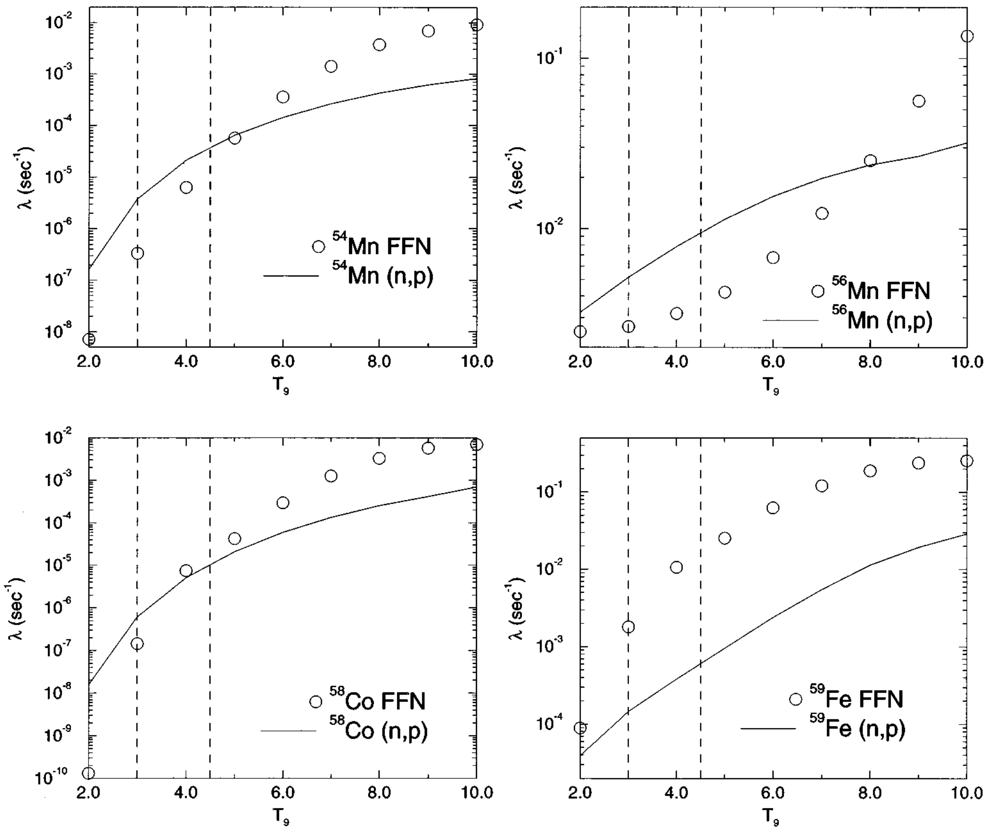

FIG. 2. Comparison of the newly calibrated stellar beta decay rates with the Fuller-Fowler-Newman rates. A density of 10^8 g/cm^3 and an electron fraction $Y_e = 0.5$ have been chosen, in order to simulate stellar conditions. The vertical lines bracket the astrophysically relevant temperature range.

the measured one. For ^{54}Fe, ^{56}Fe, ^{58}Ni, and ^{59}Co, the shifted values of this energy were -3.2 MeV, -2.0 MeV, -1.1 MeV, and -0.7 MeV, respectively. This shifted single particle energy was then used to compute strength functions for all excited states. All of these resonances were then used in computing the stellar rates, after detailed balance was enforced. For each nucleus, the shell model resonances were quenched by the same amount as the ground state resonances. For ^{54}Fe, ^{56}Fe, ^{58}Ni, and ^{59}Co this factor was 0.303, 0.337, 0.370, and 0.225, respectively. As has been noted in the past [5] these quenching factors are all close to 1/3. The computed ground state resonances are compared with experiment in Fig. 1. It can be seen that the fits are fairly good. The same quenching factors as those listed above are used for strength functions associated with all excited states of the these nuclei. We have no guidance from experiment in this since it is not possible experimentally to probe excited state strength functions. However, since the quenching factor is always near 1/3 for all fp shell ground states we have examined [5], this appears to be a fairly good estimate. Also, as noted above, mistakes in the quenching factor will affect the stellar rate much less severely than placement of the resonance.

In calculating beta decay rates for ^{54}Mn, ^{56}Mn, ^{58}Co, and ^{59}Fe the ENSDF tables [31] were used for computing partition functions, for obtaining the ft values for known transitions and for determining other possible low energy allowed GT transitions. If the ft value of a given transition was not known, a value of $\ln ft = 5$ was assumed to be consistent with the practice of FFN [11]. Besides the use of calibrated strength functions, our decay rates differ from the FFN treatment in two ways. First, we only include back resonances corresponding to states in the lowest 3 MeV of excitation energy in the daughter nucleus. FFN used the Brink assumption to include all states in an approximate way. Second, our partition functions are sums of known states up to 3 MeV, followed by an integral over the backshifted Fermi gas level density formula of Holmes *et al.* [32] for higher lying states. FFN did not have this second component. The effect of both of these differences is to have a weaker rate at high temperature ($T_9 > 5$), which is not particularly relevant for presupernova evolution.

In Fig. 2 we compare the new, calibrated beta decay rates with the FFN decay rates for ^{54}Mn, ^{56}Mn, ^{58}Co, and ^{59}Fe. It can be seen that, for the first three nuclei, our rates are approximately factors of 3–6 times larger than the FFN rates. Our decay rate for ^{59}Fe is a factor of 10 weaker than the FFN rate. All of these differences can be understood by examining the relative positions of the FFN resonances and the actual positions in Fig. 1. For the first three nuclei, the FFN resonances were too high, whereas for ^{59}Co, the FFN estimate was too low.

These nuclei make their largest contribution to the rate of change of Y_e, the electron fraction, when their charge-to-mass ratio Z/A is close to Y_e. The Z/A values of ^{54}Mn, ^{56}Mn, ^{58}Co, and ^{59}Fe are 0.463, 0.446, 0.466, and 0.441, respectively. The electron fraction begins just below 0.49 before silicon burning and drops to approximately 0.42 in the current models without the FFN beta decays. Aufderheide *et al.* [15] found the new URCA process occurring near $Y_e \approx 0.455$. It can thus be seen that ^{54}Mn, ^{58}Co, and to some extent ^{56}Mn will have their effect during this URCA process, whereas ^{59}Fe will be important afterward. The three nuclei whose decay rates have been *strengthened* work in concert at a crucial time in the evolution. The nucleus whose rate has been *weakened* is only important when the effect of the decays is waning.

We have also estimated electron capture rates for ^{54}Fe, ^{56}Fe, ^{58}Ni, and ^{59}Co. In the $3 \leqslant T_9 \leqslant 4.5$ range, our rates for the first three nuclei are very close to the FFN rates, while for ^{59}Co our rate is weaker by factors of 2–10 (depending on the density). The first three rates were unaffected because, at astrophysically relevant densities, the Q value for electron capture into the GT resonance is too negative for many electrons to make the transition. For ^{59}Co the Q value is more favorable. Since our treatment of the rates is similar to FFN apart from the GT resonance, these results are understandable. We thus find weaker electron capture rates and generally stronger decay rates.

These trends indicate that the iron-core URCA process will still be present after the FFN rates are revised by the (n,p) results. If this general trend is correct, i.e., stronger beta decays and weaker electron capture rates, then the initial conditions for core collapse are much cooler and less neutron rich than present models predict. As has been shown in the past [33–36], this is very helpful for supernova collapse calculations, by increasing the size of the inner homologously collapsing core.

Before such statements can be confirmed, however, many electron capture and beta decay rates must now be calculated, using the calibrations obtained from the (n,p) results. This will require developing systematic rules for shifting simple particle energies with the Richter interactions or confirming the scheme developed [5] for the FPVH interaction. This will be the goal of our future work.

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