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Abstract

A knowledge of electron capture strength in medium weight nuclei is necessary for an understanding of the mechanism of Type II supernovae. Normally, such strength is measured via (n,p) reactions. Here we describe a new approach in which electron capture strength is obtained from the study of (p,n) and (p,p') reactions leading to $T_o + 1$ states in the product nuclei. This technique promises to yield better resolution and a more stringent test of shell model calculations than is possible with (n,p) reactions. As an example, cross sections for the ^{58,60,62,64}Ni$(p,n)^{58,60,62,64}$Cu reactions were measured at 134.3 MeV and the approach was applied to the results for the ^{60,62}Ni targets.

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Recent interest [1–5] in β-decay transitions in medium-mass nuclei (A = 20-70) is related to outstanding unresolved issues in nuclear and astrophysics. All the charged-current weak interactions: β^+ decay, β^- decay, and electron capture (EC), are important, with EC and β^+ decay governed by the same matrix elements. Generically, we denote the strength of these allowed Gamow-Teller transitions by B(GT).

As a star evolves through its oxygen and silicon burning stages, the abundances of the elements produced in the pre-supernova star begin to depend on B(GT) when the electron Fermi energy becomes high enough to induce transitions to higher lying states. Later, B(GT) affects the nature of the ensuing core collapse and its subsequent bounce and expansion [6-8]. The effects involved are the following. The pre-collapse core of iron-like isotopes is supported largely by the pressure of the degenerate electrons, so that the amount of electron capture, and hence the neutronization of the core, affects the size it attains prior to collapse. As the collapse proceeds, the amount of neutronization affects the division of the core into an inner homologous (i.e., uniformly collapsing) core and an outer supersonic core. Thus, EC directly affects the difficulty of generating a supernova explosion following collapse and bounce; much of the bounce shock energy is spent in dissociating the outer iron core [7,8]. It follows that a detailed understanding of B(GT), for a multitude of nuclei, is critical to an understanding of the supernova process and nucleosynthesis in supernovae [3,4].

Important nuclear structure issues also arise. Reliable estimates of B(GT) for β^- (β^+) transitions can be obtained from the 0 deg (i.e., small momentum transfer) cross sections for (p,n) ((n,p)) reactions [9]; however, the (p,n) studies find only about 60% of the model independent sum rule strength at low excitation [10]. Because the sum rule depends on both β^+ and β^- strength ($\Sigma\beta^- = 3(N-Z) + \Sigma\beta^+$), knowledge of both of them is prerequisite to an understanding of the quenching of GT beta decay.

The above mentioned studies of the (p,n) reaction have provided much information on β^- strength, sometimes with energy resolution better than 250 keV. However, until recently there has been little reliable information on β^+ and electron capture (EC) strength. Only severely truncated shell model calculations have been possible for most nuclei of interest.

New Monte-Carlo techniques [5] are able to provide the total GT strength in a large shell-model space, but it is difficult to calculate details of the GT distribution. For $N > Z$ nuclei, the major part of the β^+ transition strength is not accessible energetically to direct β-decay studies. Results from (n,p) studies are available for several nuclei [1,2,11], but because of their difficulty they have relatively poor resolution, usually 1 MeV or worse. Hence, while the (n,p) results provide a critical check of the gross features of β^+ strength, they are unable to check the detailed spectroscopy. For example, in the case of the ^{56}Fe→^{56}Mn transitions, two shell model calculations using different effective interactions predict very different ratios of strengths to two strongly populated low lying states [12]. The (n,p) data [11] do not have sufficient resolution to resolve the issue. Data from the (^{12}C, ^{12}N) reaction strongly favor one of the shell model calculations [12]. Such heavy ion reactions may eventually be broadly useful, but to date results are available only for this single case, and at a sufficiently low energy that they have relatively large errors.

In this letter we propose a different and to some extent complementary approach to the problem: namely, to obtain β^+ strength from high resolution studies of charge exchange in the β^- direction. The essential point is that the strength of β^- transitions to $T_o + 1$ states in the residual nucleus, where T_o is the isospin of the target nucleus, is related by an isospin geometry factor to β^+ strength from the same nucleus, as shown in Fig. 1. Specifically, $\beta^+/\beta^- = (T_o+1)(2T_o+1)$. It is presently possible to measure (p,n) spectra with a resolution better than 300 keV; this approach could, therefore, yield more detailed information on β^+ strength than has been available in the past.

To reap this benefit, one has first to deal with an important issue: charge exchange reactions such as (p,n) do not have an isospin meter; they are not selective of isospin. However, a comparison with (p,p') reactions, with energy systematics, and with shell model calculations permits a rather convincing identification of the $T_o + 1$ transitions in selected cases.

As examples of this approach, we present here results from studies of (p,n) reactions on ^{26}Mg and ^{60,62}Ni. Reasonably convincing identification of $T_o + 1$ strength can be made for these cases. The results for ^{26}Mg are taken from the literature [13], while those for the nickel isotopes are from the present work. Our results are complementary to the results from (n,p) reactions in that they have superior energy resolution, but less certain identification of T_o+1 and hence β^+ strength. Later in this letter, we discuss how high resolution measurements of inelastic scattering and charge exchange cross sections can remove this uncertainty by yielding model-independent isospin assignments.

The beam-swinger time-of-flight system at the Indiana University Cyclotron Facility was used to measure neutron time of flight spectra resulting from the bombardment of 36 to 50 mg/cm^2 ^{58,60,62,64}Ni targets (isotopically enriched to > 96%) by 134.3 MeV protons. The detection station was placed at 0 deg, 85.8 m from the target, and consisted of three identical, large volume, mean timed NE-102 detectors with a combined frontal area of 1.55 m^2 and a thickness of 10.16 cm [14]. Data were obtained at outgoing neutron angles of 0.3, 3.9, 8.0, and 11.6 deg for several different thresholds; all thresholds gave consistent results to within ±5%. Efficiencies were calculated with the Monte Carlo code of Cecil *et al.* [15]. The overall energy resolution is 500 keV FWHM, dominated by jitter in the cyclotron timing signal, and the systematic uncertainty in the cross sections is ±13%. Some of the resulting spectra are shown in Fig. 2. The peaks of main interest are those labelled T_o+1, and located at $E_x = 14.4$ and 18.6 MeV in ^{60}Cu and ^{62}Cu, respectively.

Now we turn to the evidence for assigning T_o+1 as the isospin of these peaks. Perhaps most important is the comparison with spectra for the (p,p') reaction also shown in Fig. 2. The (p,p') reaction near zero degrees also populates 1^+ states preferentially, with a strength proportional to $B(\mathrm{GT})$ for the analog transitions, but it can populate only isospin T_o and T_o+1 states. The sharp states seen at high excitation in the (p,p') spectra have been assigned as T_o+1 [16,17] for two main reasons. First, as T_o of the target nucleus increases, these states shift systematically to higher E_x with respect to the T_o strength, as would be expected for a state of isospin T_o+1. And second, although the states are unbound to neutron decay and have low angular momentum, they are quite narrow; their observed width is consistent with the experimental resolution, presumably because the neutron decay of $T_o + 1$ states is isospin forbidden. The positions of the sharp (p, p') peaks agree with those seen in (p, n), supporting a $T_o + 1$ assignment for these states also.

Shell model calculations also support the $T_o + 1$ assignment. Detailed calculations [18] indicate that $T_o + 1$ strength is separated from T_o strength for $A > 58$, and is localized in a few strongly populated states. As expected, the separation grows as $N - Z$ increases. We shall see that these states lie low in the spectra reached via (n, p) from the same target.

Now we examine these arguments in more detail. The isospin analog of a state at E_x(target), seen in the (p, p') reaction, will occur in the (p, n) product nucleus at the same energy above the analog of the ground state (labelled IAS in Fig. 1), i.e., $E_x(p, n) = E_x(p, p') + E_x(IAS)$. In Table I the relevant energies are tabulated, showing that the energies of the analogs of the (p, p') states and of the observed peaks in ^{60,62}Cu agree within the accuracy of the present measurements (±0.1 MeV). There is also a small peak at the expected energy in ^{64}Cu (not visible on the scale of Fig. 2), but it is too weak to permit extraction of meaningful cross sections. The observed width of the present peaks is consistent with the resolution of the (p, n) experiment (note that these states are also isospin forbidden to decay by neutron emission). The excitation energies of the states in ^{A}Co reached by the corresponding ^{A}Ni(n, p) transitions is also given in Table I.

We extracted the B(GT) corresponding to these excitations by comparing their strength to that of the Fermi ($L = S = 0$) transition to the IAS (B(F)$= 3(N - Z)$), each evaluated at the same small momentum transfer ($q = 0.05$ fm^{-1}) using the standard techniques [9]. In this evaluation, we assume that the ratio of cross sections for Fermi and GT transitions of equal strength is proportional to $(E_p/54.9)^2$, where E_p is in MeV. These results are collected in Table II. The B(GT) are converted to those that would be measured in (n, p) reactions by multiplying by the appropriate ratio of Clebsch-Gordon coefficients, 15 for ^{60}Ni and 28 for ^{62}Ni.

In Table II we compare our results with shell-model calculations. The calculations for ^{26}Mg [19,13] were performed in the full 1s-0d shell using an interaction fixed so as to describe the properties of the surrounding nuclei. Those for the Ni isotopes [18] used the model space $(1f_{7/2})^{16}(2p_{3/2}, 2p_{1/2}, 1f_{5/2})^n$ for the initial state and $(1f_{7/2})^{16}(2p_{3/2}, 2p_{1/2}, 1f_{5/2})^n$ plus $(1f_{7/2})^{15}(2p_{3/2}, 2p_{1/2}, 1f_{5/2})^{n+1}$ for the final 1^+ states, with $n = A - 56$. With this basis, the $3(N - Z)$ sum rule is satisfied. The calculations were done using the FPVH interaction [20,21]. In the case of ^{26}Mg most of the experimental $T_o + 1$ strength is concentrated in a single state near 0.1 MeV in ^{26}Na [13]. The theoretical strength is similarly concentrated. and is somewhat larger than observed. For the Co isotopes the theoretical strength is concentrated in low lying states, generally with $E_x \leq 2.5$ MeV. While the total strength decreases with increasing A, the strength in low lying states is nearly constant.

As is seen for other nuclei in this mass region using (n,p) reactions [11,3], the models predict substantially too much strength. Presumably this reflects the fact that T_o+1 strength (and hence β^+ strength) is more sensitive to configuration mixing than is the strength to the lower isospin states. This sensitivity has been demonstrated explicitly [13] for the case of ^{26}Mg by comparing the full model calculations with the results of a calculation assuming an independent particle model $[j_{5/2}]^{10}$. In this case the $T_o + 1$ strength for the full-sd-shell calculation is smaller by a factor of 3.6, while the T_o $(T_o - 1)$ strengths decrease by a factor of 1.8 (1.3). The present results might then be ascribed, at least in part, to inadequate configuration mixing in the wave functions. In any case, since calculations for transitions to $T_o + 1$ states (and β^+ or electron capture transitions) are relatively sensitive to the details of a shell model calculation, it is difficult to have confidence in their results without detailed experimental tests and calibration.

It should be possible both to provide better isospin identification and to extend these measurements to nuclei with higher isospin. The isospin identification depends on the fact that the relative cross sections for (p,p') and (p,n) reactions depend on isospin. The ratio $\sigma(p,p')/\sigma(p,n)$ is $2T_o + 1$ for $T_o + 1$ states and T_o for T_o states. The difference of a factor of two or more should be sufficient to distinguish the isospin, as long as the resolution is sufficient to resolve the states involved.

Extending the technique to heavier nuclei also requires better resolution. Because the strength of a transition is roughly proportional to $1/T_o^2$, the present technique is applicable only to nuclei with isospin sufficiently small that the $T_o + 1$ states are observable. At the same time the isospin must be large enough that the splitting of T_o and $T_o + 1$ states allows one to isolate $T_o + 1$ strength with reasonable certainty. Thus for a $T_o = 1$ nucleus like ^{58}Ni the T_o and $T_o + 1$ excitations are hopelessly intermixed in the present experiment. With better resolution it should be possible to observe $T_o + 1$ states for nuclei with higher isospin. For example, a resolution of 50 keV (ten times better) can probably be achieved with the (^{3}He, t) reaction [23], and one could examine cases where the relative strength of the $T_o + 1$ excitations is a factor of ten smaller than in ^{62}Ni. This would make possible studies of $T_o + 1$ states in nuclei with T_o as large as 11 (^{62}Ni has $T_o = 3$).

In summary, we have shown that charge exchange reactions in the β^- direction (e.g., (p,n)), can provide information about β^+ and electron-capture strength provided that the isospin of the target nucleus is neither too large nor too small. As an example of this technique, strengths for the lowest lying $T_o + 1$ states were extracted from data for the ^{60,62}Ni (p,n) and ^{26}Mg (p,n) reactions and compared with shell model predictions.

It is implicit in the arguments presented here that (p,p') reactions to $T_o + 1$ states also yield the required GT strengths. Which of these reactions will be more useful is a quantitative technical question that remains to be addressed; it involves the evaluation of interfering contributions from isoscalar processes in (p,p'), slit scattering backgrounds, and achievable resolution. As pointed out above, a comparison of the cross sections for inelastic scattering and charge exchange reactions, each measured with high resolution, can provide a rigorous isospin assignments and $\beta^\pm$ strength for a wide range of nuclei. Facilities with resolutions of about 50 keV for ^{3}He induced reactions should permit detailed tests of shell model calculations for a wide range of nuclei.

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to about 50 keV seem possible. M. Fujiwara, private communication.

FIGURES

FIG. 1. Diagram of transitions via (p,n), (n,p) and (p,p') interactions. More intense transitions are shown by darker lines. With the exception of the transition to the isobaric analog state, those shown involve transfer of total angular momentum, spin, and isospin $J = S = T = 1$. States labelled with the same quantum numbers are isobaric analogs. The symbols $T_>$, T and $T_<$ stand for $T_o + 1$, T_o and $T_o - 1$. We are concerned here with the relatively weak transitions to the $1^+, T_>$ states.

FIG. 2. Spectra for ^{58,60,62,64}Ni (p,n) reactions at 134.4 MeV. The $T_o + 1$ states have been identified as described in the text, and the numbers above the peaks in the spectra are excitation energies. The inset for ^{60}Ni shows the $T_o + 1$ state as a function of excitation energy. Spectra observed in (p,p') reactions [17] on the target nuclei are plotted on the energy axis. The sharp peak at the left of each (p,p') spectrum is the $T_o + 1$ state.

TABLES

TABLE I. Expected and observed energies of $T_o + 1, 1^+$ states in the Cu isotopes following (p,n) reactions and the Co isotopes following (n,p) reactions.

Target Nucleus	$E_x(^A\mathrm{Ni})$[a] (MeV)	$E_x(\mathrm{IAS})$[b] (MeV)	$E_x(^A\mathrm{Cu}$, expected)[c] (MeV)	$E_x(^A\mathrm{Cu}$, observed) (MeV)	$E_x(^A\mathrm{Co}$, predicted)[d] (MeV)
^{60}Ni	11.85 ± 0.02	2.54 ±0.02	14.39	14.4 ± 0.1	0.8
^{62}Ni	14.00 ± 0.02	4.63 ±0.01	18.63	18.6 ± 0.1	0.5
^{64}Ni	15.62 ± 0.02	6.82	22.4		0.2

[a] From the ^{A}Ni (p,p') results of Refs. [16,17]

[b] Ref. [22]

[c] From $E_x(p,n) = E_x(p,p') + E_x(IAS)$

[d] Calculated from $E_x(^A\mathrm{Ni})$ in the first column and known Coulomb energies

TABLE II. Values of $B(\mathrm{GT})$ for transitions to 1^+, $T_o + 1$ states in ^{A}Cu and ^{26}Al-($B(\mathrm{GT})_{pn}$); and in ^{A}Co, ^{26}Na-($B(\mathrm{GT})_{np}$)

Target	$B(\mathrm{GT})_{pn}$	$B(\mathrm{GT})_{np}$[a]	$B(\mathrm{GT})_{sm}$[b]
^{26}Mg	0.12±0.024	0.72±0.14	0.85 (1.7)
^{60}Ni	0.075± 0.015	1.13±0.23	3.5 (9.9)
^{62}Ni	0.07± 0.01	1.96± 0.28	4.3 (7.3)
^{64}Ni			3.5 (4.6)

[a] Obtained by multiplying the results obtained from (p,n) listed in the second column by the relevant isospin geometry factors: 6.0 for ^{26}Mg, 15.0 for ^{60}Ni, and 28.0 for ^{62}Ni.

[b] From Madey *et al.* [13] for ^{26}Mg and Brown [18] for the Ni isotopes. All $B(\mathrm{GT})$'s are calculated with unrenormalized (free-nucleon) operators. For the Ni isotopes, the strengths quoted are the sum of those from 1^+ states lying within 250 keV of $E_x(^A\mathrm{Co})$ from Table I. In all cases the strength is dominated by that of the lowest lying 1^+ state. The quantities in parentheses are the total $B(\mathrm{GT})_{sm}$, summed over all $T_o + 1$ final states.

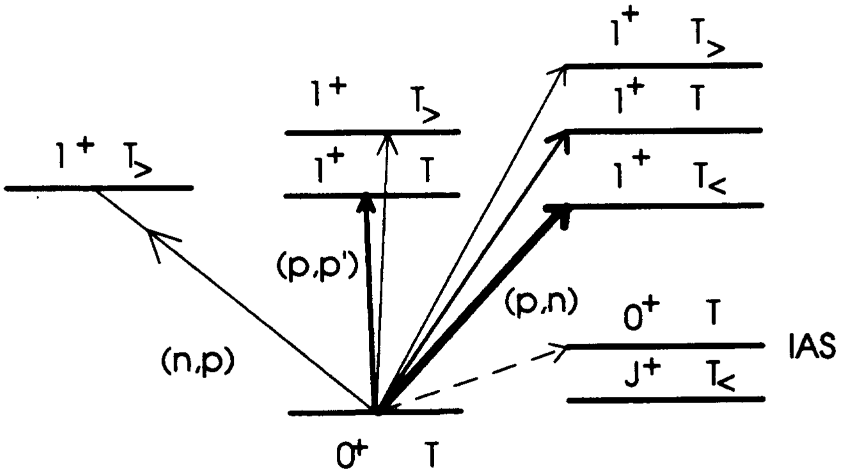

Fig. 1

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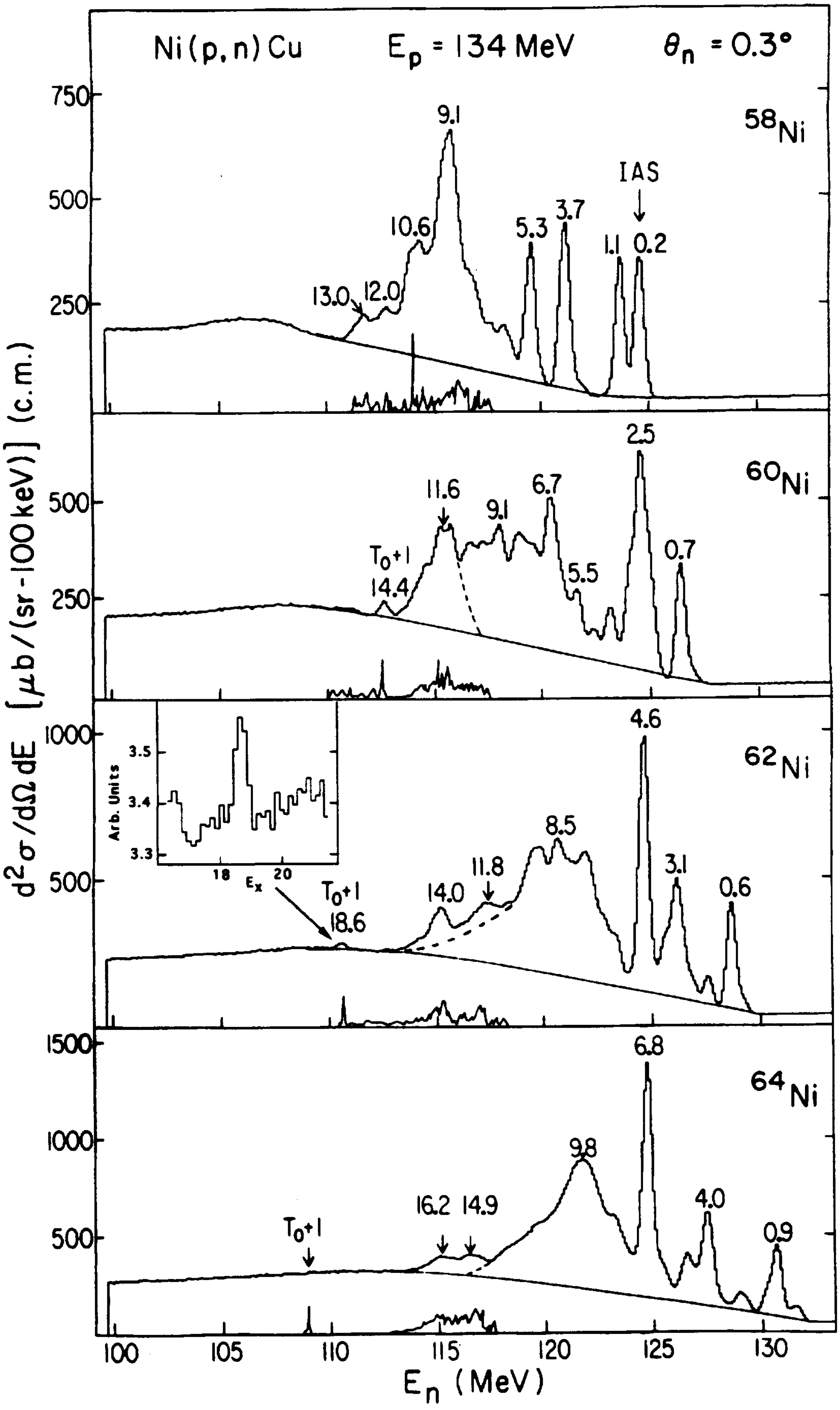

Fig. 2