Experimental location of Gamow-Teller strength for astrophysical calculations in the region of $A = 54$—58

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The (t,^{3}He) charge exchange reaction has been used to locate Gamow-Teller states with T_0+1 isospin in the region of $A = 54$—58. These data were obtained at $E_t = 25$ MeV on targets of ^{54,56,58}Fe and ^{58}Ni.

There is currently great interest in, and there has been significant progress in understanding, the formation of supernovae and the nucleosynthesis of elements following the collapse of a star and the subsequent stellar explosion.[1] Of extreme importance in the neutronization of elements in the mantle of such stars are the electron capture rates in the process $_ZA_N(e^-,\nu_e)_{Z-1}A_{N+1}$. Currently such calculations depend on theoretical shell-model estimates, which, particularly for isospin-correlated states such as Gamow-Teller (GT) transitions, tend to be quite difficult.[2–4] Experimental verification of the theoretical calculations cannot be done directly. However, it has been shown that it is possible to obtain reliable GT strength distributions by charge-exchange reactions [in the case of (p,n) reactions] at medium energy.[5] The analogous situation for (e^-,ν_e) must proceed from the nucleus $_ZA_N$ to the nucleus $_{Z-1}A_{N+1}$. The direct reactions that proceed in this fashion are the (n,p) and the (t,^{3}He) reactions that, although hadronic in nature, do as in the (p,n) case excite GT-type transitions. The (n,p) reaction, although achieving some success in this regard,[6] lacks the experimental resolution necessary to distinguish individual states in medium-mass nuclei. In this paper we report measurements of a set of GT-type transitions, made by singling out 1^+ states produced in the (t,^{3}He) reaction starting from 0^+ ground states of several nuclei, ^{54,56,58}Fe and ^{58}Ni. We also report that coupled channel calculations of multistep processes for the surface dominated (t,^{3}He) reaction amount to primarily only a renormalization factor.

Medium energy inelastic scattering of hadrons at forward angles[7,8] has permitted the excitation of GT-type transitions with reasonable distinction from other modes. There are significant background problems, however, although the experimental situation continues to improve. Inelastic electron scattering also excites GT-type transitions in $M1$ transitions. Although, in general, it is difficult to separate GT matrix elements $(\vec{\sigma}\cdot\vec{\tau})$ from other contributions,[9] there are some cases in which the GT contribution alone may be inferred, and in such cases it may be possible to obtain information on absolute GT strengths, from the $M1$ strengths, as discussed in the following. Charge-exchange reactions at medium energies have yielded significant information on the GT strength functions.[10] In particular, (p,n) reactions at 120 MeV (Ref. 11) near 0° have indicated the possibility of determining GT matrix elements, and (p,n) reactions at 200 MeV (Ref. 12) show evidence of excitation of the giant GT resonance. These interpretations are supported by the 0° peaking expected for $\Delta l = 0$ GT-type transitions. The (p,p′) and (e,e′) reactions, in general, excite the T_0 and (T_0+1) states simultaneously. The (t,^{3}He) reaction, studied in the present experiment, can only excite the (T_0+1) states, and it is thus particularly relevant to the electron capture problem.

Our experiment was performed using 25-MeV tritons from the Los Alamos three-stage Van de Graaff facility with a Q3D spectrometer used to detect the outgoing ^{3}He particles.[13] This represents the highest triton energy currently available. Higher energies would be extremely desirable to excite preferentially the spin-flip mode, as in the case of the (p,n) reaction.[11] A helically wound cathode position sensitive detector was used to identify the ^{3}He particles in the presence of the very large background of tritons, deuterons, and α particles. Special coincidence electronics was added to ensure events were single events and not multiple hits, thus reducing backgrounds. The targets were freshly evaporated, when possible, to minimize light contaminants. Finally, great care was taken in beam preparation to minimize slit scattering. The combination of these measures permitted measurements down to 5.5°, which was of considerable value in establishing the spin and parity of the observed states, thus enabling us to single out the 1^+ states which we wished to study. The present paper discusses 1^+ states up to 3 MeV in excitation energy. The 1^+ states in this energy interval can be identified with little ambiguity.[14] Twenty-five such states were found in the four nuclei that we studied (see Table I). In the $0 < E_x < 3$ MeV region the total number of states observed by us in the four nuclei is 145.

Both distorted wave (DW) and coupled-channels (CC) calculations were performed to establish spin values where unknown or unresolved states were encountered. Both these sets of calculations utilized a two-particle direct charge-exchange form factor containing a Yukawa central plus tensor interaction. The CC calculations also considered a two step $(t,\alpha)(\alpha,{}^3\text{He})$ component, which adds considerably to the magnitude of the predicted cross section, but does not significantly modify its angular shape, and to a large degree is proportional to the direct form.[14]

TABLE I. Population of possible 1^+ states in the ($t,^3He$) reactions on $^{54,56,58}Fe$ and ^{58}Ni.

E_x (keV)	σ_{rel}[a]	Relative[b] GT strength	E_x (keV)	σ_{rel}[a]	Relative[b] GT strength
	^{54}Mn			^{56}Mn	
1391	0.74±0.08	0.054	111	≡1	0.073
1454	0.65±0.06	0.048	1166	0.87±0.09	0.064
	1.4 ±0.1	10.101	1560	0.54±0.14	0.039
			(1674[c])	0.54±0.16	0.039
			(1833)	0.92±0.13	0.068
			2159	0.64±0.13	0.048
			2519	0.58±0.15	0.042
			2626	0.35±0.09	0.026
			2780	0.74±0.16	0.054
			2855[c]	0.81±0.17	0.060
				7.0 ±0.4	0.51
$\bar{E}_x=1.42$ MeV			$\bar{E}_x=1.82$ MeV		
	^{58}Mn			^{58}Co	
180	1.11±0.27	0.082	1050	1.08±0.22	0.079
298	0.82±0.22	0.060	1377	0.16±0.22	0.012
651	1.54±0.33	0.11	1436	0.23±0.20	0.016
745	1.03±0.26	0.076	1729	1.06±0.19	0.078
816	1.46±0.30	0.11	1865	1.93±0.23	0.14
1040	1.39±0.39	0.10	2249	0.25±0.05	0.019
1275	1.99±0.45	0.15		4.7 ±0.5	0.34
	9.3 ±0.9	0.69			
$\bar{E}_x=0.79$ MeV			$\bar{E}_x=1.63$ MeV		

[a]Cross section for $0° < \theta < 53°$ (c.m.) divided by the total cross section over that angular range predicted by DW calculations, and relative to that for the 111 keV state of ^{56}Mn, taken to be 1.
[b]The calibration in terms of relative GT strength is done by taking values from ^{58}Ni(e,e′) and (p,p′) measurements (see the text). Thus all values are relative to ^{58}Ni.
[c]This is a possible 1^+ state; the assignment is not certain. The σ_{rel} shown is an upper limit.

This phenomenon is well known for surface peaked reactions both with light and heavy ions. It is thus assumed, based on these calculations, that the two-step processes amount primarily to an overall renormalization factor only; and since no attempt was made to extract absolute GT strengths from these calculations, a final comparison to other data in the following will include this normalization as well. Examples of 1^+ states and the DW and CC

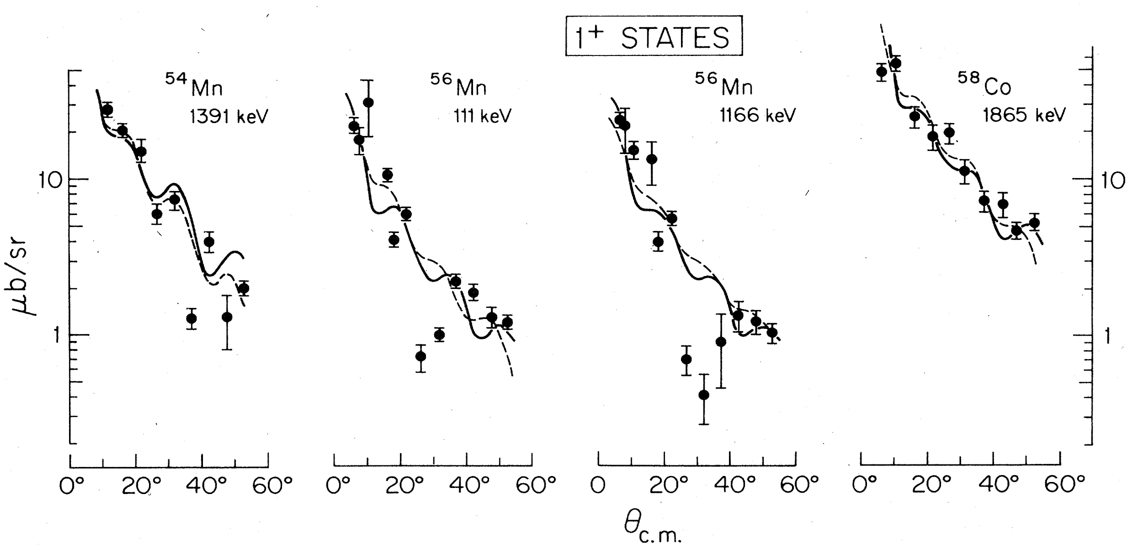

FIG. 1. Angular distributions of four 1^+ states in ^{54}Mn, ^{56}Mn, and ^{58}Co. The full lines are the result of CC and the dashed lines of DW calculations, using $L=0+2$.

predictions are shown in Fig. 1. In both cases, 1^+ states are distinguished by a strong peaking at forward angles.[14]

The ^{58}Ni(t,^{3}He)^{58}Co results represent a considerable improvement over previously published results on this reaction.[15] The present results can be compared with the recent measurements (p,p′) and (e,e′) on ^{58}Ni. This comparison is used both to test the reliability of determining the GT strength from the (t,^{3}He) reaction and to obtain an approximate absolute calibration of the GT (T_0+1) strength. It is assumed that the group of states seen comprise the GT resonance.

In the (p,p′) and (e,e′) studies on ^{58}Ni, the 1^+ $T=2$ states are found with strengths concentrated in a principal band from 9.8 to 11.9 MeV.[7,8,16,17] Five of the six states found in this band in the (p,p′) work[7,8] lie in an interval only 1.2 MeV wide from 9.8 to 11.0 MeV, which corresponds to $E_x=1.05$ to 2.25 MeV for our ^{58}Co measurements. [The sixth (p,p′) state corresponds to $E_x=3.07$ MeV in ^{58}Co, and we do not find a 1^+ state there.] We find all five of these (p,p′) states, and one additional weaker one, in that same E_x range (Table I), and all six of these states are also found in the (e,e′) work.[17] The excitation energies match very well in all three reactions, when corrected for Coulomb effects and the n-p mass difference: our ^{58}Co E_x values are displaced from the ^{58}Ni(e,e′) values by 8.78 ± 0.02 MeV for all six states. Thus for ^{58}Ni we have two important results:

(1) the energy band we cover ($E_x=0$ to 3 MeV) includes the principal 1^+ $T=2$ states found in the inelastic scattering;

(2) we correctly identify all 1^+ $T=2$ states with detectable strength in that energy interval.

We next address the problem of deducing GT strengths from our data. The reaction mechanisms we are dealing with are complex, involving both direct and two-step mechanisms in the overall strength (but in which the ratio of direct to two step fortunately seems independent of configurations), and we do not wish to rest a strength determination on a quantitative comparison of a (t,^{3}He) cross section with any specific theory. Since the reaction mechanisms for (e,e′) scattering are much less complex (although there are very large experimental difficulties), we have explored the possibility that comparison of the (t,^{3}He) with (p,p′) and (e,e′) cross sections on ^{58}Ni might show sufficiently simple behavior to enable us to use the latter measured $M1$ strengths to normalize our data and to obtain GT strengths. One must be cautious about $M1$ (e,e′) transitions as they involve not just $(\vec{\sigma}\cdot\vec{\tau})$ (i.e., GT operators) but also orbital magnetic moment contributions that are difficult to calculate for individual states. This will be minimized by summing over all observed transitions of T_0+1 character [a comparison of (e,e′) and (t,^{3}He) spectra select these uniquely] under the assumption that the total $M1$ strength seen is the total GT resonance strength, which would contain no orbital components. The (p,p′) results do not contain orbital contributions and will be used to add to the confidence level of total extracted GT strength by comparing summed strength here as well.

To utilize the (t,^{3}He) reaction to yield meaningful GT strengths, one must be ensured that the strength distribution for the states found in the reaction $_ZA$(t,^{3}He)$_{Z-1}A$ reasonably corresponds to that obtained, for the same states, from the inelastic reactions. If such correspondence occurs, it implies that for the states being compared the (e,e′), (p,p′), and (t,^{3}He) transition strengths are dominated by the GT resonance. Strong evidence for this correspondence has already been shown in ^{24}Mg and ^{28}Si,[18] and the more complete CC calculations performed here support such a conclusion.

In Fig. 2, we show the collected evidence on excitation energies and transition strengths for the three reactions, (p,p′) (Ref. 8), (e,e′) (Ref. 17), and the present (t,^{3}He) data, carried out on ^{58}Ni. We plot the inelastic data for excitation energies of 9.5 to ~12 MeV since below 9.5 MeV only T_0 states occur. We have shifted the energy scale for (e,e′) and (p,p′) to correspond to the isobaric displacement noted previously. In Fig. 2, one sees that the (p,p′) and (t,^{3}He) work agrees closely as to how many 1^+ states are found in the energy region 9.8 to 11.0 MeV, namely, five in (p,p′) and six in (t,^{3}He), and one sees that the (e,e′) spectrum shows 14 states in this same energy interval. (Only unambiguous 1^+ states are shown.) The states that are

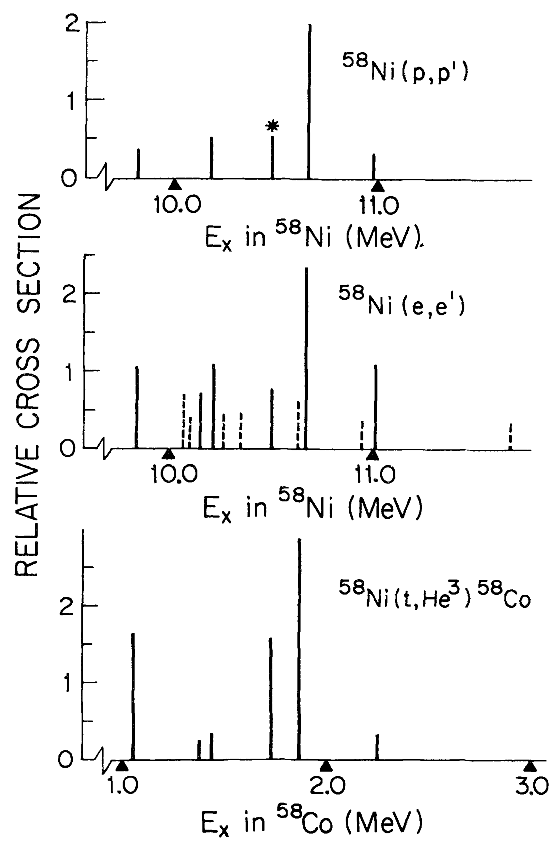

FIG. 2. Relative populations of 1^+ T_0 and T_0+1 states in ^{58}Ni via (e,e′) (Ref. 16) and (p,p′) (Ref. 7) and of 1^+ states (T_0+1) in ^{58}Co from this work. These populations are not normalized to each other. The dashed lines probably correspond to T_0 states. The (e,e′) and (p,p′) data have been plotted with a shift of 8.78 and 8.76 MeV, respectively (see the text). The intensity of the starred level was estimated by us from Ref. 7.

analogs of the (t,^{3}He) reaction in this region of excitation energy can be only T_0+1 states, and the additional 1^+ states found in (e,e′) are not T_0+1.

As to whether the strength distributions agree, for the different reactions on ^{58}Ni, Fig. 2 shows a close similarity, particularly for the strongest (t,^{3}He) states compared to (e,e′). The principal strength, for the (t,^{3}He) reaction, lies in the states at 1.05, 1.73, and 1.865 MeV. These three states together carry about 86% of the total strength of the six ^{58}Ni(t,^{3}He) states, below 3 MeV in excitation energy, with relative strengths of about 4:4:7. The three corresponding states in (e,e′) have relative strengths of about 4:3:9. The (p,p′) (Ref. 8) work indicates relative strengths of about 4:6:27. The difference in the 1050 keV state and its analogs in the three reactions may therefore represent some orbital contributions.

We are thus encouraged to estimate GT strengths from the summed (t,^{3}He) results, using the (e,e′) and (p,p′) $M1$ strengths to the relevant states in ^{58}Ni to provide a normalization of GT strength, and using the (t,^{3}He) results to determine which inelastic states are T_0+1 to include in the normalization.

It must be first ascertained that the (e,e′) may be compared to the (p,p′) to estimate the amount of orbital interference and the reliability of this method in estimating the fraction of GT strength. We also assume that the GT strength seen in the (t,^{3}He) reaction will be quenched through mixing with the Δ resonance in the same amount as seen in (n,p), (e,e′) and (p,p′) reactions. For the (e,e′), Richter[19] has shown from systematics that

$$\sum B(M1)_{\text{exp}}=\gamma^2\sum B(M1)_{\text{theor}}$$

where the quenching factor γ^2 is approximately 0.36 over a large mass region. Thus in the ^{58}Ni(e,e′) reaction, approximately 36% of the total theoretical strength of the GT resonance is seen in the region of excitation considered here. The (p,p′) results of Marty *et al.*[8] yield 31% of the theoretical sum when considering a model of both f and p particles. Thus the (p,p′) and (e,e′) results when summed over the GT resonance region give comparable results. We therefore assume that the (t,^{3}He) reaction excites 34% [an average of the (e,e′) and (p,p′) results] of the total GT strength and normalize these data in fractions of total GT strength. This is done in Table I. This is an upper estimate, as strength above 3 MeV is not considered.

We now remark on the results we obtain for the GT strengths for ^{54,56,58}Mn using the normalization just described. For the energy band $E_x<3$ MeV, the σ_{rel} values in Table I give relative total GT strengths of 0.10, 0.51, and 0.68, respectively. Before attempting any comparison with theoretical calculations, we make some further remarks on the experimental results, and on the question of further GT strength above $E_x=3$ MeV.

For ^{54}Mn and for ^{58}Mn, the 1^+ states we find below $E_x=3$ MeV are concentrated in relatively narrow bands. This result is similar to that found for the $T=2$, 1^+ states in the (e,e′) studies[9] on ^{58}Ni. For ^{56}Mn, however, the 1^+ states we find in the region below $E_x=3$ MeV do not constitute a group with peaked strength, and therefore we cannot be sure that we are seeing the full set of strong GT-type transitions. However, the observed centroid of the 1^+ states in ^{56}Mn, at 1.8 MeV (see Table I), is in reasonable agreement with a prediction by Fuller *et al.*[2] (see the following). In the case of ^{54}Mn, we observe only two clear 1^+ states below $E_x=3$ MeV. We cannot resolve possible additional states at 1.651 and 1.922 MeV but we can say that they are very weakly populated. Thus, the ^{54}Fe(t,^{3}He)^{54}Mn results are inconclusive.

We now comment on the question of further strength above $E_x=3$ MeV. There exist both some experimental information and some theoretical calculations bearing on this question. First, the (e,e′) measurements on ^{58}Ni extend up to $E_x\sim 15$ MeV, which corresponds to $E_x\sim 6$ MeV in ^{58}Ni(t,^{3}He)^{58}Co. The measurements show[17] that there is extremely little strength in the range $E_x\sim 3$–6 MeV compared to the strength in the region $E_x<3$ MeV. In fact, there are only three unambiguous 1^+ states with $E_x>3$ MeV, their isospin values are unknown, and the total $M1$ strength is only 20% of the strength of the states we have used for normalizing (t,^{3}He) to (e,e′).

Theoretical calculations for the β^+ GT strength exist for ^{56}Mn and for ^{54}Mn. For ^{56}Fe$\rightarrow$^{56}Mn, there are two sets of calculations with which we can compare our results. In ^{56}Mn, Fuller, Fowler, and Newman[2] predict five 1^+ states up to 3 MeV, with an energy centroid of 1.7 MeV and with a strength of 61% of the total GT strength. This can be compared with our result of ten states (although three of these are uncertain) with an energy centroid of 1.8 MeV, in remarkable agreement with the prediction.

A second more recent calculation for ^{56}Mn has been made by Fuller and Bloom.[20] That work gives, for the region $E_x<3$ MeV, a strength that is about 58% of the total strength (without quenching), excluding the 111 keV state in ^{56}Mn. If we include that state, using the experimental result (Table I) that it is one-sixth of the total strength of the other states below 3 MeV, we would modify the theoretical estimate for 58% strength below 3 MeV, and would expect 62% of the total strength to lie below 3 MeV. We note that this 62% agrees very closely with the 61% predicted in Ref. 2.

With regard to observed strength, Table I indicates that the total GT strength of the ^{56}Mn states below 3 MeV is 0.51 using the normalization which has been adjusted to give 0.34 for the ^{58}Co states in this E_x range. To correctly relate this 0.51 to the theoretical estimate of 61% of the total ^{56}Mn β^+ strength, one must have a similar detailed theory of ^{58}Ni, which has not been carried out by the authors of Refs. 2 and 20.

There is also a recent theoretical calculation of the ^{54}Mn β^+ GT strength distribution,[21] from which one finds that the strength below 3 MeV is 45% of the unquenched total. Since our experimental results for ^{54}Mn are inconclusive, as discussed above, we will not attempt to make a comparison with theory. There are no theoretical analyses of ^{58}Mn available.

We summarize our results: We have identified 1^+ states in the energy interval $E_x<3$ MeV for the (t,^{3}He) reaction on ^{54,56,58}Fe and on ^{58}Ni. We have calculated both DWBA and CC cases to indicate that multistep contributions amount primarily to only a renormalization. We utilize the fact that the (p,n) reaction has already been proven to give GT strength in charge exchange reactions. Comparison with 1^+ states produced in (p,p′) and (e,e′) reactions on ^{58}Ni indicates that we successfully and clearly identify all 1^+ T_0+1 states in this energy interval. We can thus identify, for both the (p,p′) and the (e,e′) reactions on ^{58}Ni, the T_0+1 1^+ states. We are then able to make an approximate determination of the GT strengths for the transitions we observe by noting that both the (e,e′) and (p,p′) summed cross sections yield similar fractions of the total expected GT strength in ^{58}Ni. We assume that this fraction, which is due to quenching to levels at very high excitation energy, is the same as the (t,^{3}He) reaction would observe, and obtain a relative GT strength conversion factor. This procedure produces estimates of the total β^+ GT strength, up to $E_x=3$ MeV, for the four nuclei we have studied.

We then compare the theoretical β^+ GT strength up to $E_x=3$ MeV. Comparing the experimental value with this theoretical value gives a good energy centroid agreement, for ^{56}Mn observed strength. For two of the other three nuclei (^{58}Mn and ^{58}Co) we have no theoretical estimate with which to compare; and for ^{54}Mn our experimental results are inconclusive.

The study of (t,^{3}He) reactions, used in conjunction with information from (p,p′) and (e,e′), appears to be a promising way of measuring the GT strengths relevant to some important astrophysical calculations. In view of a large predicted splitting of GT strength to the Δ resonance,[3] such experimental measurements are extremely important. This study represents a direct measurement of GT strength available to the (e^-,ν_e) process on neutron-rich nuclei during stellar collapse.

We appreciate the help of Judith Gursky, who prepared the targets we used. Professor W. A. Fowler suggested that we study the implications of the (t,^{3}He) reaction for astrophysics, and we are grateful to him for his comments and his interest. Professor Ben Mottelson pointed out that orbital effects in the (e,e′) reaction would be minimized by summing over states within the $M1$ resonance. It is a pleasure to acknowledge very helpful discussions with S. D. Bloom, W. Mettner, J. Rapaport, and W. Selove. This work was supported by the U.S. Department of Energy.

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