Specificity of the (p,n) Reaction at 35 MeV for Gamow-Teller Strength

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Calculations are presented for the reaction $^{71}\mathrm{Ga}(p,n)^{71}\mathrm{Ge}$ at $E_p = 35$ MeV. Differential cross sections to the ground state and the 0.175- and 0.500-MeV states are estimated and compared with experimental results. It is shown that the 0° (p,n) cross section at $E_p = 35$ MeV is not directly proportional to the Gamow-Teller strength and thus the experimental results cannot be used to used to estimate the absorption of solar neutrinos.

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In a recent publication Orihara *et al.*[1] employed the reaction $^{71}\mathrm{Ga}(p,n)^{71}\mathrm{Ge}$ at 35-MeV incident energy to measure the cross sections for excitation of the lowest-lying levels and to deduce the transition Gamow-Teller (GT) strengths. The use of such a low energy results in an energy resolution sufficient to separate the close-lying ground and 175-keV states of ^{71}Ge, a very important advantage if the excitation strengths of individual levels are to be estimated. Whether the reaction is sufficiently specific to determine the strength of the interconnecting GT matrix elements is, however, questionable. This note explores facets of this question and points to the importance of other components in the transition strengths.

There is particular interest in the GT strengths of transitions between the ^{71}Ga ground state and the low-lying states of ^{71}Ge because the ^{71}Ga to ^{71}Ge transformation is the basis of a practical method of measuring the flux of low-energy solar neutrinos,[2] those thought to be emitted in the most basic step of thermonuclear astrophysical processes. These neutrinos, emitted in p-p burning to deuterium, are mainly contained in a continuum whose end point is at 420 keV. The ^{71}Ga to ^{71}Ge ground state ($\frac{3}{2}^-$) to ground state ($\frac{1}{2}^-$) transition requires 236 keV of neutrino energy; the $\frac{3}{2}^-$ to $\frac{5}{2}^-$ transition, only 175 keV higher, might clearly be important. The 35-MeV (p,n) results indicate that at forward neutron directions the 175-keV state is excited almost as strongly as is the ground state, 0.145 mb/sr compared to 0.153 mb/sr. On the assumption of a direct proportionality between GT strength ($\Delta J = 1$, $\Delta L = 0$) and the measured 0° (p,n) cross section, $\log ft$ values for these transitions are estimated in Ref. 1. We present calculations that show that this assumption is not valid in the present case and that contributions of multipoles other than $\Delta L = 0$ are extremely important.

The reaction mechanism is treated in a distorted-wave calculation with inclusion of knock-on exchange between the projectile and bound nucleons by the code DWBA-70 as modified by Love and Franey.[3] The interaction potential that produces the transition is the local, finite-range effective interaction (M3Y) given by Love.[4] The distorting potentials responsible for modifying the incoming proton and outgoing neutron are taken from the optical-model parameters of Becchetti and Greenlees.[5] We have studied the sensitivity to the interaction potential by using a Reid and a Paris potential as obtained by Anantaraman *et al.*[6] and found almost identical results. Distorting potentials derived from systematics of neutron optical potentials[7] were also tried. The results were almost identical in shape with those obtained with the optical-model parameters from Ref. 5 and within a 10% agreement in magnitude.

Calculations were done for transitions using an extreme single-particle model as well as transitions using one-body matrix elements obtained from an interacting shell model. The single-particle wave functions were calculated under the assumption of either a harmonic oscillator ($\alpha = 0.475\ \mathrm{fm}^{-1}$) or Woods-Saxon potential. The results were not sensitive to either choice.

For the interacting shell model, both initial- and final-state wave functions were calculated within the full $(p_{3/2}f_{5/2}p_{1/2})$ basis, and, for the final states, configurations with up to one hole in the $f_{7/2}$ orbit were also included. Very important for our purposes here is the fact that with this choice of basis the entire (p,n) sum rule is included. The dimensions of the states of interest, denoted as $(2J, 2T)$, were (1,7) 567, (3,7) 1033, (5,7) 1330, and (3,9) 10. The two-body interaction within the $(p_{3/2} \times f_{5/2}p_{1/2})$ basis is the modified surface delta whose parameters were determined, along with the single-particle energy levels, by a least-squares fit to energy levels of the Ni and Cu isotopes in the mass region $A = 57$–61.[8] The two-body matrix elements between the $f_{7/2}$ orbit and the other (fp) shell orbits were those determined as least-squares fits to nuclei in the $A = 51$–55 region by Van Hees and Glaudemans.[9] The calculations were carried out with the code OXBASH.[10] The calculated energies, 0.40 and 1.05 MeV, of the first two excited states, the $\frac{5}{2}^-$ and $\frac{3}{2}^-$, are in rough agreement with experiment.

Each transition involves various angular momentum transfer (ΔJ) contributions which are, of course, added incoherently to obtain the final sum. The results for the calculations using the (fp) transition amplitudes are shown in Fig. 1. The calculations using the extreme single-particle transitions give a similar shape but a very different magnitude. The (fp) calculations are compared with the data obtained from Ref. 1 in Fig. 2. The sum cross sections for the ground state and 0.17-MeV transitions are compared with the theoretical calculations in Fig. 3. The calculated curves have been multiplied in each case by a factor N to normalize to the experimental data. The overall fit to the angular shapes is good, and compares quite favorably with that presented with the published data. However, the strength cannot be attributed simply to the GT contribution. The importance of transitions other than $\Delta J^{\pi} = 1^+$ is to be noted, and one must conclude that at 35 MeV there are at work mechanisms other than simple spin-isospin transfer; therefore, the measured 0° (p,n) cross section is not a direct GT measurement.

Further study demonstrates that the 35-MeV (p,n) cross section at 0° has a large contribution

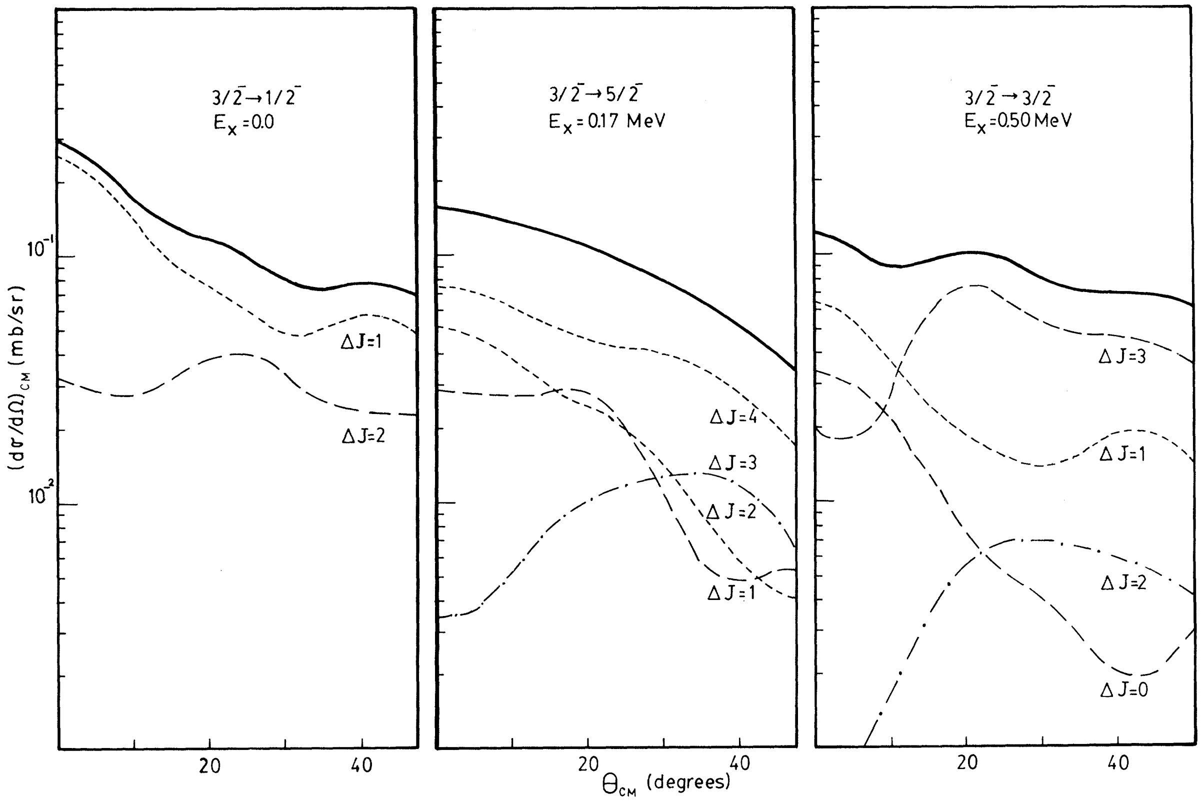

FIG. 1. Distorted-wave calculations for the reaction ^{71}Ga$(p,n)^{71}$Ge at $E_p = 35$ MeV. The transition matrix elements were obtained from a complete (fp) shell-model-based calculation. The contributions of individual multipolarities are indicated; the solid line represents the sum cross section.

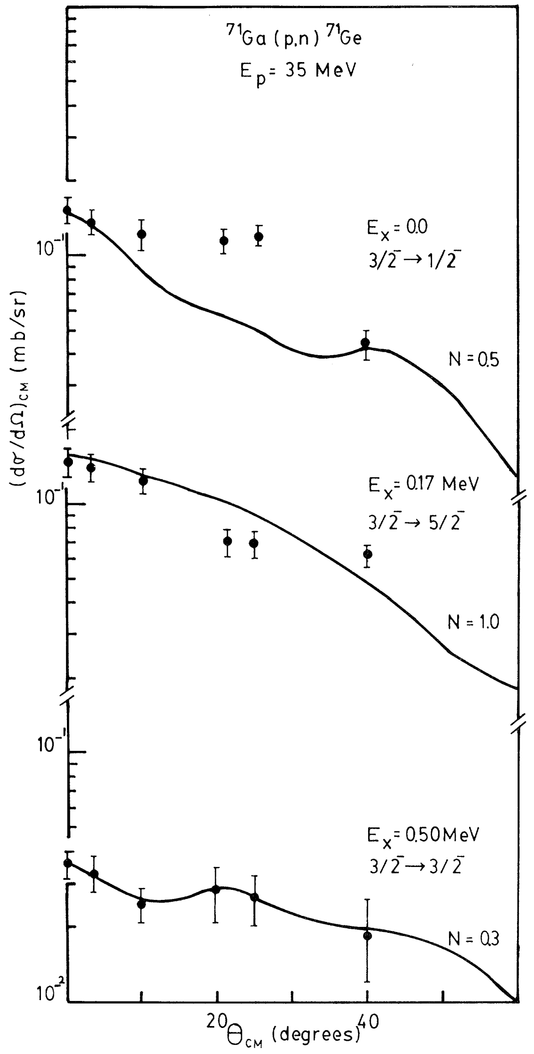

FIG. 2. The experimental data from Ref. 1 compared with the calculations shown in Fig. 1 multiplied by the factor N as shown.

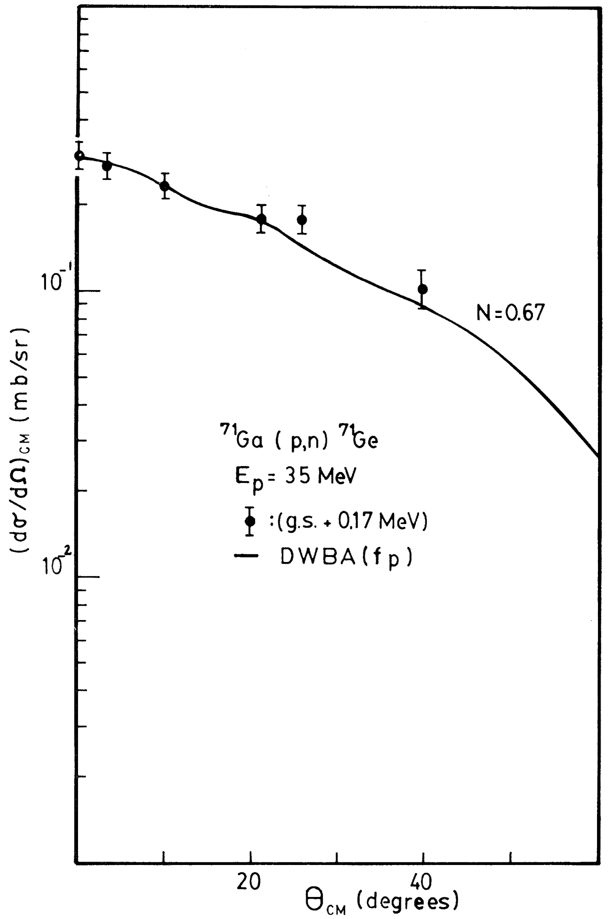

FIG. 3. The sum experimental cross section (Ref. 1) for the ground-state and 0.17-MeV state transitions compared with the sum theoretical cross section multiplied by $N = 0.67$.

from $\Delta L = 2$ ($\Delta S = 1$) amplitudes (for $\Delta J = 1$ and $\Delta J > 1$). This conclusion is based on calculations with the single-particle model via the examination of the pure $p_{3/2}^{-1} \rightarrow f_{5/2}^{-1}$ transition; this is $\Delta L \geqslant 2$ and a forbidden GT transition. (It is to be noted that it is an important component in the interacting-shell-model description of the reaction between $\frac{3}{2}^-$ and $\frac{5}{2}^-$ states.) The results of the extreme single-particle calculation (Table I) do not show the GT forbiddenness: (1) There is a sizable 0° cross section, about 4 times greater than that observed in the actual $\frac{3}{2}^- \rightarrow \frac{5}{2}^-$ reaction, and (2) the shape is much like that calculated for the allowed transitions and is a good match to that seen experimentally for the $\frac{3}{2}^- \rightarrow \frac{5}{2}^-$ reaction. These effects come about because of contributions from both the central and the tensor[11] forces; both contributions are made possible by distortion effects that would be absent were the Born approximation valid. At higher energies, 100–200 MeV, such $\Delta L = 2$ contributions are relatively much smaller both because of the diminution of distortion and because the spin-transfer part of the central force becomes more dominant; thus, at 120 MeV, another calculation with the extreme single-particle model shows that the 0° cross section for $p_{3/2}^{-1} \rightarrow f_{5/2}^{-1}$ is only 5% of the $p_{3/2}^{-1} \rightarrow p_{1/2}^{-1}$ cross section, instead of 40% at 35 MeV. Then, GT components in the transition are favored, and the 0° (p,n) cross section becomes proportional to GT strength.[12]

We present in Table I a summary of the calculated 0° (p,n) cross sections for both the (fp) interacting shell model and the extreme single-particle (sp) model. These are to be compared with the GT

TABLE I. Calculated 0° cross sections in millibarns per steradian for $^{71}\text{Ga}(p,n)^{71}\text{Ge}$; $E_p = 35$ MeV.

	$\frac{3}{2}^- \to \frac{1}{2}^-$ (g.s)		$\frac{3}{2}^- \to \frac{5}{2}^-$ ($E_x = 0.17$ MeV)		$\frac{3}{2}^- \to \frac{3}{2}^-$ ($E_x = 0.50$ MeV)	
ΔJ	(fp)[a]	(sp)[b]	(fp)[a]	(sp)[b]	(fp)[a]	(sp)[b]
0	...	...	...	...	0.035	0.31
1	0.259	1.23	0.029	0.257	0.067	1.27
2	0.032	0.19	0.052	0.286	0.001	0.04
3	...	...	0.003	0.012	0.020	0.08
4	...	...	0.075	0.206	...	...
Σ	0.291	1.42	0.159	0.761	0.123	1.70
$\%\Delta J = 1$[c]	89	86	18	34	54	75
B(GT)	0.238	1.33	0.011	0	0.058	1.67

[a] (fp) shell-model space.

[b] Extreme single-particle transition.

[c] The percentage of $\Delta J^\pi = 1^+$ is calculated to indicate the importance of other multipoles in the 0° cross section. However, this contribution is not just GT strength because of the importance of ($\Delta L = 2$, $\Delta S = 1$) components at this bombarding energy.

strengths, B(GT), calculated with these same models, shown in the last row. [It is to be noted that neither calculation matches the $B(\text{GT})$ $(\frac{3}{2} \to \frac{1}{2}) = 0.09$ deduced from the experimentally determined ft value[13]; certainly the interacting shell model comes closer, and perhaps the inclusion of a larger interacting model space, as provided by the addition of the g shell,[14] will help; however, the discussion here is independent of this comparison.] The key point is that there is not a one-to-one relation between B(GT) and the 0° cross section at 35 MeV. Part of the reason, the importance of higher multipoles, has already been seen. Another part lies in the configuration dependence of the phases of the scattering amplitudes, so that they differ from each other and from simple values appropriate to a GT matrix element; then the necessary additivity is lost for wave functions containing a configuration mix. Thus, the $(p_{3/2}^{-1} \to p_{1/2}^{-1})$ and $(f_{5/2}^{-1} \to f_{5/2}^{-1})$ ($\Delta J = 1$, $\Delta M = 1$) 0° amplitudes differ in phase difference by $\sim 80°$ at 35 MeV; at 120 MeV the phase difference is just $\sim 8°$. Since the effect goes as $\cos^2\phi/2$ it is seen to be a nontrivial problem, but one that disappears at higher energies.

For these several reasons, then, there is a lack of correspondence between B(GT) values and 0° $^{71}\text{Ga}(p,n)^{71}\text{Ge}$ cross sections taken at 35 MeV; this forms a central failure that invalidates the usefulness of this reaction at 35 MeV. For a strong transition, and especially where only $\Delta J^\pi = 1^+$ ($\Delta L = 0, 2; \Delta S = 1$) operates, these failures may not appear important. The $^{58}\text{Ni(g.s.)} \to {}^{58}\text{Cu(g.s.)}$ transition provided by Orihara *et al.*[1] as an additional test calibration is just such a case. However, the concern expressed in this Letter is with weaker transitions where a larger number of multipoles can enter, and/or with wave functions which may contain many configuration mixtures. In the present case, $^{71}\text{Ga}(\text{g.s.}, \frac{3}{2}^-) \to {}^{71}\text{Ge}(0.17, \frac{5}{2}^-)$ may proceed with $\Delta L = 0, 2, 4$ and $\Delta S = 0, 1$ and, as discussed in the text, only an *a priori* knowlege of the wave functions and effective interactions permit an evaluation of the (GT) contribution in the 35-MeV experimental data. Since the failures disappear at higher energies, it is important to repeat this experiment at higher energies to obtain reliable Gamow-Teller strengths to estimate solar neutrino absorption by gallium.

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