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A. J. Baltz

U.S. Department of Energy
Washington, D.C. 20545

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J. Weneser

Brookhaven National Laboratory
Upton, New York 11973

B. A. Brown

Michigan State University
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The motivation for considering the $^{71}Ga(p,n)^{71}Ge$ reaction is to help determine the properties of ^{71}Ga as a detector of solar neutrinos. The proposed solar neutrino experiment[1], $^{71}_{31}Ga(\frac{3}{2}^- g.s.)(\nu,e-)^{71}_{32}Ge(\frac{1}{2}^- g.s.)$, has a threshold of only .236 MeV, and is thus sensitive to neutrinos produced in the basic burning process in the sun

$$p + p \rightarrow {}^{2}H + e^{+} + \nu,$$

which has a .420 MeV endpoint. The excitation of the $5/2^-$ state at .175 MeV in $^{71}_{32}Ge$ could be important, however. Were the Gamow-Teller (G-T) transition to the 175 keV state equal in strength to the ground state transition there would be ~25% added to the detector signal, the greater part of this coming from the ^{7}Be neutrinos (based on the "standard" solar model of J. N. Bahcall[2]); the desired sensitivity to the p-p neutrinos would then be less.

In a recent publication Orihara et al.[3] employed the $^{71}Ga(p,n)^{71}Ge$ reaction at 35 MeV incident energy to measure the cross-sections for excitation of the lowest-lying levels and to deduce the transition Gamow-Teller strengths. The use of such a low energy results in an energy resolution sufficient to separate the close-lying ground and 175 keV state of ^{71}Ge, a very important advantage if the excitation strengths of individual levels is to be estimated. The 35 MeV (p,n) results indicate that at forward neutron directions the 175 keV is excited almost as strongly as is the ground state, .145 mb/sr compared to .153 mb/sr. Whether the reaction is sufficiently specific to determine the strength of the inter-connecting G-T matrix elements is, however, questionable. Orihara et al. assumed that the 35 MeV (p,n) reaction directly measures the G-T transition strength and deduced that the G-T transition to the .175 MeV ($5/2^-$) state is therefore large. However the G-T transition is simply $\Delta S = 1$ with no spatial dependence, that is, $\Delta L = 0$, $\Delta J = 1$. We will present DWBA calculations which show that the assumption of G-T dominance is not valid and that contributions of multipoles other than $\Delta L = 0$ are extremely important at 35 MeV.

The reaction mechanism is treated in a distorted wave calculation with inclusion of "knock-on" exchange between the projectile and bound nucleons using a DWBA-70 code as modified by Love and Franey[4]. The interaction potential that produces the transition is the local, finite range effective interaction (M3Y) given by Love[5]. The distorting potentials responsible for modifying the incoming proton and outgoing neutron are taken from the optical model parameters of Becchetti and Greenlees[6]. We have studied the sensitivity to the interaction potential by using a Reid and a Paris potential as obtained by Anantaraman et al.[7] and found almost identical results. Distorting potentials derived from systematics of neutron optical potentials[8] were also tried. The results were almost identical in shape with those obtained with the optical model parameters from Ref. 6 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 either assuming an harmonic oscillator ($\alpha = 0.475\ fm^{-1}$) or Woods-Saxon potentials. 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 together with up to one hole in the $f_{7/2}$ orbit. 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 $(p_{3/2}f_{5/2}p_{1/2})$ 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.[9] 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[10]. The calculations were carried out with the OXBASH code.[11] The calculated energies 0.40 and 1.05 MeV, of the first two excited states, the $5/2^-$ and $3/2^-$, are in rough agreement with experiment. Very important for our purposes here, the entire (p,n) sum rule is included.

Each transition involves various angular-momentum (ΔJ) transfer contributions which are, of course, added incoherently to obtain the final sum. The angular distributions for the calculations using the (fp) transition amplitudes have been presented elsewhere[12]. The calculations using the extreme single particle transitions give a similar shape but a very different magnitude. 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 G-T. 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 G-T measurement.

Table I. Calculated Zero Degree Cross-Sections in mb/sr for $^{71}Ga(p,n)^{71}Ge$; E_p = 35 MeV

Transition:	$3/2^- \rightarrow 1/2^-$ gs		$3/2^- \rightarrow 5/2^-$ E_x = 0.17 MeV		$3/2^- \rightarrow 3/2^-$ E_x = 0.50 MeV	
Config:	(fp)[a]	(sp)[b]	(fp)[a]	(sp)[b]	(fp)[a]	(sp)[b]
ΔJ						
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
%ΔJ=1[c]	89	86	18	34	54	75
B(GT)	0.238	1.33	0.011	0	0.058	1.67

a) Complete (fp) shell model space.
b) Extreme single particle transition.
c) The % of $\Delta J^\pi = 1^+$ is calculated to indicate the importance of other multipoles in the zero degree cross-section. However, this contribution is not just GT strength because of the importance of (ΔL = 2, ΔS = 1) components at this bombarding energy.

We present in Table I a summary of the calculated 0° (p,n) cross-sections for both the (f,p) interacting shell model and the extreme single particle (sp) model. These are to be compared with the G-T strengths, B(GT), calculated with these same models, shown in the last row. (It is to be noted that neither calculation matches the B(GT)(3/2 → 1/2) = .09 deduced from the experimentally determined ft-value[2]; 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[13] 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.

An additional lesson can be drawn from the single particle configurations by comparing B(GT) with both $(d\sigma/d\Omega)_{0°}$ and $[d\sigma/d\Omega(\Delta J = 1)]_{0°}$. The forward direction is chosen for discussion because this minimum momentum transfer condition most nearly approaches the low momentum transfers of low-energy nuclear β-decays. The results of the calculations are shown in Table II, III. The calculations of 35 MeV, Table II, employ the reaction model, code and parameters outlined above (except that Woods-Saxon bound state wave-functions were employed rather than oscillator wave functions). The 120 MeV calculations, Table III, use the same reaction model and code; the effective transition interactions are represented by the t-matrix from (140 MeV values) of Love and Franey[14]; the distortion potentials are those of Schwandt et al.[15]. The inherent trustworthiness of the reaction method of extracting B(GT) can be judged at a glance. Column 3 lists the ΔJ = 1 contribution to $(d\sigma/d\Omega)_{0°}$ alone; column 4 lists the ΔJ = 1 contribution to $(d\sigma/d\Omega)_{0°}$ that would occur if it were possible to omit the effects of the tensor force and of knock-on exchange; column 5 lists the $(d\sigma/d\Omega)_{0°}$ with all ΔJ, forces, direct and exchange contributions. Column 5 is then most directly comparable with experiment, while columns 3 and 4 are useful for theoretical analysis. At 35 MeV, Table II, it is clear, the cross-section for the weaker but allowed transitions

Table II. Single particle transitions
E_p = 35 MeV

(Numbers in paranthesis are normalized relative to the corresponding value for the ($p_{3/2}^{-1} \rightarrow p_{1/2}^{-1}$) transitions.)

Column # 1 Transition	# 2 B(GT)	# 3 $(d\sigma/d\Omega)_{0°}$ $\Delta J=1$	# 4 $(d\sigma/d\Omega)_{0°}$ $\Delta J=1$ direct-central only	# 5 $(d\sigma/d\Omega)_{0°}$ all ΔJ
$p_{3/2}^{-1} \rightarrow p_{1/2}^{-1}$	1.33 (1)	1.31 mb/sr (1)	3.2 mb/sr (1)	1.52 mb/sr (1)
$p_{3/2}^{-1} \rightarrow p_{3/2}^{-1}$	1.60 (1.20)	1.29 (.99)	4.0 (1.25)	2.05 (1.35)
$p_{1/2}^{-1} \rightarrow p_{1/2}^{-1}$	.33 (.25)	.13 (.10)	1.27 (.40)	.13 (.09)
$f_{5/2}^{-1} \rightarrow f_{5/2}^{-1}$	.71 (.53)	.16 (.12)	1.63 (.51)	.43 (.28)
$p_{3/2}^{-1} \rightarrow f_{5/2}^{-1}$	0 (0)	.25 (.19)	.70 (.22)	.63 (.41)

Table III. Single particle transitions
E_p = 120 MeV

(Numbers in paranthesis are normalized relative to the corresponding value for the ($p_{3/2}^{-1} \rightarrow p_{1/2}^{-1}$) transitions.)

Column # 1 Transition	# 2 B(GT)	# 3 $(d\sigma/d\Omega)_{0°}$ $\Delta J=1$	# 4 $(\sigma/d\Omega)_{0°}$ $\Delta J=1$ direct-central only	# 5 $(d\sigma/d\Omega)_{0°}$ all ΔJ
$p_{3/2}^{-1} \rightarrow p_{1/2}^{-1}$	1.33 (1)	4.52 mb/sr (1)	10.03 mb/sr (1)	4.63 mb/sr (1)
$p_{3/2}^{-1} \rightarrow p_{3/2}^{-1}$	1.60 (1.20)	5.58 (1.23)	12.43 (1.24)	6.20 (1.34)
$p_{1/2}^{-1} \rightarrow p_{1/2}^{-1}$	.33 (.25)	1.34 (.30)	2.61 (.26)	1.34[a] (.29)
$f_{5/2}^{-1} \rightarrow f_{5/2}^{-1}$	.71 (.53)	2.82 (.62)	5.80 (.58)	3.28 (.71)
$p_{3/2}^{-1} \rightarrow f_{5/2}^{-1}$	0 (0)	.13 (.03)	.14 (.01)	.22 (.05)

[a] estimate

corresponds to the G-T strength only within a factor of 2-3; even separation of the ΔJ = 1 component, were that experimentally feasible, does not ameliorate the situation. However, could we extract that part of the DWBA transition amplitude which corresponds most closely to the G-T transition, namely the central, direct ΔJ = 1 transition, we would obtain a better correspondence between reaction cross-section and G-T strength, as is seen in the fourth column of Table II. Of course, the $p^{-1}_{3/2} \rightarrow f^{-1}_{5/2}$ transition is still fairly large in relative reaction strength, contrary to the zero strength of B(GT). At 120 MeV, Table III, the situation is, as expected, enormously cleaner, so that within 25% there is a proportionality between B(GT) and the ΔJ = 1 zero degree cross-section. The proportionality would be even better were we to consider the forward cross-section resulting from the central free, direct ΔJ = 1 transition only (column 4). The ΔJ ≠ 1 contributions do not overwhelm the correspondence; further they are amenable to at least partial separation by distinctive differences in angular dependence. Finally at 120 MeV the G-T forbidden $p^{-1}_{3/2} \rightarrow f^{-1}_{5/2}$ transition shows a distinctively smaller cross-section.

It is also useful to note the relative phases of the amplitudes produced by the different pure single-particle configurations. Samples are given in tables IV and V. It will be immediately seen that at 35 MeV the variability in

Table IV. Phases of θ = 0° scattering.
E_p = 35 MeV

Configuration	ΔJ	ΔM	Central forces only: Direct only	Central forces only: Direct + Exchange	Central and Tensor Forces: Direct only	Central and Tensor Forces: Direct + Exchange
$f^{-1}_{5/2} \rightarrow f^{-1}_{5/2}$	0	0	180.3°	37.4°	179.2°	50.4°
	1	0	185.6	284.0	156.2	208.5
		1	230.1	230.8	214.5	194.9
	2	0	115.4	227.2	114.9	228.6
		1	113.6	250.1	113.8	241.6
$p^{-1}_{1/2} \rightarrow p^{-1}_{3/2}$	1	0	260.5	262.3	259.8	260.7
		1	271.0	272.8	272.1	274.1
	2	0	106.3	228.7	109.1	228.8
		1	226.1	217.9	233.5	231.8
$f^{-1}_{5/2} \rightarrow p^{-1}_{3/2}$	1	0	204.7	196.5	221.7	220.4
		1	29.5	19.3	313.4	288.4
	2	0	100.2	218.4	107.2	218.3
		1	216.2	200.5	221.9	216.8

Table V. Phases of θ = 0° scattering.
E_p = 120 MeV

Configuration	ΔJ	ΔM	Central forces only: Direct only	Central forces only: Direct + Exchange	Central and Tensor Forces: Direct only	Central and Tensor Forces: Direct + Exchange
$f^{-1}_{5/2} \rightarrow f^{-1}_{5/2}$	1	0	332.0°	328.4°	333.4°	330.3°
		1	343.8	338.8	338.2	327.5
$p^{-1}_{1/2} \rightarrow p^{-1}_{3/2}$	1	0	340.3	338.9	343.5	334.1
		1	338.0	335.9	338.2	335.8

phases makes impossible any simple correspondence between the G-T amplitudes of mixed configurations (which are real) and the reaction amplitudes which are relatively complex. As an example, the (ΔJ = 1, ΔM = 1) amplitude of the ($f_{5/2}$ + $f_{5/2}$) and of the ($p_{1/2}$ + $p_{3/2}$) have a phase difference, ϕ, of 80°; since $\cos^2\phi/2$ ~ .6, the inherent lack of correspondence is manifest. At 120 MeV this phase problem almost disappears.

In summary, it is worth noting that at 35 MeV the overwhelming evidence is that there is a lack of simple correspondence between reaction cross-sections and G-T strengths. The $p_{3/2}$ + $f_{5/2}$ G-T forbidden transition has a large enough cross-section so that in appropriate nuclear configurations, it could overwhelm the G-T transitions. We have also seen that non-ΔJ = 1 transitions can be strong; furthermore the ΔJ = 1 transitions themselves have significantly variable contributions from knock-on exchange and from tensor amplitudes, all of which tend to vitiate the G-T analysis. Finally, Table IV shows the phases for θ = 0 scattering at 35 MeV that depend on the transition configurations. Clearly, the variability of phase arising from the reaction mechanism, again vitiates the simple G-T analysis.

As a contrast, the situation at 120 MeV is more satisfactory. Knock-on exchange is important (Table III), but its effect seems to scale fairly well with the direct central, which are closest to pure G-T amplitudes. Phases show very little variability in contrast to the 35 MeV case (Table V). Thus it would be very useful to obtain resolved (p,n) data at higher energies to obtain reliable G-T strengths to estimate solar neutrino absorption by gallium.

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