Gamow-Teller Strength Function in ^{71}Ge via the (p,n) Reaction at Medium Energies

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The Gamow-Teller strength function in ^{71}Ge has been measured by use of the reaction ^{71}Ga(p,n) at $E_p = 120$ and 200 MeV. While a significant fraction of the total strength is associated with excited states located below particle-emission threshold, the first excited state exhibits little strength. Excited-state contributions to the total solar-neutrino capture rate for a ^{71}Ga detector are about 14 solar neutrino units for the neutrino spectrum of the standard solar model and about 3–4 solar neutrino units for representative nonstandard solar models.

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The discrepancy between the solar-neutrino capture rate observed in the ^{37}Cl experiment[1] and that predicted by the standard solar model[2] (SSM) has been a problem for almost two decades. The ^{37}Cl detector is sensitive only to neutrino energies above 814 keV, resulting in a response which is primarily dependent on the higher-energy (0–14 MeV) ^{8}B neutrinos.[3] Solar-neutrino capture via the reaction ^{71}Ga$(\nu_e, e^-)^{71}$*Ge* has a threshold[4] of only 233 keV and has been proposed[5] as a way to determine whether the ^{37}Cl discrepancy is caused by an inadequacy in our understanding of the solar interior (astrophysics) or by neutrino oscillations or decay (neutrino propagation). The flux of low-energy (0–420 keV) neutrinos arising from the reaction $p+p \rightarrow {}^2\mathrm{H}+e^+ +\nu$ is relatively insensitive to the solar model, but neutrino oscillations would for some range of neutrino masses reduce solar electron-neutrino fluxes by factors which depend upon neutrino energy.[4,6]

The neutrino-capture cross section to the ground state (g.s.) of ^{71}Ge can be calculated reliably by use of the *ft* value for ^{71}Ge$(\beta^+)^{71}$Ga. On the basis of beta-decay systematics in the neighboring mass region, Bahcall[7] estimated small contributions to the total capture cross section from low-lying excited states in ^{71}Ge. It follows that 63% of the capture events on ^{71}Ga would come from $p+p$ neutrinos if the SSM flux is assumed. Transitions to highly excited states would enhance the overall response of the Ga detector but thereby dilute its relative sensitivity to $p+p$ neutrinos. Since electron capture (EC) half-lives cannot be measured for the excited states and theoretical calculations[8,9] are model dependent, we have utilized the established relationship[10] between β-decay Gamow-Teller transition strength B(GT) and (p,n) zero-degree differential cross section $\sigma(0°)$ for $E_p \sim 100$–200 MeV to measure the total GT strength function in ^{71}Ge. Assuming a similar relationship at 35 MeV, Orihara *et al.*[11] extracted comparable GT strength for both the g.s. and strength for both the g.s. and 175-keV first excited state. However, at 35 MeV the $\sigma(0°)$ for the 175-keV state may not be directly related to GT strength.[12]

In this Letter we report the study of the reaction ^{71}Ga$(p,n)^{71}$Ge at proton bombarding energies of 120 and 200 MeV using the neutron time-of-flight facility at the Indiana University Cyclotron Facility.[13] Six $100\times15\times15$-cm^3 detectors of NE-102 were placed at a neutron flight path of 130 m. Initial measurements made with a 54.3-mg/cm^2 enriched ^{71}Ga^{24}Mg$_3$ target yielded overall energy resolution of about 350 (800) keV FWHM at the lower (higher) beam energy. Higher-resolution data at 120 MeV were obtained with a metallic ^{71}Gd target (enriched to 99.8%), which had an effective thickness of 14 mg/cm^2 on the basis of comparison with the data from a stable GaMg$_3$ target. Detector contributions to the resolution were empirically minimized for neutron energies corresponding to the ^{71}Ge g.s. region by use of longitudinal time compensation.[14] The ^{7}Li$(p,n)^7$Be(g.s.) measurements at nearly identical Q value to that of the ^{71}Ge g.s. suggest a (205 ± 15)-keV FWHM contribution from all non-target-thickness effects, leading to an expected energy resolution of 215 ± 20 keV FWHM for the ^{71}Ge g.s. Conversion of time of flight spectra to $d^2\sigma/d\Omega\, dE_x$ spectra was accomplished via energy and absolute neutron-detection efficiency calibrations based on the ^{7}Li(p,n) reaction.[10] A 0° neutron spectrum, with the background of low-energy (wrap-around) neutrons from the previous beam burst subtracted, is shown in Fig. 1(a).

The (p,n) $\sigma(0°)$ at the E_p studied is dominated by GT and Fermi (F), $\Delta L=0$ transitions. Values of B(GT) can be extracted from absolute cross sections with a calibration derived from (p,n) systematics.[10] The total F strength $\sum B(\mathrm{F}) = N-Z=9$ is assigned to the isobaric analog state (IAS) at $E_x = 8.95\pm0.1$ MeV. An alternative calibration, which does not require knowledge of absolute cross sections, can be done internally within the spectrum with an empirical GT-to-F strength ratio.[15] B(GT) values derived from both calibrations are in agreement, with estimated uncertainties of $\pm15\%$, except at low E_x where statistical uncertainties dominate.

Data at angles of 0.2°, 5.2°, and 9.4° (0° and 3°) were measured at 120 (200) MeV. As described by Rapaport *et al.*,[16] we have subtracted from the original $\sigma(0°)$ spectra that cross section per energy bin which is not characteristic of $\Delta L=0$ strength. Figure 1(b) shows the resulting spectrum at 120 MeV (with the IAS peak removed) after conversion to B(GT) per 100 keV in E_x. In an alternative method we subtracted the $\sigma(5°)$ from the $\sigma(0°)$ (θ of maximum $\Delta L=0$ strength) spectra and scaled the resulting difference spectrum by that factor required to regain the original $\sigma(0°)$ of the $\Delta L=0$ IAS transition. The dashed line in Fig. 1(b) indicates the only significant modification to the B(GT) spectrum which is obtained in the latter method. This disagreement arises from a dominance of $\Delta L>0$ strength in the region above the giant GT resonance.[16] The 200-MeV data analysis required smaller corrections for $\Delta L>0$ contributions to $\sigma(0°)$ and utilized a higher threshold cut such that the g.s. region was free of wrap-around neutrons. The resulting B(GT) spectrum is consistent with that derived from the above analysis of the higher-resolution 120-MeV data. The summed B(GT) observed below an excitation energy of 15 MeV is $(60\pm9)\%$ of the sum-rule minimum value of $3(N-Z)=27$ and is consistent with systematics. We measured a B(GT) of 4.3 ± 0.7 for the region up to the 7.4-MeV particle-emission threshold relevant to neutrino captures yielding detectable ^{71}Ge. The 0.5-MeV state has B(GT) of 0.010 ± 0.005.

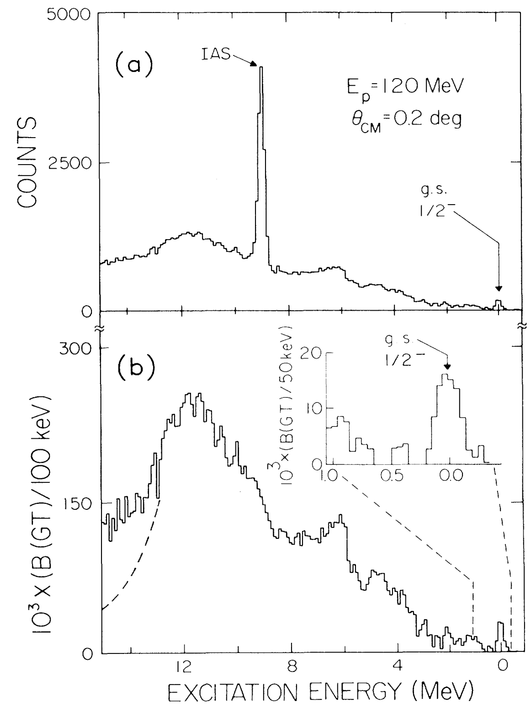

FIG. 1. (a) The neutron spectrum after subtraction of wrap-around neutrons and energy rebinning. (b) The GT strength function in ^{71}Ge [free-neutron $B(\mathrm{GT})=3.0$].

The half-life and Q_{EC} for the ^{71}Ge g.s. decay have recently been remeasured,[4,17] yielding B(GT) of 0.091 for the inverse neutrino-capture process. The peak in the g.s. region of Fig. 1(b) has a B(GT) value of 0.085 ± 0.015 and a width (about 205 keV FWHM) characteristic of a single peak. Attempts to identify in this B(GT) spectrum additional strength having a centroid at E_x of 175 keV were unsuccessful. Thus, on the basis of our energy calibration, expected energy resolution, and experimental B(GT) value, the observed B(GT) peak in Fig. 1(b) is consistent with only a g.s. contribution. Figure 2 presents low-excitation $d^2\sigma/d\Omega\, dE_x$ spectra with arrows at the predicted locations (± 50 keV) of possible low-lying GT strength. The g.s. peak exhibits a satellite peak, which is populated with increasing proportion to the g.s. as the scattering angle increases, characteristic of $\Delta L > 0$ transition strength at $E_x \cong 175$ keV. Note that because of this non-$\Delta L = 0$ character, the satellite peak does not appear in Fig. 1(b). Comparison of the measured angular distribution with distorted-wave Born-approximation calculations using the (fp) wave functions of Ref. 12 yields a $\Delta J^\pi = 1^+$ contribution to the first excited state of ≤ 40 μb/sr. This value is consistent with our adopted upper limit of $B(\mathrm{GT}) \leq 0.009$ for the first excited state. Our upper limit is about an order of magnitude smaller than the value obtained by Orihara *et al.*[11] A detailed distorted-wave Born-approximation analysis will be given in a future paper.

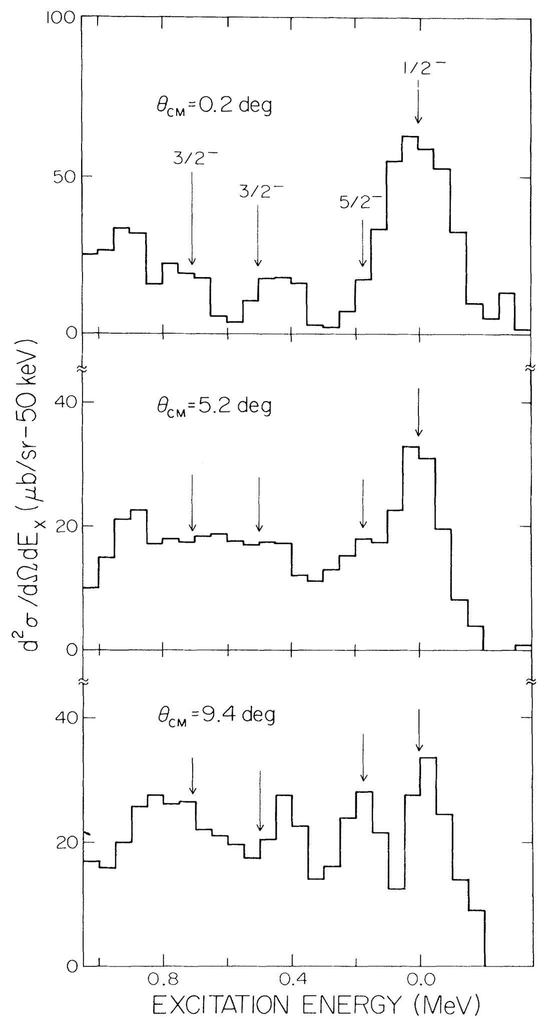

FIG. 2. The center-of-mass double differential cross section for regions of low excitation at $E_p = 120$ MeV. Uncertainties per bin of $\geq 25\%$ arise from the large (subtracted) background.

The correction factor Q, the ratio of total (σ_{total}) to g.s. ($\sigma_{\mathrm{g.s.}}$) capture cross section, represents the contribution from excited-state transitions to σ_{total} for a specific neutrino source.[7] Table I presents these corrections for each solar neutrino source and for ^{51}Cr and ^{65}Zn calibration sources based on our (p,n) measurements, and, for comparison, on the shell-model calculations of Mathews *et al.*[9] and the estimates of Bahcall.[7] The calculations of capture cross sections used the usual atomic and nuclear physics corrections.[7] In agreement with calculations,[8,9] our measurements show large GT strengths in the 2- to 7-MeV region. To the g.s. capture rate of 107.5 solar neutrino units or SNU (assuming recent g.s. EC results[4,17] and the SSM flux), our measured excited-state strength adds 14 ± 3.5 SNU (1-σ limits), which includes 1.5 ± 1.5 SNU for capture into the first excited state consistent with its B(GT) upper limit. The results of Orihara *et al.*[11] suggest an added 32 SNU, due primarily to capture into the first excited state. The calculations of Ref. 9 (Ref. 7) yield a total capture rate of 124 (117) SNU. Uncertainties in our measured excited-state GT strengths cause about $\pm 3\%$ uncertainty in the total capture rate, considerably smaller than that arising from other parameters (about $\pm 10\%$[2,18]). For representative non-SSM's[7,19] consistent with the ^{37}Cl experiment, this uncertainty is about ± 1–2% and the

TABLE I. Calculated correction factors Q for neutrino-capture cross sections in a ^{71}Ga detector.

Neutrino source	E_ν^{max} (MeV)	$Q = \sigma_{\mathrm{total}}/\sigma_{\mathrm{g.s.}}$ Present	Mathews *et al.*[a]	Bahcall[b]
$p+p$	0.420	1.00	1.00	1.00
pep	1.442	1.27	1.20	1.45
^{7}Be	0.862	1.065	1.16	1.18
^{7}Be	0.384	1.00	1.00	1.00
^{8}B	14.02	10.9[c]	10.4[c]	1.86[c]
^{13}N	1.198	1.08	1.15	1.18
^{15}O	1.737	1.23	1.18	1.34
^{51}Cr	0.746	1.06	1.15	1.15
^{51}Cr	0.426	1.02	1.12	1.04
^{65}Zn	1.343	1.23	1.19	1.42
^{65}Zn	0.330	1.00	1.00	1.00

[a]Reference 9.
[b]Reference 7.
[c]Including excited states only up to 0.75 MeV yields values of 1.22, 1.25, and 1.86, respectively.

excited-state contributions are reduced to 3–4 SNU. The $p+p$ neutrinos constitute about 57% (81%) of the total capture rate if the SSM (non-SSM) flux is assumed.

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