Solar-Neutrino Detection: Experimental Determination of Gamow-Teller Strengths via the ^{98}Mo and ^{115}In (p,n) Reactions

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The empirical distributions of Gamow-Teller strengths in ^{98}Tc and ^{115}Sn have been obtained via the (p,n) reaction at $E_p = 120$ MeV and $E_p = 200$ MeV on ^{98}Mo and ^{115}In targets. This information is used to calculate the cross sections for absorption of solar neutrinos in ^{98}Mo and ^{115}In, nuclides which are being considered as neutrino detectors to accomplish solar-neutrino spectroscopy.

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There is a long-standing discrepancy[1] between the solar-neutrino capture rate measured in the ^{37}Cl experiment[2] and the value predicted from a standard solar model and calculated neutrino-absorption cross sections.[3] This discrepancy may be caused by a lack of understanding of the physics of the solar interior[4] or, if the sun produces the expected spectrum of neutrinos, then their character is altered before they reach the earth (by oscillation or decay).[5]

In order to distinguish between these two classes of solutions, a number of neutrino detectors have been proposed to accomplish what may be regarded as solar-neutrino spectroscopy. Much experimental and theoretical work has been devoted to proposed radiochemical experiments[6,7] employing ^{71}Ga and ^{81}Br targets, a geochemical experiment using the production[8] of ^{98}Tc from ^{98}Mo, and a counter experiment[9] using ^{115}In.

Quantitative estimates of neutrino capture rates can be made by combining the Gamow-Teller (GT) and Fermi (F) strengths for each level in a given target with the calculated solar-neutrino spectra. For the gallium detector, most of the capture rate is expected to arise from the experimentally determined ground-state to ground-state transition. However, for the other three detectors mentioned above, there are large or dominant transitions occurring between states that are not connected by experimentally accessible beta-decay transitions. The Fermi strength can be calculated, but for all the above nuclei there is no complete determination experimentally of the GT strength function. Some model-dependent calculations of the GT strengths have been performed and estimates based on nuclear systematics have also been used. However, it is difficult to assign errors to these predictions.

We focus attention here on the promising ^{98}Mo and ^{115}In solar-neutrino experiments, which are being actively developed by several different groups.[8,9] The ^{98}Mo detector offers a unique opportunity to measure the flux of ^{8}B neutrinos millions of years ago[8] and the ^{115}In experiment (in which individual electrons are detected) can provide detailed information about the spectrum of neutrinos and possibly also directional information.[9]

We evaluate empirically the distribution of GT strengths in ^{98}Tc and ^{115}Sn using measured zero-degree (p,n) cross sections at 120 MeV of ^{98}Mo and ^{115}In. The method used has been described in earlier papers[10] and has been used to evaluate the ^{37}Ar GT strength function,[11] yielding a result that is in good agreement with the value found from an analysis of weak-interaction data.[3]

Using the measured (p,n) cross sections, we have calculated the cross section for absorption of ^{8}B neutrinos by ^{98}Mo leading to the particle-stable final states of ^{98}Tc. We include all of the standard atomic and nuclear corrections.[3] Our value for the neutrino-absorption cross section is a factor of 3.5 larger than that suggested by the simple scaling argument (which neglects nuclear structure effects) of Cowan and Haxton.[8] Our result increases the expected signal-to-noise ratio in this important experiment. We have also calculated the neutrino-absorption cross sections for the production of ^{115}Sn from ^{115}In. We find that for the ^{115}In detector almost all of the expected capture rate is associated with the production of a low-lying metastable state at 0.61 MeV which was originally discussed by Raghavan.[9] Our cross sections for the dominant low-energy neutrino absorptions in ^{115}In are in good agreement with the earlier estimates of Raghavan[9] and Bahcall,[3] although the total ^{8}B cross section (which includes transitions to many different excited levels) is a factor of 3 larger.

The Indiana University cyclotron and beam-swinger facilities were used to bombard ^{98}Mo (97.2% enriched, 33.1 mg/cm^2) and ^{115}In (99.99% enriched, 40.9 mg/cm^2) targets with 120- and 200-MeV protons. Neutron time-of-flight spectra were obtained at 0° and 5° (120 MeV) and at 0° and 3.2° (200 MeV) at a flight path of 130 m. An energy resolution of approximately 300 keV was achieved at 120 MeV and 800 keV at 200 MeV. The neutron energy scale was calibrated by use of (p,n) transitions in ^{7}Li and ^{12}C targets which have well known Q values. Absolute normalization of the data was accomplished with the $^{7}\mathrm{Li}(p,n)$ total cross-section technique.[12] The energy dependence of the neutron-detector efficiency was empirically checked by measuring the known value of the 0° cross section for the reaction $^{12}\mathrm{C}(p,n)^{12}\mathrm{N}(\mathrm{g.s.})$.

The measured $0°(p,n)$ cross section characterized by an angular momentum transfer $L=0$ can be represented by the approximate relation[11,13,14]

$$\frac{d\sigma}{d\Omega}(\theta=0°) \approx \left(\frac{\mu}{2\pi\hbar^2}\right)^2 \frac{k_f}{k_i} N_\alpha^D |J_\alpha|^2 B(\alpha),$$

where μ denotes the relativistic reduced energy divided by c^2 and k is the wave number; N^D is a distortion factor and J is the Fourier transform at momentum transfer $q=0$ of the free N-N t matrix. The index α represents either a Fermi or GT transition. The nuclear-structure coefficient $B(\alpha)$ represents the corresponding strength; the latter is the square of the reduced matrix element as defined by Bohr and Mottelson.[15] The distorted-wave impulse-approximation code DWBA-70[16] was used to calculate N_α^D values as described by Goodman *et al.*[17] Values for the interaction strength as parametrized by Love and Franey[18] at $E_p=140$ and 210 MeV and optical-model potential parameters obtained from Schwandt *et al.*[19] were used. In the above expression empirically determined J_α values[9] were assumed to estimate the proportionality between the measured 0° cross section and the $B(\alpha)$ values. This proportionality is energy dependent because of the energy dependence of N^D and k.

The non-$(L=0)$ contributions in the measured 0° cross section were evaluated by use of the $\theta=0°$ and $\theta=5°$ spectra at 120 MeV with the method described by Goodman and Bloom.[20] The evaluation of the GT strength from the data at 200 MeV is in excellent agreement with the results obtained from the data at 120 MeV. Because of the better resolution obtained at the lower energy, we present and discuss the latter results.

In Fig. 1(a) the $^{98}\mathrm{Mo}(p,n)^{98}\mathrm{Tc}$ spectrum obtained at $\theta=0°$ and $E_p=120$ MeV is presented. The density of low-lying states in ^{98}Tc is high. Twenty-four excited states are reported[21] below 700 keV of excitation. As noted above, the 0° (p,n) spectra at intermediate energies give a good representation of the $L=0$ strength. The isobaric analog transition, which carries the Fermi strength, $B(\mathrm{F})=2T=14$, is located[22] at $E_x=9.7$ MeV and corresponds to the sharp peak in Fig. 1(a). Near the ground state the observed neutron group has an energy resolution of approximately 600 keV, indicating that it corresponds to the excitation of several states. The observed 0° cross section, 1.3 mb/sr, may be translated to a $B(\mathrm{GT}) \sim 0.44$ by use of the procedure indicated above. In Fig. 1(b) we present a spectrum derived from the $\theta=0°$ and a $\theta=5°(p,n)$ spectrum but with the isobaric analog state (IAS) removed, and with the y scale in $B(\mathrm{GT})$ units. The main part of the GT strength seems to be concentrated at $E_x \sim 12.3$ MeV

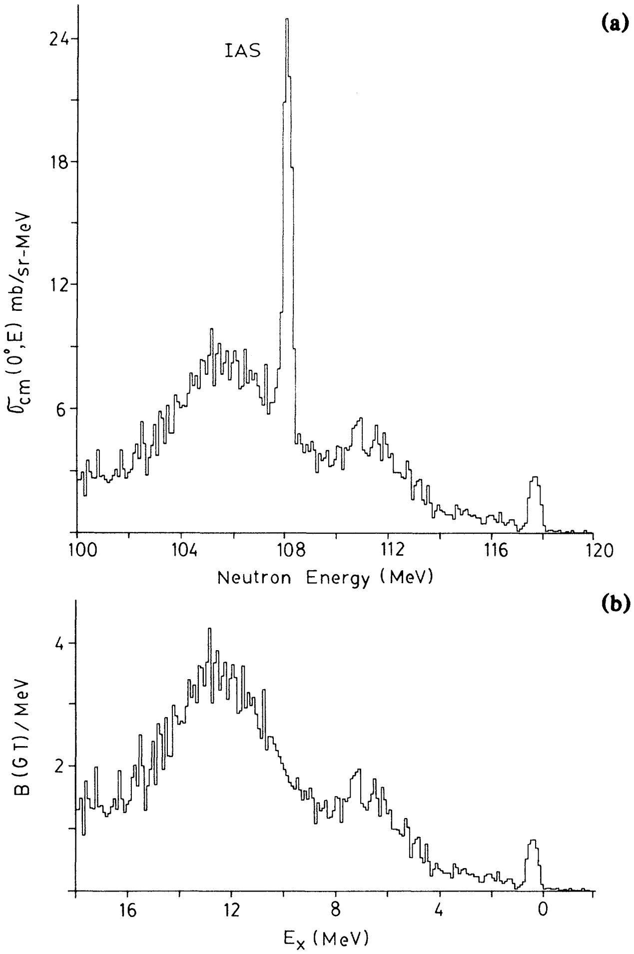

FIG. 1. (a) Neutron spectrum for the reaction ^{98}Mo$(p,n)^{98}$Tc obtained at $E_p = 120$ MeV and $\theta_L = 0°$. The time-of-flight spectrum has been converted to an energy scale. (b) Gamow-Teller strength distribution derived from the above spectrum and a 5° spectrum. Units are such that for a free neutron B(GT) = 3.0.

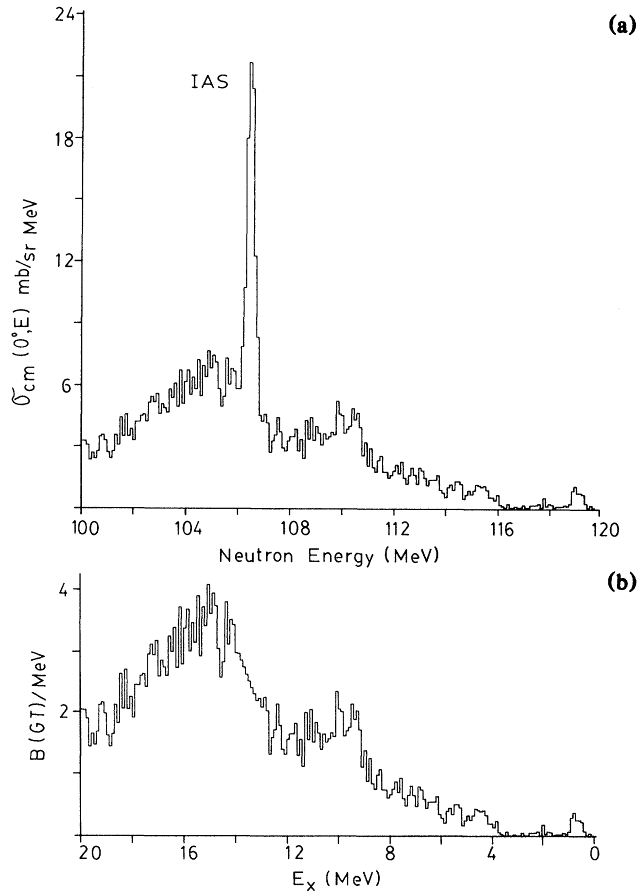

FIG. 2. (a) Neutron spectrum for the reaction ^{115}In$(p,n)^{115}$Sn obtained at $E_p = 120$ MeV and $\theta_L = 0°$. The time-of-flight spectrum has been converted to an energy scale. (b) Gamow-Teller strength distribution derived from the above spectrum and a 5° spectrum. Same units as in Fig. 1.

in ^{98}Tc while a smaller fraction of the strength is centered at about 6.6 MeV. A $\sum B(\mathrm{GT}) = 28 \pm 5$ is estimated up to 18-MeV excitation energy which is 0.67 ± 0.08 of the minimum value $3(N-Z) = 42$.

In Fig. 2(a) the 0° spectrum obtained from the reaction ^{115}In$(p,n)^{115}$Sn is shown. The sharp neutron group at $E_n \sim 106.5$ MeV represents the excitation of the IAS at $E_x = 13.25$ MeV[23] and it carries the Fermi strength, $B(\mathrm{F}) = 17$. The first state to carry GT strength is the 0.614-MeV state $(J^\pi = \frac{7}{2}^+)$. It has a $\sigma(0°) \sim 0.5$ mb/sr which is translated to a $B(\mathrm{GT}) = 0.17$. Figure 2(b) represents a spectrum derived from the 0° and a 5° (p,n) spectrum with the IAS transition removed and with a y scale in units of B(GT). The giant GT strength is concentrated at $E_x \sim 14.5$ MeV while a smaller fraction of the strength appears at $E_x \sim 9$ MeV. A value $\sum B(\mathrm{GT}) = 30 \pm 5$ is estimated up to 19-MeV excitation energy which is about $(59 \pm 9)\%$ of the minimum value $3(N-Z) = 51$. The fraction of the $3(N-Z)$ value for the sum GT strength observed in both cases agrees with similar values reported in nearby nuclei.[24]

The experimentally determined strengths to the various excited states in ^{98}Tc have been used to calculate, taking account of all the usual atomic- and weak-interaction factors,[3] the cross section for absorption of ^{8}B neutrinos by ^{98}Mo. We included transitions to all particle-stable states in ^{98}Tc, integrating the GT strength in 0.5-MeV bins. We find

$$\sigma(^8\mathrm{B}) = 3.0 \times (1.0 \pm 0.3) \times 10^{-42}\ \mathrm{cm}^2, \qquad (1)$$

where the largest contribution to the indicated error (the indicated uncertainty is one standard deviation) is from the (p,n) measurements of the B(GT) values.

The cross section given in Eq. (1) is a factor of 3.5 larger than was estimated by Cowan and Haxton[8] and, therefore, makes the proposed ^{98}Mo solar-neutrino experiment seem even more attractive.

There are a number of excited states[3] in the ^{115}Sn nucleus that can be produced by solar neutrinos incident on ^{115}In. Our experimental *(p,n)* cross sections, when combined with the weak-interaction cross-section factors, show that (for all but the ^{8}B neutrinos) solar-neutrino absorption by ^{115}In is dominated by transitions to the 0.614-MeV excited state[9] of ^{115}Sn. Previous calculations[3,9] of neutrino-absorption cross sections for ^{115}In made use of Raghavan's estimate for B(GT) to the 0.61-MeV excited level in ^{115}Sn. Our empirical determination implies that the cross sections for all neutrino sources considered in Ref. 3, except for the relatively unimportant ^{8}B neutrinos, should be multiplied by a best-estimate factor of $0.89(1.0 \pm 0.2)$ (indicated uncertainty, one standard deviation). The cross section for ^{8}B neutrinos is estimated to be $2.4(1.0 \pm 0.3) \times 10^{-42}$ cm^2, a factor of 3 larger than the capture rate to the 0.61-MeV state alone.

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