

Gamow-Teller Strengths of the Inverse Beta Transition $^{176}\text{Yb} \rightarrow ^{176}\text{Lu}$ for Spectroscopy of Proton-Proton and Other Sub-MeV Solar Neutrinos

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Discrete Gamow-Teller (GT) transitions $^{176}\text{Yb} \rightarrow ^{176}\text{Lu}$ at low excitation energies have been measured via the ($^3\text{He}, t$) reaction at 450 MeV and at 0° . For ^{176}Yb , two low-lying states are observed, setting low thresholds $Q(\nu) = 301$ and 445 keV for neutrino (ν) capture. Capture rates estimated from the measured GT strengths, the simple two-state excitation structure, and the low $Q(\nu)$ in Yb-Lu indicate that Yb-based ν detectors are well suited for a direct measurement of the sub-MeV solar electron-neutrino (ν_e) spectrum including pp neutrinos.

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The major result of experimental solar-neutrino research to date shows that the observed fluxes of solar neutrinos are much reduced compared with theoretical predictions based on the standard solar model (SSM) [1]. Particularly sharp questions are posed by the results from the Gallex [2] and Sage [3] experiments at the low-energy end of the spectrum (from the $p + p$, ^7Be , and CNO reactions in the sun) that are in contrast with those from Super-Kamiokande at high energies (from the decay of ^8B) [4]. The low-energy results imply a negligible flux of ^7Be neutrinos which is inconsistent with the observed sizable flux of high-energy ^8B neutrinos because the ^8B activity in the sun cannot arise without the precursor ^7Be in the reaction $^7\text{Be} + p \rightarrow ^8\text{B}$. These results suggest mechanisms beyond possible astrophysical shortcomings of the SSM. The only other possibility is nonstandard neutrino physics, viz., the conversion of the original electron-flavor solar neutrinos (ν_e) to undetected μ and τ flavors. Evidence for $\nu_\mu - \nu_\tau$ flavor conversion has recently been observed by Super-Kamiokande [5].

The conceivable conversion mechanisms produce ν_e flux deficits that are energy dependent (typically strongest at low energies) and result in large deficits of either the pp and/or the ^7Be ν_e fluxes, the two dominant features of the sub-MeV spectrum. A deficit in the model-independent pp -neutrino flux and/or a ^7Be ν_e flux measurably smaller than the total all-flavor flux (expected from the Borexino [6] and SNO [7] experiments in particular), would provide the most direct proof of flavor conversion. A real-time

measurement of the complete ν_e spectrum from the sun and source-specific fluxes is, thus, of central interest for solving the solar- ν problem. Such data are not available yet since the operating low-energy Ga detectors yield only the integral signal rate above a threshold, not the fluxes from specific solar ν sources.

Recently, Raghavan [8] suggested a possible way to construct a low-threshold, flavor-specific scheme for real-time detection of solar neutrinos via neutrino captures based on the charged current mediated Gamow-Teller (GT) transitions $\nu_e + ^{176}\text{Yb} \rightarrow e^- + ^{176}\text{Lu}^*$ and $\nu_e + ^{160}\text{Gd} \rightarrow e^- + ^{160}\text{Tb}^*$. The basic idea is to identify absorption events of pp and ^7Be neutrinos by a delayed coincidence between a prompt e^- event and a cascade γ ray via isomeric states in ^{176}Lu or ^{160}Tb . The coincidence tag (with time gates $\leq 10^{-7}$ s) allows suppression of background events by a factor of 10^7 . For the first time, this scheme offers the tools for practical real-time spectroscopy even of pp neutrinos despite the formidable backgrounds that have precluded low-energy ν spectroscopy so far. Feasibility studies are in progress for constructing such a solar ν detector LENS (Low-Energy Neutrino Spectroscopy) [9].

The basic input data for designing LENS are the cross sections of the GT transitions in Yb and Gd for which the weak matrix elements $B(\text{GT})$ must be determined for each of the low-lying 1^+ states excited by neutrino capture. The low-energy excitations in Yb-Lu and Gd-Tb consist of several close-lying known 1^+ states. Clarification of

the states relevant to LENS thus requires high-resolution spectra. We have therefore measured high-resolution (${}^3\text{He}, t$) spectra at 0° using a ${}^3\text{He}$ beam at 450 MeV. This work complements a different approach to find $B(\text{GT})$ via (p, n) measurements [10] on the same targets.

The (${}^3\text{He}, t$) reaction at 450 MeV has already been demonstrated to be useful in getting $B(\text{GT})$ values. Since the full Fermi transition strength $B(\text{F}) = N - Z$ is exhausted by the isobaric analog state (IAS), the $B(\text{GT})$ values can be obtained from the singles (${}^3\text{He}, t$) spectra by using the ratio of the cross sections to the 1^+ states and the IAS [11]. The measurements described below show that the $B(\text{GT})$ values obtained here can be used reliably to estimate solar-neutrino rates in LENS.

The (${}^3\text{He}, t$) experiment was performed at $E({}^3\text{He}) = 450$ MeV at the RCNP cyclotron facility of Osaka University using the spectrometer Grand Raiden [12] which was set at $\theta = 0^\circ$ with a solid angle of $\Delta\Omega = 1.6$ msr. Both the incident ${}^3\text{He}^{++}$ beam and the reaction products entered into the spectrometer set at 0° . A metallic target of ${}^{176}\text{Yb}$ (96.7% enrichment, 3.3 mg/cm 2) was used. The ${}^3\text{He}^{++}$ beam, which has a much smaller magnetic rigidity than the tritons, was stopped at the internal Faraday cup inside the first dipole ($D1$) magnet. Details of the experimental setup are described in Ref. [12]. Particles analyzed by the spectrometer were detected in the focal-plane detection system consisting of two multiwire drift chambers (MWDC's) and two ΔE plastic scintillation counters, whose signals were used for particle identification as well as for triggering the events. The MWDC's gave information on the arrival positions at the focal plane and the scattering angles of the tritons.

Very good particle identification with the focal-plane detector of the spectrograph was required to overcome the huge background due to the ${}^3\text{He}^{++} \rightarrow {}^3\text{He}^+$ atomic charge-exchange process [13], since the Q value for the (${}^3\text{He}, t$) reactions on ${}^{176}\text{Yb}$ leading to the lowest 1^+ states in the residual nuclei is ≤ 0.3 MeV. For this purpose, we added a plastic scintillation counter with a thickness of 1 mm in front of the two ΔE counters of 10 mm thickness for improved particle identification. This front counter should be very thin to avoid creating tritons induced by (${}^3\text{He}, t$) reactions in the scintillator itself. With this technique, we could obtain a spectrum free from the ${}^3\text{He}^{++} \rightarrow {}^3\text{He}^+$ atomic charge-exchange process.

To achieve a high-energy resolution of around 100 keV, we installed an energy-defining slit in the beam-transport system from the $K = 400$ MeV ring cyclotron to the target position. The image-defining slit was set at the first beam-focusing position of the beam line. The technique of dispersion matching between the beam line and the spectrometer was employed to obtain the required high resolution. An overall energy resolution of $\Delta E = \sim 100$ –140 keV was obtained, which was sufficient to resolve the low-lying 1^+ states in ${}^{176}\text{Lu}$.

To confirm the validity of the particle identification, we performed an additional experiment where the ${}^{176}\text{Yb}$ tar-

get was backed with a thin Mylar foil (0.086 mg/cm 2) to reduce the huge ${}^3\text{He}^{++} \rightarrow {}^3\text{He}^+$ yields. In this run, a high-resolution measurement was not possible because of the achromatic beam-transport mode. However, it was confirmed that the unresolved yield for the 1^+ states at 195 and 339 keV has the same relative intensity as the summed yield for these two states in the 0° ${}^{176}\text{Yb}({}^3\text{He}, t)$ spectrum taken in the dispersion-matching high-resolution mode.

To gauge the $B(\text{GT})$ values obtained in the (${}^3\text{He}, t$) analysis, a calibration measurement was performed using the neighboring ${}^{164}\text{Dy}({}^3\text{He}, t)$ reaction, leading to the 1^+ ground state in ${}^{164}\text{Ho}$. The ${}^{164}\text{Ho}$ ground state is known to β -decay to the ${}^{164}\text{Dy}$ ground state with a $\log ft$ value of 4.6 (Ref. [14]). This yields a $B(\text{GT})$ value of 0.293 ± 0.006 for the Dy-Ho transition. The ${}^{164}\text{Dy}$ result can thus be used to independently calibrate the strong-interaction part of the (${}^3\text{He}, t$) reaction cross sections for measurements on the 1^+ states.

Figure 1 shows the (${}^3\text{He}, t$) spectrum on ${}^{176}\text{Yb}$ at $\theta = 0^\circ$. We deduced the relative transition strengths of the 194.5 keV to the 338.9 keV states, by fitting the peaks with a Gaussian shape (see Fig. 1), to be 1.0:0.55. The transition strengths to the excited states were compared to that of the IAS. The excitation strengths to GT states and the IAS depend, however, on the volume integrals of the central parts of the effective interaction, J_τ and $J_{\sigma\tau}$, and distortion effects parametrized by N_τ^D and $N_{\sigma\tau}^D$ [15]. Using the observed strengths to the ground 1^+ state and the IAS in the ${}^{164}\text{Dy}({}^3\text{He}, t){}^{164}\text{Ho}$ reaction at the same bombarding energy of 450 MeV, we calibrated the ratio of the interaction strengths including the distortion

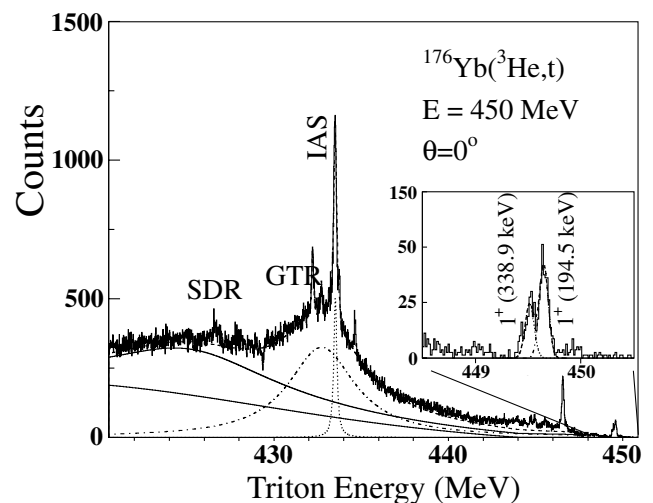


FIG. 1. Triton energy spectrum from the ${}^{176}\text{Yb}({}^3\text{He}, t)$ reaction at 0° taken with a ${}^3\text{He}$ beam of 150 A MeV. A sharp IAS peak and two broad bumps corresponding to the Gamow-Teller resonance (GTR), and the spin dipole resonance (SDR) are observed. The global structure of the spectrum is fitted by assuming an underlying continuum due to quasifree scattering. Discrete states at the low excitation energy are displayed in the expanded inset. Sharp peaks near IAS are due to C and O contaminations.

effects as

$$\frac{N_{\sigma\tau}^D |J_{\sigma\tau}|^2}{N_{\tau}^D |J_{\tau}|^2} = \frac{(d\sigma/d\Omega)_{GT} B(F)}{(d\sigma/d\Omega)_{IAS} B(GT)} = 7.44 \pm 0.79. \quad (1)$$

Here we used $B(GT) = 0.293 \pm 0.006$, $B(F) = N - Z = 32$, and $(d\sigma/d\Omega)_{GT}/(d\sigma/d\Omega)_{IAS} = 0.068 \pm 0.007$ for the transition to the ground state of ^{164}Ho . The value of 7.44 ± 0.79 for the $(^3\text{He}, t)$ reaction at 150 A MeV agrees nicely with the values obtained by the scaling relation $[(E/A)/55 \text{ MeV}]^2$ which fits the systematics of (p, n) reaction data [16], and has been verified specifically for the $^{176}\text{Yb}(p, n)$ reactions with values of 4.76 obtained for $E_p = 120 \text{ MeV}$ and 8.46 for 160 MeV [10].

The present calibration method is applicable since the distortion effect and the ratio of the effective interactions $|J_{\sigma\tau}/J_{\tau}|$ are expected to be the same as those for the $^{176}\text{Yb}(^3\text{He}, t)$ reaction and the kinematic factors are canceled out. Empirically, the volume integrals of the effective interaction and the distortion effect are not significantly different among target nuclei in the same mass region.

The $B(GT)$ values for the 1^+ states in ^{176}Lu were obtained using the equation

$$B(GT) = B(F) \frac{1}{7.44} \frac{(d\sigma/d\Omega)_{GT}}{(d\sigma/d\Omega)_{IAS}}, \quad (2)$$

where $B(F)$ is $(N - Z)$, and the ratio of $(d\sigma/d\Omega)_{GT}/(d\sigma/d\Omega)_{IAS}$ is obtained from the $(^3\text{He}, t)$ spectra at 0° . The $B(GT)$ values deduced from the 0° cross sections measured in the $(^3\text{He}, t)$ experiment at 450 MeV are listed in Table I. The $B(GT)$ values obtained for the possible

TABLE I. Gamow-Teller and Fermi strengths $B(GT)$ and $B(F)$ of the levels observed in the $^{176}\text{Yb}(^3\text{He}, t)^{176}\text{Lu}$ and $^{160}\text{Gd}(^3\text{He}, t)^{160}\text{Tb}$ reactions.

J^π	$^{176}\text{Yb}_{106}(^3\text{He}, t)^{176}\text{Lu}_{105}$ $E_x(\text{keV})$	$B(GT)$ or $B(F)$
1_1^+	194.5	0.20 ± 0.04
1_2^+	338.9	0.11 ± 0.02
1_3^+	3070	0.62 ± 0.08
0_{IAS}^+	$16\,026 \pm 6$	36
J^π	$^{160}\text{Gd}_{96}(^3\text{He}, t)^{160}\text{Tb}_{95}$ $E_x(\text{keV})$	$B(GT)$ or $B(F)$
1_1^+	138.7	0.054 ± 0.009
1_2^+	232.8	0.014 ± 0.002
1_3^+	478.2	0.160 ± 0.03
1_4^+	573.0	0.021 ± 0.004
1_5^+	664.7	0.031 ± 0.005
1_6^+	1120	~ 0.034
1_7^+	1310	~ 0.025
1_8^+	1500	~ 0.043
1_9^+	1610	~ 0.034
1_{10}^+	1670	~ 0.051
1_{11}^+	1750	~ 0.051
1_{12}^+	1900	~ 0.056
1_{13}^+	2040	~ 0.259
0_{IAS}^+	$15\,019 \pm 6$	32

low-lying 1^+ levels in ^{160}Tb from $^{160}\text{Gd}(^3\text{He}, t)^{160}\text{Tb}$ are also listed for reference. The $B(GT)$ values for ^{176}Yb obtained here are in agreement with the (p, n) results [10].

The reliability of the $B(GT)$ values obtained here is supported by the following considerations: (1) scaling of reaction cross sections for GT resonances relative to the Fermi strength observed in the IAS, (2) direct use of the known ^{164}Dy weak matrix element to calibrate the strong-interaction factor, (3) agreement of the deduced strong interaction factor with the energy scaling systematics of (p, n) reactions in general and those for ^{176}Yb in particular, and (4) agreement of the $B(GT)$ values obtained in the $(^3\text{He}, t)$ and (p, n) works for ^{176}Yb and ^{160}Gd .

The impact of the $B(GT)$ values for ^{176}Yb may now be examined. The complete level scheme involved in an Yb-based detector is shown in Fig. 2. These data and those of Table I show that only the two 1^+ levels at 194.5 and 338.9 keV in the final nucleus ^{176}Lu are populated by ν capture below 3 MeV. The thresholds for ν capture are determined by the level energies and the ^{176}Yb - ^{176}Lu mass difference as $Q(\nu) = 301$ and 445 keV for the above two states. The Q value of 301 keV lies below 420 keV, the end point of the $pp \nu$ continuum. The $B(GT)$ value for this transition is the larger of the two.

The above data on the ν -capture level structure and the capture strengths establish the fundamental suitability of Yb LENS for the long-standing problem of not only the detection but also the spectroscopy of solar neutrinos. The response of Yb LENS to solar neutrinos, calculated for a 20 ton natural Yb target with fluxes given by the SSM [1] is shown in Fig. 3a. The observable spectrum is that of the prompt electron e^- with the energy $E_{e^-} = E_\nu - Q_\nu$ that follows ν capture. Consequently, the incident ν_e spectrum is recorded directly. The principal features of the pp , ^7Be , pep , and the underlying continuum from CNO reactions

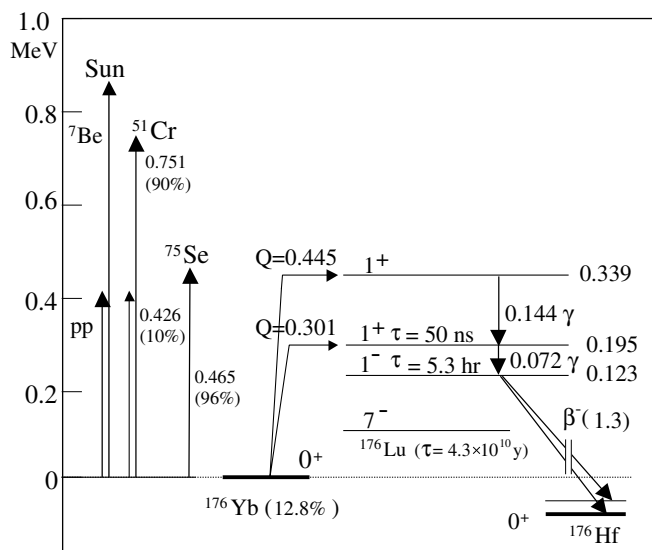


FIG. 2. Level scheme and γ -ray tags for solar-neutrino detection by ^{176}Yb (12.8% natural abundance). All energies are in MeV.

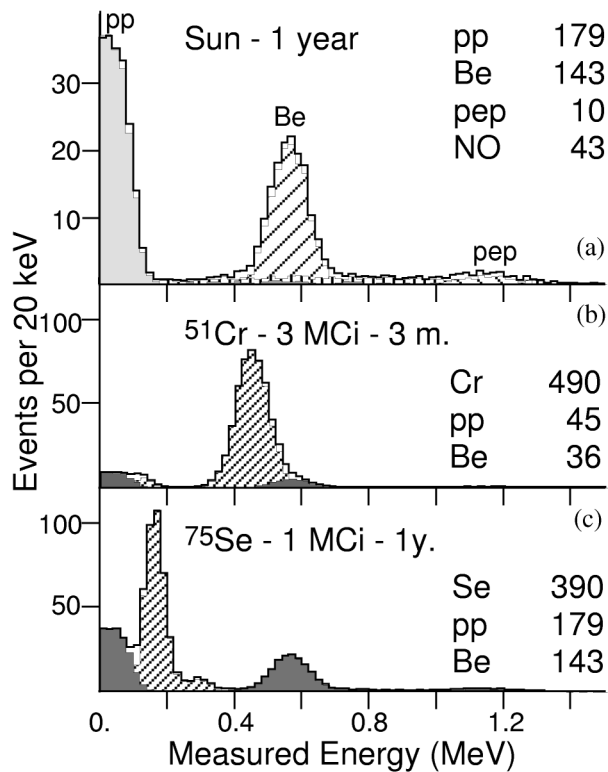


FIG. 3. Calculated ν_e spectra in an Yb-doped scintillator with a mass of 20 tons of natural Yb exposed by ν 's from (a) the sun, (b) a radioactive source of ^{51}Cr , and (c) a source of ^{75}Se .

in the sun are clearly resolved assuming a conservative 1σ energy resolution of $\Delta E/E \sim 7\%/\sqrt{E(\text{MeV})}$.

Because of the importance of absolute fluxes for the three major ν sources [pp ($E_{\text{max}} = 420$ keV), ^7Be (862 keV), and pep (1442 keV)] $B(\text{GT})$ values must be known individually for the two states in ^{176}Lu . The simplicity of the level structure of ^{176}Lu (only two states below 3 MeV) is valuable in contrast to the case of ^{160}Gd (see Table I) in which five levels below 1 MeV participate and more than 13 levels below ~ 2 MeV. Therefore, the use of Gd is less favorable than Yb since interpretation of the experimental data is more complicated besides presenting severe problems in the practical operation of the detector.

The merits of ^{176}Yb are reinforced by plans to measure the ν -absorption cross sections directly using monoenergetic ν 's from megacurie (MCi) radioactive sources. Such a calibration requires a series of sources, each with a single neutrino line, selected to discriminate level thresholds so that cross sections to individual levels can be deduced at least from the combined data. In principle, as many sources (lines) are needed as target levels revealed in this work. Clearly, such measurements are practically ruled out for Gd with so many levels to characterize. For the two levels in ^{176}Yb , two sources are proposed. The first, ^{51}Cr [17–19], produces a 752 keV line which populates both the Yb transitions (the weaker line at 426 keV produces a much weaker signal). The second source, ^{75}Se

[20,21], produces a line at 465 keV which is sensitive only to the lower level. Figures 3b and 3c depict the LENS response for these two calibration lines. They show that the neutrino response of an Yb LENS can be calibrated experimentally without interference from a “background” of solar neutrinos.

In summary, we report experimental results on the Gamow-Teller transitions from ^{176}Yb to ^{176}Lu using the $(^3\text{He}, t)$ reaction at $E(^3\text{He}) = 450$ MeV. A high-resolution measurement enabled us to resolve the low-lying 1^+ states in the residual nucleus. By taking the ratios of the excitation strengths for the IAS and the Gamow-Teller states, we deduce the $B(\text{GT})$ values for low-lying 1^+ states after calibrating the reaction mechanism. The data establish the foundations for a practical real-time ^{176}Yb detector for sub-MeV solar ν 's including pp ν 's. Solar ν absorption rates for a 20-ton Yb detector are given together with those for the ^{51}Cr and ^{75}Se ν calibrations.

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- [1] J.N. Bahcall, Nucl. Phys. **B77**, 64 (1999).
- [2] T.A. Kirsten, Nucl. Phys. **B77**, 26 (1999).
- [3] V.N. Gavrin, Nucl. Phys. **B77**, 20 (1999).
- [4] Y. Fukuda *et al.*, Phys. Rev. Lett. **81**, 1158 (1998).
- [5] Y. Fukuda *et al.*, Phys. Rev. Lett. **81**, 1562 (1998).
- [6] C. Arpesella *et al.*, “Borexino: A real time detector for low energy solar neutrinos,” edited by G. Bellini and R. S. Raghavan, INFN-Milano, 1991 (unpublished).
- [7] J. Boger *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **449**, 172 (2000).
- [8] R.S. Raghavan, Phys. Rev. Lett. **78**, 3618 (1997).
- [9] LENS Collaboration, Proposal to Laboratori Nazionali del Gran Sasso (LNGS), 1999.
- [10] M. Bhattacharya *et al.*, following Letter, Phys. Rev. Lett. **85**, 4446 (2000).
- [11] M. Fujiwara *et al.*, Nucl. Phys. **A599**, 223c (1996).
- [12] M. Fujiwara *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **422**, 484 (1999).
- [13] K. Dennis *et al.*, Phys. Rev. A **50**, 3992 (1994).
- [14] E.N. Shurshikov and N.V. Timofeeva, Nucl. Data Sheets **65**, 365 (1992).
- [15] C.D. Goodman *et al.*, Phys. Rev. Lett. **44**, 1755 (1980).
- [16] C.D. Goodman, Nucl. Phys. **A577**, 3c (1994).
- [17] R.S. Raghavan, in Proceedings of the Conference on “Status and Future of solar neutrino research” (Brookhaven National Laboratory Report No. BNL-50879, 1978, Vol. II, p. 270).
- [18] W. Hampel *et al.*, Phys. Lett. B **420**, 114 (1998).
- [19] M. Cribier *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **378**, 233 (1996).
- [20] J-F. Cavaignac and M. Cribier (private communication).
- [21] V.N. Kornoukhov *et al.*, Institute of Theoretical and Experimental Physics Report No. ITEP 18-99, 1999.