New Tools for Solving the Solar-Neutrino Problem

R. S. Raghavan
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

Sandip Pakvasa
Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, Hawaii 96822

and

B. A. Brown
Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824
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Neutrino (ν) excitation of nuclear levels (NUEX) via neutral currents is shown to be crucially important to the solar-ν problem as a method of detecting ν's regardless of flavor. We examine 11B, 40Ar, and 35Cl as NUEX targets. The 11B system offers means for concurrent solar-ν spectroscopy by NUEX and by charged-current ν_e capture with a set of differing thresholds. It promises a self-contained solution to the solar-ν problem as well as key probes for revealing the structure of resonant flavor and nonflavor ν oscillations in the sun. This approach may be feasible in an ICARUS-type underground experiment.

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The central dilemma of the solar-neutrino (ν) problem is that it is impossible to decide if ν oscillations or the shortcomings of the standard solar model are at the root of the disparity between predictions and experiment. Either possibility is of fundamental importance to astrophysics or particle physics. The concept of resonant enhancement of ν oscillations in solar matter implies that even for small flavor-mixing angles, serious distortions at all energies of the standard solar-ν spectrum are possible, setting us the difficult task of acquiring very precise, wide-ranging spectral data. A direct attack on the problem is possible by the devising of a method to observe ν's regardless of flavor in the same experiment designed to detect only electron neutrinos (ν_e). A difference in the solar-ν flux as measured by the two detection modes would be specific evidence for ν oscillations while the flux seen by the "all-flavor" mode should be the true ν flux from the sun. We show that this strategy can be achieved by flavor-independent ν excitation of nuclear levels (NUEX) via neutral currents.

NUEX is a process of general applicability to solar-ν detectors. It can be observed in practice by the signatures of a subsequent deexcitation mode or product (ν + A → A^+ + ν' → A + γ or A'+ p, n, α) in close analogy to γ excitation. The choice of the NUEX mode is guided by our desire for comparative operation of NUEX and a flavor-dependent charged-current (CC) ν_e-detection mode. Known schemes for CC solar-ν_e detection may thus be examined first for NUEX capability. The NUEX target could be the original CC target, an isotopic or other constituent, or a new target species mixed into the detector. The viability of the NUEX mode depends on sensitivity to solar ν's in terms of threshold energies and excitation strengths specific to the target, a signature to identify NUEX events, and compatibility of the NUEX mode with the technique of CC ν_e detection. A particular case of this method is deuteron breakup by ν or ν̅ combined with ν_e or ν̅_e capture by deuterons, as employed by Reines, Sobel, Pasierb or as proposed by Chen for solar-ν detection. Following the new avenues opened by the NUEX mode of ν detection, we consider three solar-ν targets: 11B and 40Ar (direct counting) and 35Cl (in the Homestake chemical detector).

The 11B system is uniquely tailored to the NUEX-CC method. The salient features are as follows: safely predictable NUEX (11B+ν → ν'+11B+γ) strengths to a set of levels in 11B (Fig. 1); a well-defined set of

![Fig. 1. The 11B-31C mirror system (E_i, E'_i, Δ are in megaelectronvolts).](image)
mirror levels in $^{11}$C for CC $\nu_e$ captures; and a light nuclear mass and high isotopic abundance (80.2%). They offer powerful facilities for a self-contained solution of the solar-$\nu$ problem: (a) a strong NUEx spectral peak yielding at once the astrophysical $^8B\nu$ flux; (b) a CC/NUEx event ratio independent of nuclear matrix elements offering a sharp test for $\nu$ oscillations; and (c) CC captures with a set of differing thresholds promising specific data on the structure of resonant $\nu$ oscillations in the sun.

In standard electroweak theory, at low momentum transfers, NUEx proceeds only by the isovector (ISV) axial-vector current. The relevant matrix element is

$$\frac{1}{2} g_A \langle \sigma \tau_2 \rangle$$

$g_A$ is the $\beta$-decay $A/V$ coupling ratio. $\langle \sigma \tau_2 \rangle$ can be estimated by shell-model calculations or by the ISV dipole $(M1)$ spin-excitation strength $B_{ISV}(M1)$ derived from experiment. The NUEx strength is

$$\lambda_{NX} = \frac{4\pi}{3} \frac{1}{\mu_{ISV}} B_{ISV}(M1).$$

(1)

With $\mu_{ISV}$ the ISV nucleon magnetic moment, $= 4.7$, and $g_A = 1.25$, then $\lambda_{NX} = 0.296 B_{ISV}(M1)$. The specific NUEx yield $\gamma_{NX}$ to the level of energy $E_i$ is

$$\gamma_{NX} = \frac{G_F^2}{\pi} \phi_{st} \lambda_{NX} P_{NX},$$

(2)

where $G_F$ is the Fermi constant and $E_i$ is the NUEx threshold. Only $^8B$ solar $\nu$'s are of interest here. $\phi_{st}$ is their flux in the standard model and their normalized spectral profile $S(E_\nu)$ is used in the phase-space integral $P_{NX}$. The NUEx events for all $E_\nu > E_i$ appear as $y$ rays localized at the sharp energy $E_i$.

Strong $M1$ excitation of $^{11}$B to levels at $E_i = 2.125$, 4.445, and 5.021 MeV has been observed and the $B(M1)$ measured by $(\gamma, \gamma')$ and $(e,e')$ scattering. A shell-model calculation [which reproduces these $B(M1)$ well] gave the ratio of ISV-spin-$M1$ to the $B(M1)$ strength which was quenched by a factor 0.75 and used to scale the measured $B(M1)$ to yield an "effective" $B_{ISV}(M1)$.

The CC $\nu_e$ captures in $^{11}$B lead to levels in $^{11}$C at the energies $E_i' = 2.000, 4.319,$ and 4.804 MeV, and appear as broad distributions of the total event energy $E = E_i' + E_\nu$, where the recoil electron kinetic energy is $E_\nu = E_i' + \Delta$ ($= 1.982$ MeV). These levels in $^{11}$C are isospin mirrors of the above three $^{11}$B levels. The $\nu_e$ capture is related to the mirror NUEx mode by a rotation in isospin space. Thus for these three isodoublets $\lambda_{CC} = 4\lambda_{NX}$, predicting the CC/NUEx yield ratio

$$\omega_i = \frac{\gamma_{CC}}{\gamma_{NX}} = \frac{4P_{CC}}{P_{NX}}.$$  

(3)

Since $S(E_\nu)$ and thus $P_i$ do not depend on solar models, $\omega_i$ is independent of nuclear and solar-structure physics. Substantial deviations from (3) can arise only from new neutrino physics.

Calculated parameters and specific yields from $^{11}$B with use of $\phi_{st} = 4 \times 10^6$ cm$^2$/sec are listed in Table I. We anticipate (see below) a $B$-containing ionization track chamber with typical properties such as $\Delta E/E \approx 10\%$ at 5 MeV, modest spatial resolution to identify the well-separated electron and $\gamma$-ray track patterns of a typical $\nu$ event, and backgrounds allowing a cutoff below a total event energy of $\sim 4$ MeV. Figures 2(a)–2(c) show computed CC spectra for each state (I–III) in $^{11}$C. They can be experimentally sorted by means of the $E_i'$ $\gamma$-ray tag; the ground-state capture appears as an isolated electron track. The transitions to the doublets I and IV at $\sim 5$ MeV are shown summed in Fig. 2(a). The easily identifiable NUEx peaks are separated by 550 keV, enough to give their yield ratio with adequate precision for use in Eq. (3). Data as in Fig. 2(a) can reveal the true solar $^8B\nu$ flux and $\nu$ oscillations with large mixing angles ($\sin^2\theta$)

<table>
<thead>
<tr>
<th>Target</th>
<th>$E_i$ (MeV)</th>
<th>$B(M1)$ (expt.) $(\mu_e^2)$</th>
<th>$B_{ISV}(M1)$ (eff.) $(\mu_e^2)$</th>
<th>$\lambda_{NX}$</th>
<th>$\gamma_{NX}^a$ (MeV)</th>
<th>$E_i'$ (MeV)</th>
<th>$\lambda_{CC}$</th>
<th>$\gamma_{CC}^a,b$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{11}$B</td>
<td>2.12</td>
<td>0.575(45)</td>
<td>0.472(50)</td>
<td>0.140(15)</td>
<td>415</td>
<td>0</td>
<td>1.55$^c$</td>
<td>5760</td>
</tr>
<tr>
<td></td>
<td>4.45</td>
<td>0.90(9)</td>
<td>0.77(9)</td>
<td>0.228(27)</td>
<td>285</td>
<td>2.00</td>
<td>0.562</td>
<td>1125</td>
</tr>
<tr>
<td></td>
<td>5.02</td>
<td>1.253(50)</td>
<td>1.261(60)</td>
<td>0.375(18)</td>
<td>375</td>
<td>4.32</td>
<td>0.913</td>
<td>675</td>
</tr>
<tr>
<td></td>
<td>4.45 + 5.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.81</td>
<td>1.50</td>
<td>840</td>
</tr>
<tr>
<td>$^{40}$Ar</td>
<td>6.1</td>
<td>0.192</td>
<td>0.058</td>
<td>11</td>
<td>4.38</td>
<td>4</td>
<td>1680$^d$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9.6</td>
<td>0.876</td>
<td>0.26</td>
<td></td>
<td></td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10.42$^e$</td>
<td>2.82</td>
<td>0.835</td>
<td></td>
<td></td>
<td>5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$Yield/(kiloton target element) yr.

$^b$Yield for total energy $E > 4$ MeV.

$^c$From Eq. 16.

$^d$Yield for total energy $E > 4$ MeV.

$^e$From Ref. 16.

$'n$-unstable, but yields 6.1-MeV $\gamma$ by $^{40}$Ar($n, \gamma$).
and tiny mass parameters \( \Delta m^2 \sim 10^{-12} \text{ eV}^2 \). Resonant \( \nu \) oscillations in solar matter as suggested by Mikheyev and Smirnov\(^1\) \( \Delta m^2 > 10^{-7} \text{ eV}^2 \), small \( \sin^2 \theta \) can be studied in detail by the total data of Fig. 2 as shown below.

Extending the ideas in Ref. 1, Rosen and Gelb\(^3\) show that the set of \( \nu \)-oscillation parameters consistent with the Homestake\(^2\) result fall into two classes. In class I \( \Delta m^2 \sim 10^{-4} \text{ eV}^2 \), \( \sin^2 \theta > 4 \times 10^{-3} \), only high-energy \( \nu_\beta \)'s \( (> 5 - 7 \text{ MeV}) \) are resonantly converted. For \( \Delta m^2 < 10^{-6} \text{ eV}^2 \), \( \Delta m^2 \sin^2 \theta \sim 10^{-4} \) (class II), low-energy \( \nu_\beta \)'s are also converted. The strong energy dependence of \( \nu_\beta \) flavor survival is typical of resonant \( \nu \) oscillations in the sun.

Since the CC capture thresholds range from \( E_{1\nu} = 2 \) to 7 MeV, they respond to different parts of the \( ^8\text{B} \nu_\beta \) spectrum (0–15 MeV) and act as unique indicators of such resonance effects. Curves marked \( \alpha, \beta, \gamma \) in Figs. 2(a)–2(c) show the spectral response of the \( ^{11}\text{B} \) detector to parameter pairs selected from the above two classes of solutions. The CC spectra of the lower levels II and III for solution \( \beta \) [Fig. 2(b), curve \( \beta \) and Fig. 2(c), curve \( \beta \)], in contrast to that of the higher-energy doublet [Fig. 2(a), curve \( \beta \)], illustrate the resonance effect of the first class. The marked shift of spectral weight away from the lower toward higher energies for solution \( \gamma \), especially for the doublet, typifies that of the second class.

Interesting insight into the dynamics of resonant \( \nu \) oscillations is offered by the relative yields of the four transitions. Using all the \( \nu \) events of \( E > 4 \text{ MeV} \), a "dynamical index" \( \Omega \) can be defined as \( \Omega = Y_{\text{CC}} / Y_{\text{NC}} \). Figure 3 shows a plot of \( \Omega_0 \) (normalized to the no-oscillation \( \Omega_0 = 0.447 \)) vs \( \sin^2 \theta \) for the parameter space of Ref. 3. For \( \sin^2 \theta < 0.2 \), \( \Omega_0 \) takes only the "marker" values \( \Omega_0 = 0.11, \Omega_0 = 0.24, \) and \( \Omega_0 = 0.40 \), corresponding uniquely to the mass groups \( \Delta m^2 \sim 10^{-4} \), \( 2 \times 10^{-5} \), and \( < 10^{-6} \text{ eV}^2 \), which largely categorizes the nature of \( \nu \)-flavor oscillations and indicates its effect on the entire solar-\( \nu \) spectrum. For example, an \( \Omega_0 \) in the range of 0.4 (smallest \( \Delta m^2 \) ) would predict a depleted yield for the low-energy Ga solar-\( \nu \) detector. In contrast, Ga would not be affected at all if \( \Omega_0 \) lies in the lower groups. Only at large angles \( (\sin^2 \theta > 0.2) \) is the mass discrimination nonunique. Dual ratios such as \( Y_{\text{CC}} / Y_{\text{IV}} \) and spectral shapes could resolve the mass ambiguity in this regime also and indicate the effects of high- and low-\( \Delta m^2 \) solutions on lower-energy solar \( \nu \)’s.

Occurrence of the index well above the highest flavor-oscillation marker value and a suppressed \( \text{NUEX} \) yield would be a strong signal for nonflavor \( \nu \) oscillations into sterile particles\(^4\) \( \nu_{\text{eR}} \) conversion into sterile \( \nu_{\text{eR}} \) due to \( \nu \) dipole moments\(^5\) results in \( \Omega_0 = 1 \) and a time variation in the \( \text{NUEX} \) yield correlated with magnetic activity in the sun. For certain areas in the parameter space, \( \nu \) passage through the Earth can even cause fresh \( \nu_\beta \) spectral distortions.\(^2\) With the real-time spectrometry of the \( ^{11}\text{B} \) approach, a day-night spectral redistribution in CC (I–III) events, or a daily cyclic

FIG. 2. Total-event-energy (E) distribution of solar-\( \nu \) yields in a \( ^{11}\text{B} \) detector from transitions to (a) the 5-MeV doublets (I and IV); (b) 2-MeV levels (II); (c) ground state of \( ^{11}\text{C} \) (III). Curves 0 are for the standard solar model and no \( \nu \) oscillations. The incident \( \nu \) energy is \( E_\nu = E + 1.982 \text{ MeV} \) (CC only).

FIG. 3. \( \nu \)-mass \( (\Delta m^2) \) discrimination by the dynamical index \( \Omega_0 \) in the \( ^{11}\text{B} \) solar-\( \nu \) detector.
change in $\Omega_0$ with an invariant NUEX yield, can be observed as dramatic proof of such an effect. $\Omega_0$ and the NUEX yield thus offer early warning of the prevailing scenario of $\nu$ oscillations while, ultimately, the spectral shapes are the deciders.

In addition to NUEX and $\nu_e$ capture in $^{11}$B, the ubiquitous $e-\nu$ scattering also occurs at a substantial rate. The sharp forward directionality of the $e-\nu$ events not only aids their separation from the broadly distributed CC (III) events in $^{11}$B but also provides proof of their solar origin.

A large ionization track chamber of the ICARUS-type using a B-rich hydrogenous organic liquid or a B-rich scintillating liquid could offer two alternative approaches to the $^{11}$B experiment. An underground $^{11}$B detector of these types, mounted so as to minimize external background, carries key devices to control the crucial problem of internal background, especially $\gamma$ rays ($E_\gamma$ > 4 MeV) induced by $\alpha$'s from U and Th impurities. Such a detector is live to all ionizing particles above some 500 keV. Thus, $\alpha$-induced $\gamma$ rays, e.g., are always accompanied by one or more dense tracks due to $\alpha$'s, outgoing particles or target recoils, or precursor tags such as $(\beta,\gamma)$'s preceding $\alpha$ decay of $^{212,214}$Po (or muon tracks in the case of muon-induced $\gamma$ rays), any of which can veto these events. Additional neutron vetoes of events like $(\alpha,n) \rightarrow (n,n'\gamma)$ and $(\alpha,n\gamma)$ arise from possible $p$ recoils during $n$ slowing down and the almost certain $\alpha+^{7}$Li tracks from the terminal $B(n,\alpha)$ reaction ($\sigma_{eff}$ = 800 b). This $n$-scavenging reaction also minimizes $(n,\gamma)$, the main source of high-energy $\gamma$ rays. Encouraged by these self-shielding and multiple-veto facilities we are developing a detailed design of the $^{11}$B solar-$\nu$ experiment.

The CC $\nu_e$ capture by $^{40}$Ar in a liquid Ar (L-Ar) chamber is a sensitive detector of the $^8$B solar-$\nu_e$ spectrum as first suggested by Raghavan. It is a major aspect of the ICARUS project (6.5 kiloton L-Ar or L-CH$_4$). Spectrometric as this approach is, its data alone may not be decisive without the aid of NUEX. To assess this possibility ($^{40}$Ar + $\nu \rightarrow ^{40}$Ar + $\nu_e + \gamma$), we performed shell-model calculations which located the main $M_1$ strength in $^{40}$Ar at 10.42 MeV and some 10% of it each in states at 6.1, 7.8, and 9.6 MeV. The solar NUEX of $^{40}$Ar, mainly to the 6.1 and ~10-MeV levels (Table I), is not encouraging.

Finally, the NUEX mode may also be applied to the Homestake solar-$\nu$ detector. The nuclear data indicate significant solar NUEX only in $^{35}$Cl (75% of the target). Experiments and our calculations show that NUEX, dominantly to a group of closely spaced proton-unstable levels at $\approx$ 8.7 MeV ($\nu + ^{35}$Cl $\rightarrow ^{34}$S + $p + \nu$), could be observed if stable $^{34}$S can be chemically separated and detected by isotopically selective single-atom laser or accelerator methods. We estimate that a ($= 10$) larger Cl $\nu$ detector could gauge the true $^8$B solar-$\nu$ flux.

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6. $^{10}$B(19.8%) is not favorable for solar NUEX or CC transitions.
10. Based upon the $p$-shell two-body interaction matrix element from D. J. Milliner, private communication.
12. In (3), $P_{CC} = \int S(E_\nu) W_\nu(W_\nu^2 - 1)^{1/2} F(Z, W_\nu) dE_\nu$, where $W_\nu = (E_\nu - E_{th} + 1)$ (in $m_0c^2$ units) and $F(Z, W_\nu)$ is the Fermi function.
15. B. Okun et al., Institute of Experimental and Theoretical Physics, Moscow, Report No. ITEP-20, 1986 (to be published).