New Tools for Solving the Solar-Neutrino Problem

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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 ^{11}B, ^{40}Ar, and ^{35}Cl as NUEX targets. The ^{11}B 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[1,2] 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.[3] 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 ($\nu + A \rightarrow A^* + \nu' \rightarrow A + \gamma$ or $A' + p,n,\alpha$) 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 $\bar{\nu}$ combined with ν_e or $\bar{\nu}_e$ capture by deuterons, as employed by Reines, Sobel, Pasierb[4] or as proposed by Chen for solar-ν detection.[5] Following the new avenues opened by the NUEX mode of ν detection, we consider three solar-ν targets: ^{11}B and ^{40}Ar (direct counting) and ^{35}Cl (in the Homestake chemical detector).

The ^{11}B system is uniquely tailored to the NUEX-CC method. The salient features are as follows: safely predictable NUEX (^{11}B$+\nu \rightarrow \nu' + {}^{11}B+\gamma$) strengths to a set of levels in ^{11}B (Fig. 1); a well-defined set of

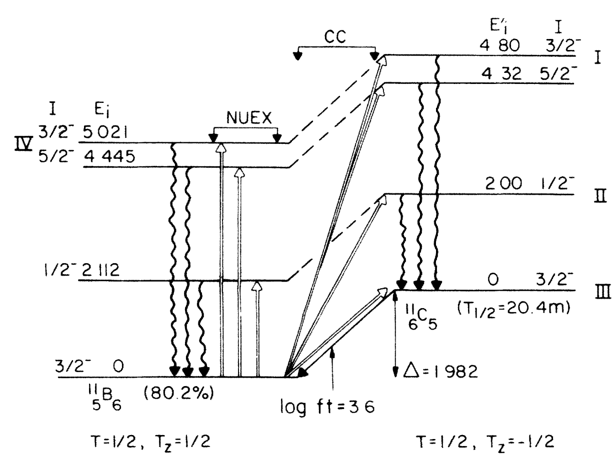

FIG. 1. The ^{11}B-^{11}C mirror system (E_i, E_i', Δ are in megaelectronvolts).

mirror levels in ^{11}C for CC ν_e captures; and a light nuclear mass and high isotopic abundance (80.2%).[6] They offer powerful facilities for a self-contained solution of the solar-ν 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* ν *oscillations;* and (c) CC captures with a set of differing thresholds promising *specific data on the structure of resonant* ν *oscillations in the sun.*

In standard electroweak theory, at low momentum transfers, NUEX proceeds only by the isovector (ISV) axial-vector current.[7] The relevant matrix element is $\frac{1}{2}g_A\langle\sigma\tau_z\rangle$ (g_A is the β-decay A/V coupling ratio). $\langle\sigma\tau_z\rangle$ can be estimated by shell-model calculations or by the ISV dipole ($M1$) spin-excitation strength $B_{\rm ISV}(M1)\uparrow$ derived from experiment. The NUEX strength is[7]

$$\lambda_{\rm NX}=\tfrac{1}{4}g_A^2\langle\sigma\tau_z\rangle^2=g_A^2\frac{4\pi}{3}\,\frac{1}{\mu_{\rm ISV}^2}B_{\rm ISV}(M1)\uparrow. \quad (1)$$

With $\mu_{\rm ISV}$ the ISV nucleon magnetic moment, $=4.7$, and $g_A=1.25$, then $\lambda_{\rm NX}=0.296B_{\rm ISV}(M1)\uparrow$. The specific NUEX yield rate $Y_{\rm NX}^i$ to the level of energy E_i is

$$Y_{\rm NX}^i=(G_{\rm F}^2/\pi)\phi_{\rm st}\lambda_{\rm NX}^iP_{\rm NX}^i,$$
$$P_{\rm NX}^i=\int S(E_\nu)(E_\nu-E_i)^2dE_\nu, \quad (2)$$

where $G_{\rm F}$ is the Fermi constant and E_i is the NUEX threshold. Only ^{8}B solar ν's are of interest here. $\phi_{\rm st}$ is their flux in the standard model and their normalized spectral profile $S(E_\nu)$[8] is used in the phase-space integral $P_{\rm NX}^i$. The NUEX events for all $E_\nu > E_i$ appear as γ 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 $B(M1)\uparrow$ measured by (γ,γ) and (e,e') scattering.[9] A shell-model calculation [which reproduces these $B(M1)$ well][10] gave the ratio of ISV-spin-$M1\uparrow$ to the $B(M1)\uparrow$ strength which was quenched by a factor 0.75[11] and used to scale the measured $B(M1)\uparrow$ to yield an "effective" $B_{\rm ISV}(M1)\uparrow$.

The CC ν_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 $E=E_i'+E_e$, where the recoil electron kinetic energy is $E_e=E_\nu-E_{\rm th}$. The CC threshold is $E_{\rm th}=E_i'+\Delta$ ($=1.982$ MeV). These levels in ^{11}C are isospin mirrors of the above three ^{11}B levels. The ν_e capture is related to the mirror NUEX mode by a rotation in isospin space. Thus for these three isodoublets $\lambda_{\rm CC}=4\lambda_{\rm NX}$, predicting the CC/NUEX yield ratio[12]

$$\omega_i=Y_{\rm CC}^i/Y_{\rm NX}^i=4P_{\rm CC}^i/P_{\rm NX}^i. \quad (3)$$

Since $S(E_\nu)$ and thus P^i do not depend on solar models,[8] ω_i is independent of nuclear and solar-structure physics. *Substantive deviations from (3) can arise only from new neutrino physics.*

Calculated parameters and specific yields from ^{11}B with use of $\phi_{\rm st}=4\times10^6/{\rm cm}^2$ sec[13] are listed in Table I. We anticipate (see below) a B-containing ionization track chamber with typical properties such as $\Delta E/E\approx10\%$ at 5 MeV, modest spatial resolution to identify the well-separated electron and γ-ray track patterns of a typical ν event, and backgrounds allowing a cutoff below a total event energy of ≈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' γ-ray tag; the ground-state capture appears as an isolated electron track. The transitions to the doublets I and IV at ~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 ^{8}B ν flux and ν oscillations with large mixing angles ($\sin^22\theta$)

TABLE I. NUEX and CC ^{8}B solar-ν yields (standard model) for ^{11}B and ^{40}Ar.

	NUEX					CC		
Target	E_i (MeV)	$B(M1)\uparrow$ (expt.) (μ_N^2)	$B_{\rm ISV}(M1)\uparrow$ (eff.) (μ_N^2)	$\lambda_{\rm NX}^i$	$Y_{\rm NX}^i$ [a]	E_i' (MeV)	$\lambda_{\rm CC}^i$	$Y_{\rm CC}^i$ [a,b]
^{11}B						0	1.55[c]	5760
	2.12	0.575(45)	0.472(50)	0.140(15)	415	2.00	0.562	1125
	4.45	0.90(9)	0.77(9)	0.228(27)	285	4.32	0.913	675
	5.02	1.253(50)	1.261(60)	0.375(18)	375	4.81	1.50	840
	4.45 + 5.02				660	Total		8400
^{40}Ar	6.1		0.192	0.058	11	4.38	4	1680[d]
	9.6		0.876	0.26	4			
	10.42[e]		2.82	0.835	5			

[a]Yield/(kiloton target element) yr.
[b]Yield for total energy $E>4$ MeV.
[c]From log $ft=3.6$.
[d]From Ref. 16.
[e]n-unstable, but yields 6.1-MeV γ by ^{40}Ar(n,γ).

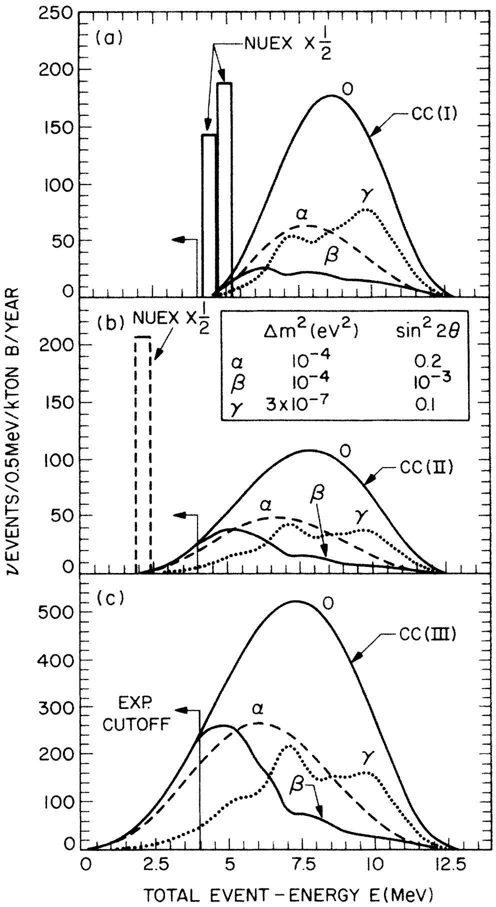

FIG. 2. Total-event-energy (E) distribution of solar-ν yields in a ^{11}B detector from transitions to (a) the 5-MeV doublets (I and IV); (b) 2-MeV levels (II); (c) ground state of ^{11}C (III). Curves 0 are for the standard solar model and no ν oscillations. The incident ν energy is $E_\nu = E + 1.982$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

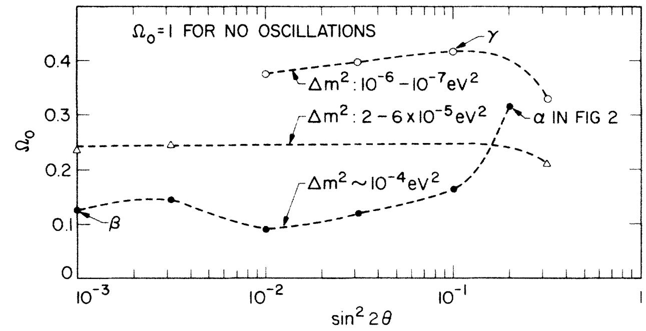

FIG. 3. ν-mass (Δm^2) discrimination by the dynamical index Ω_0 in the ^{11}B solar-ν detector.

and tiny mass parameters ($\Delta m^2 \sim 10^{-12}$ eV^2). *Resonant* ν oscillations in solar matter as suggested by Mikheyev and Smirnov[1] ($\Delta m^2 > 10^{-7}$ eV^2, small $\sin^2 2\theta$) 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 ν-oscillation parameters consistent with the Homestake ^{37}Cl result fall into two classes. In class I ($\Delta m^2 \sim 10^{-4}$ eV^2, $\sin^2 2\theta > 4\times10^{-4}$), only high-energy ν_e's (> 5–7 MeV) are resonantly converted. For $\Delta m^2 < 10^{-6}$ eV^2, $\Delta m^2 \sin^2 2\theta \sim 10^{-7.5}$ (class II), low-energy ν_e's are also converted. The strong energy dependence of ν_e flavor survival is typical of resonant ν oscillations in the sun.

Since the CC capture thresholds range from $E_{\rm th} = 2$ to 7 MeV, they respond to different parts of the ^8B ν_e spectrum (0–15 MeV) and act as unique indicators of such resonance effects. Curves marked (α, β, γ) in Figs. 2(a)–2(c) show the spectral response of the ^{11}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 β [Fig. 2(b), curve β and Fig. 2(c), curve β], in contrast to that of the higher-energy doublet [Fig. 2(a), curve β], illustrate the resonance effect of the first class. The marked shift of spectral weight away from the lower toward higher energies for solution γ, especially for the doublet, typifies that of the second class.

Interesting insight into the dynamics of resonant ν oscillations is offered by the relative yields of the four transitions. Using all the ν events of $E > 4$ MeV, a "dynamical index" Ω can be defined as $\Omega = Y^{\rm I}_{\rm CC} \times Y^{\rm II}_{\rm CC} / Y^{\rm IV}_{\rm NX} Y^{\rm III}_{\rm CC}$. Figure 3 shows a plot of Ω_0 (normalized to the no-oscillation Ω of 0.447) vs $\sin^2 2\theta$ for the parameter space of Ref. 3. For $\sin^2 2\theta < 0.2$, Ω_0 takes only the "marker" values $\Omega_0 \simeq 0.11$, $\simeq 0.24$, and $\simeq 0.40$, corresponding uniquely to the mass groups $\Delta m^2 \sim 10^{-4}$, $(2\text{–}6)\times10^{-5}$, and $< 10^{-6}$ eV^2, which largely categorizes the nature of ν-flavor oscillations and indicates its effect on the entire solar-ν spectrum. For example, an Ω_0 in the range of 0.4 (smallest Δm^2) would predict a depleted yield for the low-energy Ga solar-ν detector. In contrast, Ga would not be affected at all if Ω_0 lies in the lower groups. Only at large angles ($\sin^2 2\theta > 0.2$) is the mass discrimination nonunique. Dual ratios such as $Y^{\rm I}_{\rm CC} / Y^{\rm III}_{\rm CC}$ and spectral shapes could resolve the mass ambiguity in this regime also and indicate the effects of high- and low-Δm^2 solutions on lower-energy solar ν's.

Occurrence of the index well above the highest *flavor*-oscillation marker value *and a suppressed NUEX yield* would be a strong signal for *nonflavor* ν oscillations into sterile particles.[14] ν_{eL} conversion into sterile ν_{eR} due to ν dipole moments[15] results in $\Omega_0 = 1$ *and a time variation in the NUEX yield correlated with magnetic activity in the sun.* For certain areas in the parameter space, ν passage through the Earth can even cause fresh ν_e spectral distortions.[2] With the real-time spectrometry of the ^{11}B approach, a day-night spectral redistribution in CC (I–III) events, or a daily cyclic change in Ω_0 *with an invariant NUEX yield,* can be observed as dramatic proof of such an effect. Ω_0 and the NUEX yield thus offer early warning of the prevailing scenario of ν oscillations while, ultimately, the spectral shapes are the deciders.

In addition to NUEX and ν_e capture in ^{11}B, the ubiquitous e-ν scattering also occurs at a substantial rate. The sharp foward directionality of the e-ν 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[16] using a B-rich hydrogenous organic liquid or a B-rich scintillating liquid[17] 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 γ rays ($E_\gamma > 4$ MeV) induced by α's from U and Th impurities. Such a detector is live to *all ionizing particles* above some 500 keV. Thus, α-induced γ rays, e.g., are always accompanied by one or more dense tracks due to α's, outgoing particles or target recoils, or precursor tags such as (β,γ)'s preceding α decay of ^{212,214}Po (or muon tracks in the case of muon-induced γ 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,α) reaction ($\sigma_{\rm eff} = 800$ b). This n-scavenging reaction also minimizes (n,γ), the main source of high-energy γ rays. Encouraged by these self-shielding and multiple-veto facilities we are developing a detailed design of the ^{11}B solar-ν experiment.

The CC ν_e capture by ^{40}Ar in a liquid Ar (L-Ar) chamber is a sensitive detector of the ^{8}B solar-ν_e spectrum as first suggested by Raghavan.[18] It is a major aspect of the ICARUS project (6.5 kiloton L-Ar or L-CH_4).[16] Spectrometric as this approach is, its data alone may not be decisive without the aid of NUEX. To assess this possibility ($^{40}{\rm Ar} + \nu \rightarrow {}^{40}{\rm Ar} + \nu' + \gamma$), we performed shell-model calculations which located the main $M1$ 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 $\sim$10-MeV levels (Table I), is not encouraging.

Finally, the NUEX mode may also be applied to the Homestake solar-ν detector. The nuclear data indicate significant solar NUEX only in ^{35}Cl (75% of the target). Experiments[19] and our calculations show that NUEX, dominantly to a group of closely spaced proton-unstable levels at ≈ 8.7 MeV ($\nu + {}^{35}{\rm Cl} \rightarrow {}^{34}{\rm S} + p + \nu'$), 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 ($\approx \times 10$) larger Cl ν detector could gauge the true ^{8}B solar-ν flux.

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