New Prospects for Real-Time Spectroscopy of Low Energy Electron Neutrinos from the Sun

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Flavor-specific real-time spectroscopy of solar electron neutrinos (ν_e) from the $p + p$, ^{7}Be $+ e^-$, and CNO reactions in the Sun may become practical for the first time via a newly discovered class of ν_e reactions. Highly specific signatures of ν_e capture by the targets ^{176}Yb, ^{160}Gd, or ^{82}Se can discriminate against a background $\sim 10^7$ times larger than the ν_e signals. A high-quality liquid scintillator containing up to ~ 15 wt % Yb has been developed for observing these ν_e reactions. Experiments based on the new approach can, in principle, resolve basic puzzles set by current solar neutrino results and the underlying question of ν_e-flavor conversion. [S0031-9007(97)03069-X]

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Neutrinos of electron flavor (ν_e) are emitted dominantly in the energy range of 1 MeV in the proton-proton (pp) nuclear reaction sequence that generates the energy of the Sun [1]. The minor CNO cycle also adds to the solar ν_e flux, ϕ_e, at 0–1.7 MeV. Many methods have been developed for solar ν astronomy, albeit with compromises imposed by the extreme weakness of ν interactions. A "complete" method for detecting *sub-MeV* solar neutrinos in *real time*, specifying *e flavor*, *energy*, and *spectral detail* identifying the original solar *source S*, remains arguably one of the most elusive quests in all science. So far, only the vital goal of sub-MeV ν_e sensitivity has been attained by Gallex and Sage, detectors based on ν_e activation of ^{71}Ga and radiochemical assay [2] for a non-real-time measurement of the integral flux $\phi_e(\Sigma S(= pp, pep, {}^7\text{Be}, {}^{13}\text{N}, {}^{15}\text{O}, {}^8\text{B}))$ from *all* solar sources. The ^{71}Ga ν_e signal thus specifies the *e* flavor but not the original ν_e source in the Sun. A major advance will come from Borexino [3] (now in construction), a real-time spectroscopic device based on ν_X-electron scattering, to measure a flux $\phi_X(^7\text{Be})$ that depends on all the ν-flavors $X = e, \mu, \tau$. These data will thus specify the solar source but not the ν flavor.

Gallex and Sage now observe a low integrated flux, implying a seriously low $\phi_e(^7\text{Be})$ [2]. This result is incompatible with the specific flux $\phi_X(^8\text{B})$ from Kamiokande [4] because a $\phi(^8\text{B})$ of that size is inexplicable from a ^{7}Be-poor sun implied by the Ga result, given the reaction $p + {}^7\text{Be}$ is the sole source of ^{8}B in the Sun [5]. It is widely agreed that the apparent paradox cannot be resolved by astrophysical causes [6]. The only recourse in sight is energy-dependent conversion of ν_e to other flavors $\nu_{\mu,\tau}$ undetectable by Ga, caused by nonzero ν masses. This idea can be tested only by the *individual* fluxes $\phi_e(S)$—at least $\phi_e(^7\text{Be})$ or $\phi_e(pp)$, serious loss of either of which will lead to the Ga result. A $\phi_e(pp)$ short of its "standard candle" value is direct evidence for flavor conversion. If the Ga result is primarily due to the conversion of $\nu_e(^7\text{Be})$, it must be near complete, say, $\phi_e(^7\text{Be}) \sim 0.1\Phi_{\text{Sun}}$. In this case, the Borexino flux which depends also on converted flavors via the neu-

tral weak current, is $\phi_X(\text{Be}) \approx 0.28\Phi_{\text{Sun}} \sim 300\%$ larger. The value of $\phi_e(^7\text{Be})$ can thus expose disparity in fluxes of different flavor sensitivity for the same monoenergetic neutrino, directly proving flavor conversion.

There is thus renewed impetus to press uncompromisingly towards the complete solar ν_e detector defined above. This Letter describes a new path to this goal, opened by the discovery of low-threshold ν_e reactions on ^{176}Yb, ^{160}Gd, and ^{82}Se which can directly measure $\phi_e(S)$ with real-time signatures for discriminating ν_e signals from a $\sim 10^7$ times larger background. The only signatured sub-MeV reaction known yet, $\nu_e + {}^{115}\text{In}$ [7], could not be realized in practice because of the faint β radioactivity of ^{115}In. The new ν_e targets are *stable*, the long-sought breakthrough that removes this basic obstacle. On the technical side, a liquid scintillator with up to 15 wt % Yb, suitable for 100-ton-scale sub-MeV nuclear spectroscopy has been developed, defined a mode of detection of the new ν_e reaction [8].

Signal rate estimates for the new ν_e-reaction await ν_e cross sections deduced via $0°$ (p, n) reaction measurements [9] now in progress. A favorable nuclear structure of one of two ν_e-reaction channels in Yb, however, already sets the framework for a measurement of at least the key $\phi_e(^7\text{Be})$ flux. A signal $S = 60 - 180$ events/yr with $S/B \gg 1$ (background B measurable precisely *in vivo*) may be possible for the standard flux $\phi_e(\text{Be})$ with a 100 ton (10 ton Yb element) scintillator. The weaker $\phi_e(\text{N}, \text{O})$ and $\phi_e(pep)$ may also be accessible with longer lifetimes. All the new targets are sensitive to $\nu_e(pp)$ in principle, offering hopes for complete low energy ν_e spectral data with one or more of these detectors.

Flavor-specific ν_e detection is possible only by the charged current based ν_e capture: $\nu_e + I(Z) \rightarrow e + F(Z + 1)$. The e^- signal directly yields the incident ν_e spectrum, $E_e = E_\nu - Q_\nu [Q_\nu = M(F) - M(I)]$. With the low signal rates (~ 1 per day) and signal energies, practical observation of the undistinctive e^- signal of this reaction faces a formidable background from trace natural radioactivity present in all materials. In Borexino, with the undistinctive signal of a ν-scattered e^- in a liquid

scintillator, ν-grade radiopurity implies $\sim 10^{-16}$ g U, Th/ g [3], the feasibility of which was demonstrated recently by a 5 ton counting test facility (CTF) [10]. Such purity is ruled out generally for scintillators loaded with a foreign element such as I. The only hope for low energy ν_e detection is active background suppression with a highly discriminatory reaction signature as suggested 20 years ago [7]. If ν_e capture leads to an *excited* final state F^* with lifetime $\tau \sim 10^{-8} - 10^{-6}$ s, a delayed coincidence is set up: $[e^- + F^* \rightarrow$ delay $\tau \rightarrow F + \gamma]$. With $\tau \sim 100$ ns, a signal rate $S = 1$ event/d and a modest event localization within 1% of a typical ~ 100 m^3 volume, the random singles rate in the signal or gate window in the full detector can be $N \sim 10^7 S \sim 100$ Hz for a signal/ (random *coincidence* background) ratio ~ 1. This implies scintillator specific activities of Hz/m^3 (vs μHz/m^3 in Borexino) that permit the relatively common target purity of $10^{-10} - 10^{-9}$ and simpler detector shielding.

No tagged ν_e reactions on *stable* targets have been found up to now. The breakthrough occurred with the realization that *double β decay* prescribes the precise framework for discovering new tagged low energy ν_e reactions without the target stability problem. Isobaric triplets $[I(A, Z,$ even A, even Z, spin $0^+), F(A, Z + 1), FF(A, Z + 2)]$ are chosen specifically with $M(I) < M(F)$ to search for the extremely rare $\beta\beta$ decay $I \rightarrow FF$, energetically forbidding the far stronger normal β decay $I \rightarrow F$. I is thus *stable*, which meets the basic criterion for a solar ν target. The staggered odd-odd and even-even mass parabolas are structured so that a high $\beta\beta$ decay energy $[M(I) - M(FF)]$ usually results when $M(I) \sim M(F)$; further, the typical odd-odd nucleus F has *low-lying* spin 1^+ excited states F^*. These two aspects point to *low ν_e thresholds* $Q_\nu = [(M(F^*) - M(I)]$ and a $0^+ \rightarrow 1^+$ *spin sequence* most favorable for ν_e capture. Odd-odd nuclear levels in this region typically decay by low energy $E2$ or hindered $E1$ γ's, promoting *isomerism* in F^* or a daughter state of F^* that leads to delayed coincidence ν_e *tags*. Finally, β-decay data show surprisingly that $0^+ \rightarrow 1^+$ ν_e capture by nonspherical nuclei could be *strong*. A search immediately located a whole class of "$\beta\beta$-solar-ν_e" target candidates, ^{176}Yb, ^{160}Gd, and ^{82}Se. In this Letter I focus on the promising case, ^{176}Yb as an example [11].

In the Yb system [12] (Fig. 1), ν_e channel A feeds the isomeric state F_A^* (^{176}Lu 195 keV, $\tau = 50$ ns), triggering a prompt e_1^- in delayed coincidence with a 72 keV γ_2 ($\sim 50\%$ converted e) in the same spatial "cell." The event pattern [prompt $e_1 +$ (delay ~ 50 ns)γ_2/e] is the ν_e signature. With a threshold $Q_\nu = 301$ keV, channel A is sensitive to all ν_e sources including $\nu_e(pp)$. The scale of the γ_2-gated signal spectrum is $E_e = (E_\nu - 301)$ keV. A second channel B feeds F_B^* (^{176}Lu 339 keV) with $Q_\nu = 301 + 144 = 445$ keV, sensitive to all solar ν_e's except $\nu_e(pp)$. F_B^* decays promptly by $\gamma_1/e = 144$ keV (57% e, 43% γ). At this energy, γ_1/e is mostly confined within a ~ 10 ℓ cell of liquid (with $\sim 10\%$ Yb that helps contain the 144 keV photons by photoabsorption) and sums with
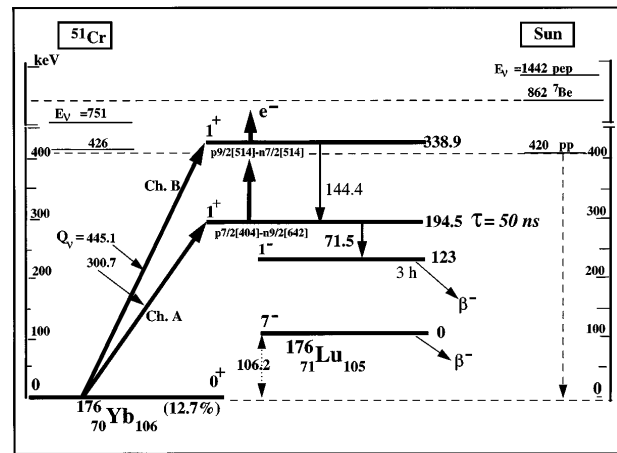

FIG. 1. Nuclear data for the Yb solar ν_e detector system. Only the total deexcitations of the levels are shown.

the simultaneous signal e_1. The delayed coincidence $[(e_1 + \gamma_1/e) + $ (delay 50 ns)$\gamma_2/e]$ in the same cell is the ν_e signature. Gated by $\gamma_2/e = 72$ keV common to A and B, the B signal energy scale is $E_e = E_\nu - (301 + 144) + 144 = (E_\nu - 301)$ keV, exactly as in A, the 0 energy signal appearing at 144 keV. A unique signal spectrum (schematically shown in Fig. 2) can thus be observed, directly yielding the incident ν_e spectrum offset by the lowest ν_e threshold. Figure 2 also shows the signal for a laboratory ν_e source of ^{51}Cr [13], well matched for a live calibration of the ^{176}Yb ν_e cross sections.

As well known, single-particle Gamow-Teller β transitions in heavy *odd* nuclei are hindered, $\log_{10} ft \gtrsim 6$, unless the initial $n(p)$ and final $p(n)$ configurations are spin-orbit doublets of the same Nilsson orbital, when $\log_{10} ft \sim 4.7 - 5$ [14]. In contrast, the 43 known $\log_{10} ft$ values of $0^+ \rightarrow 1^+$ β^- (and equivalent reverse) transitions from (even-even $A = 148 - 180) \rightarrow (odd, odd)$ nuclei show [11] that most of them are markedly faster; $\log_{10} ft = 3.5 - 4.4$ for 20 cases, many of them identified as spin-orbit partners. 4.5–4.9 (14 cases), 5–5.4 (7 cases), 5.5 for one case and $\log_{10} ft > 6$ in 2 cases. A $\log_{10} ft \sim 3.5$, normally classifiable as a "superallowed"
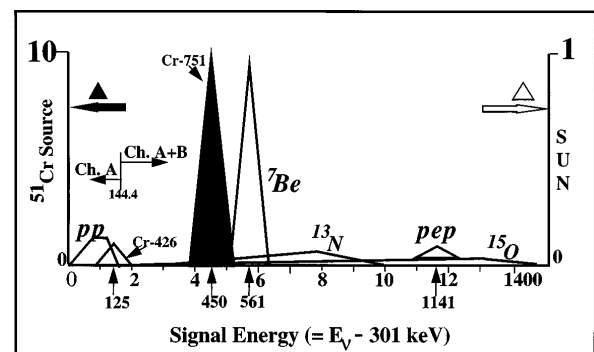

FIG. 2. Schematic signal patterns for $\nu_e + ^{176}$Yb by solar and ^{51}Cr ν_e's, illustrating energies and qualitative intensities of signal features.

transition, is unexpected at such low energies in such heavy nuclei. Channel B feeds ^{176}Lu (339 keV) with the ideal configuration $[514]p9/2 - [514]n7/2$ for which the above systematics suggest $\log_{10} ft = 3.7 - 4.2$, among the strongest transitions. The $\nu_e(pp)$-sensitive channel A to ^{176}Lu (195 keV), not ideal with n, p assigned nominally in different major shells, may have $\log_{10} ft \geq 5$. Standard solar signal rates *assuming* $\log_{10} ft(\text{ch. } A) = 5$ and $\log_{10} ft(\text{ch. } B) = 3.7$, are given in Table I.

Liquid scintillators loaded with the target element offer a practical route to real-time ν spectroscopy. A key factor is event localization, achievable best by segmenting the detector into many modules each with 2 phototubes [7,15,16]. It is the ν_e tag that makes unsheildable radiation from module walls or nearby phototubes manageable. Test modules of In-loaded liquid [16] or In-plastic scintillator [17] have demonstrated spectroscopy down to $\sim$25 keV and a spatial resolution of 10–14 cm ($\pm 1\sigma$) for $\sim$100 keV events by light time-of-flight, validating a localization index $\Lambda \sim 1 \, \ell/150 \, \text{k} \, \ell \sim 7 \times 10^{-6}$. Event localization with $\Lambda \sim 10^{-4}$ needed for a Yb detector is thus practical for a scintillator with at least similar photon yield.

The basic criterion for a viable Yb scintillator is high Yb loading with low loss of photon yield. A simple chemical technique has been developed in this laboratory for a Yb liquid scintillator that substantially meets the above criteria [8]. Yb was loaded as Yb-2ethyl-hexanoate $[\text{Yb}(\text{EH})_3; \text{EH} = \text{CH}_3(\text{CH}_2)_3\text{CH}(\text{C}_2\text{H}_5)\text{CO}_2]$ into common scintillator solvents. The $\text{Yb}(\text{EH})_3$, synthesized from the chloride in aqueous phase, was extracted into an organic phase. The extract was dried or filtered and concentrated by evaporating the organic phase. The $\text{Yb}(\text{EH})_3$, dissolved in a scintillator cocktail, yields a water-white, transparent Yb-scintillator liquid. Yb loading up to $\sim$15 wt % [$\text{Yb}(\text{EH})_3$ 50 wt %] was achieved. Significantly, a $\sim$10 wt % Yb [$\text{Yb}(\text{EH})_3$ 33%] scintillator retains $\sim$60% of the scintillation yield of the unloaded scintillator and a practical $\sim$40% yield even at 15 wt % Yb loading (see Fig. 3). Since the unloaded scintillator typically produces $\sim$10^4 photons/MeV a 10% Yb scintillator yields $\sim$6 $\times$ 10^3 photons/MeV, generally implying 200–300 photoelectrons/MeV. This signal yield exceeds that of In loaded scintillators [15–17]. The basic feasibility of liquid scintillators viable for ν_e spectroscopy with >10 wt % Yb is thus in hand.

With the removal of single uncorrelated events by the delayed-coincidence tag, background in the present approach is a non-neutrino *double event* closely imitating the ν_e-tag sequence. The first class of false tags is random coincidences of uncorrelated events, optimally allowable up to $\sim$30% – 100% of the signal, since they can be precisely measured *in vivo* at long delays over a wide time window and statistically removed from the signal spectrum. The sources (Table I) are natural activities specific to the target (Gd, Sm, Lu) and active traces (^{14}C, U, Th, K) common in the loaded scintillator. The false tag rate is $R \propto N_1 N_2 \tau \Lambda$, where $N_{1,2}$ is the singles rate in the full detector in the energy bins of e_1 and γ_2, and τ, the coincidence time window. The key factor is the localization $\Lambda \approx 10^{-4}$ [$\sim$300 cm^2 $\times$ 33 cm($\pm 2\sigma$) = 10 ℓ/100 k ℓ] readily achieved with a conservative spatial precision with the above photon yields for 10% – 12% Yb. A basic limit on N_1, thus on all the false-tag rates, is set by ^{14}C, with a β spectrum (0–160 keV) overlapping the γ_2 trigger. Limits on N_2 in signal windows are set mostly by impurities in the

TABLE I. Illustrative background estimates for the Yb detector [N_1, N_2 per 100 ton liquid scintillator with 10 ton Yb element; gate time 100 ns; event localization $\Lambda = 10^{-4}$ (10 ℓ/100 k ℓ); no discrimination of α particles or vicinity signal veto; B = random coincidence rate; S = signal rate from standard solar model fluxes].

Background source↓	N_1 50–150 keV	N_2 450–650 keV	N_2 1–1.2 MeV	N_2 0.2–1.5 MeV
U/Th/Ra (10^{-10})	20	10	5	50
K (10^{-7})	4	6	2	20
Lu (5 ppm)	0	250	540	3250
Sm (1 ppm)	2	0	0	0
^{14}C (10^{-18})^a	15	0	0	0
Rn(10 mBq/T LS)	2	2	2	5
PMT's (@ 1m)	4	2	2	5
Total N_1, N_2	47	270	551	3340
B/yr^b	0.7^c	4	8	50
Solar ν_e source→	pp	^{7}Be	pep	N,O
S/yr (A: $\log_{10} ft$ 5)	$\sim$19	$\sim$11	$\sim$1	$\sim$6
S/yr (B: $\log_{10} ft$ 3.7)		$\sim$172	$\sim$15	$\sim$100
S ($A + B$)/yr	$\sim$19	$\sim$183	$\sim$16	$\sim$106

^{a}^{14}C/^{12}C in Scint., Ref. [10].
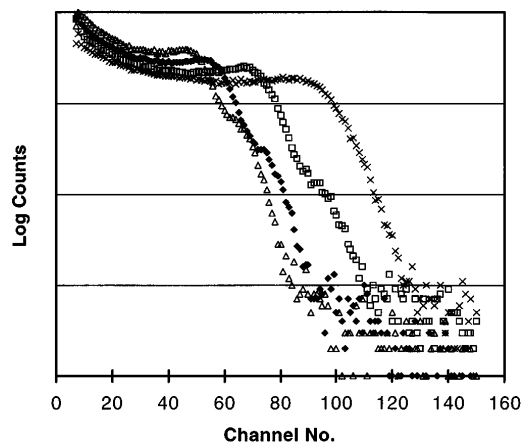^{b}3.15$N_1 N_2 10^{-4}$.
^{c}3.15$N_1^2 10^{-4}$.

FIG. 3. Scintillation photon yield vs elemental Yb loading measured by the Compton edges of the 854 keV line of ^{54}Mn in Yb-loaded scintillators in 25 mℓ counting vials. Data with crosses are for the unloaded scintillator (photon yield =1), squares for $\sim$5 wt % Yb (yield = 77%), diamonds for $\sim$9 wt % Yb (yield = 61%), and triangles for $\sim$13 wt % Yb (yield = 54%). Note the appearance of the full energy photo "bump" with increasing Yb loading.

target material. Illustrative estimates of false tag rates (Table I) show that the key contaminant will be 30 Gy ^{176}Lu (2.6% in Lu) since, as a chemical neighbor of Yb, Lu is less easily removed than other rare earths. The Yb purity levels listed in Table I are considered commercially practical.

The energies of the ν_e tag call for e_1, γ_1/e, and γ_2/e confined within a 10 ℓ vertex cell within a module, which suggests a veto by pulses exceeding a certain threshold in the surrounding modules within ~ 5 ns. A hard γ ray (e.g., 2.6 MeV of ^{232}Th from a module wall or a phototube), mimicking a low energy $e_1/\gamma_1/\gamma_2$ in one module, must shower the remaining high energy in adjacent modules, thus vetoing itself. False tags with α's may be separable by their slower pulse decay times compared to e/γ's in liquid scintillators. Even without these devices, the background (in Table I) is only a few percent of the key ^{7}Be signal and generally optimal for the full *pp*I, *pp*II, and CNO signal range.

The second class of background is *delayed cascades* in radio impurities, $[(\alpha, \beta, \gamma)'_1 + (\text{delay})\gamma'_2]$ in the windows $\gamma'_2 = 30 - 150$ keV, $150 < \gamma'_1 < 1200$ keV, and $10 < \tau < 100$ ns, which are not distinguishable from ν_e events. Natural traces of ^{85}Kr and ^{212,214}Bi-Po (Ra/Th) produce (β, γ) (Kr) and (β, α) (Ra, Th) delayed cascades, but well outside the tag windows. Yb activities made by intense cosmic rays above ground cannot be separated from the target. The longest Yb lifetime, however, is 50 d for ^{169}Yb with well-rejectable delayed cascades.

Deep under ground, activities are made *in vivo* by muons by capture, spallation, or reactions of GeV secondaries. In a segmented design, the muon track, depositing known minimum ionizing energy in the modules in transit, can be reconstructed fairly precisely. A *reacting* muon produces an unmistakably larger signal in a single module (or group) in the track, identifying the μ-reaction site. In a design with $\Lambda \sim 10^{-4}$ for low energy events, the μ-reaction sites can be located (less precisely due to remote secondary production and/or diffusion of the activity in its lifetime), with, say, $\Lambda \sim 10^{-3}$. All events from this site can be removed by a local blanket veto for a time T_v depending on the spallation frequency, measuring in the CTF (Gran Sasso) as 0.3 ton/d [10]. With the same rate for a $\sim 10\%$ Yb scintillator (the Yb/C atom ratio is only $\sim 1\%$), ~ 30 spallations/d occur in a 100 ton Yb detector, blocking $\sim 3\%$ of the detector per d. A local veto lasting up to $T_v = 3.3$ d thus costs $\leq 10\%$ overall dead time. Activities induced by slow neutrons leaking in undetected (e.g., marginally interfering 3 h ^{177}Yb) can be vetoed by the prompt n-capture γ rays (>5 MeV). The tagged activities themselves provide a rich set of markers for calibrating spectroscopic efficiencies and resolutions.

Every known delayed cascade in nuclei $A = 140 - 180$ within generous limits of the tag profile was examined for interference. Most candidates have lifetimes <20 h, thus rejectable with high efficiency at Gran Sasso. Of the 5 remaining candidates, the most likely are 8.2 d ^{171}Lu ($\tau =$

265 ns) and 5.3 d ^{155}Tb ($\tau = 9.4$ ns). Cross sections of GeV n/p reactions for these nuclides is estimated to be 1–2 mb [18], implying rates of $\sim 3.5 - 7$ yr^{-1} per 10 ton Yb at Gran Sasso. With false cascades barely fitting the tag profile, they do not offer major interference. Lower spallation rates in deeper underground detector sites provide a safety factor of ~ 100.

In summary, I present a new approach to solar neutrino astronomy for flavor specific, spectroscopic, real-time data, for the first time on sub-MeV electron neutrinos from the *pp*I, *pp*II, and CNO reactions in the Sun. A major objective is the key $\phi_e(^7\text{Be})$ flux for comparison with $\phi_X(^7\text{Be})$ to be measured in Borexino, for definitive evidence of flavor conversion. The basic detection technique for this approach has been defined by the development of Yb loaded scintillators in this laboratory. A first level analysis shows no major obstacles for constructing and operating a Yb detector based on current technology, with background at a few precent of the standard model signal from ^{7}Be solar neutrinos.

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