Indium-Loaded Liquid Scintillator for Low-Energy Solar-Neutrino Spectroscopy

Loren Pfeiffer, Allen P. Mills, Jr., R. S. Raghavan, and E. A. Chandross
Bell Laboratories, Murray Hill, New Jersey 07974
(Received 10 April 1978)

Liquid scintillators loaded with indium up to 200 g/l have been made to study the feasibility of detecting solar neutrinos by the ^{115}In inverse β reaction scheme of Raghavan. To evaluate the background contribution due to the natural β decay of ^{115}In, we have measured its β spectrum and find $T_{1/2} = 4.41(25)\times 10^{14}$ y and $E_{\text{endpoint}} = 482(15)$ keV. A direct counting indium detector of solar neutrinos appears feasible and possible configurations for such an experiment are briefly discussed.

It is widely believed that neutrinos (ν) would provide a unique and sensitive probe of stellar interiors. In the pioneering experiment of Bahcall and Davis,[1] employing the $^{37}\text{Cl}(\nu,e^-)^{37}\text{Ar}$ inverse beta reaction, the measured neutrino flux ($E_\nu = 5-10$ MeV) is far lower than expected on the basis of standard solar models. The source of this discrepancy could be either a serious flaw in these models or unknown phenomena in neutrino propagation.[1] The solar neutrino flux at low energies is dominated by the model-independent ν flux ($E_\nu < 0.42$ MeV) from the basic p-p reaction. Detection of these neutrinos is a crucial step towards resolving the solar-neutrino problem.

To carry out this program, an attractive approach which takes advantage of the unique properties of the reaction $^{115}\text{In}(\nu,e^-)^{115}\text{Sn}^*$ has been suggested by Raghavan.[2,3] This detection scheme has a ν energy threshold of only 128 keV and thus has the necessary high sensitivity to p-p neutrinos to settle the question of neutrino propagation. Unlike radiochemical experiments such as $^{71}\text{Ga}(\nu, e^-)^{71}\text{Ge}$ which have been proposed[1] to measure the integrated flux of p-p neutrinos, the ^{115}In experiment counts neutrinos directly and is capable of yielding the *energy spectrum* of the detected solar neutrinos. Such a spectrum, yielding the flux of p-p neutrinos and independently, that from the ^{7}Be decay in the sun, would not only reveal the source of the present discrepancy but also give specific data on the solar interior complementing the ^{37}Cl results on high-energy neutrinos. Thus the ^{115}In experiment, together with the presently running ^{37}Cl experiment, would lead to complete information on all the three parts of the proton-proton reaction sequence in the sun, resulting in compelling guidelines to future solar models. In this Letter, we report on the feasibility of this approach and describe the successful fabrication and operation of a practical radiation detector containing indium.

As pointed out by Raghavan,[2] ^{115}In provides a unique ν detection signature: A neutrino of energy E_ν induces the inverse β reaction,

$$\nu + {}^{115}\text{In} \to e^- + {}^{115}\text{Sn}^*, \tag{1}$$

with a threshold of 128 keV. The energy ($E_\nu - 128$ keV) appears promptly as the kinetic energy of the emitted electron. The 614-keV level of $^{115}\text{Sn}^*$ (see inset of Fig. 2) then decays with a 3.26-μsec half-life into coincident γ rays of 116 and 498 keV. To define this signature and distinguish it from background, it is important that a radiation detector incorporating In have sufficiently good time, energy, and spatial resolution. Energy resolution is also required as we wish to measure the energy spectrum of the prompt electrons which gives directly the neutrino energy spectrum.

The cross section[2,3] for Reaction (1) implies that a detector containing 3.7×10^6 g In is needed to yield a neutrino event rate of ~ 1/day. It is thus desirable that the detector be easily scaled to large dimensions and be capable of operating stably for long periods. Organic liquid scintillators have many of the necessary properties for this experiment; however, until now no scintillator liquid containing significant concentrations of In has been reported. We have found a new liquid scintillator based on the solvent phenethyl alcohol. This solvent combines the high solubility for polar compounds characteristic of alcohols with the efficient energy-transfer properties associated with phenyl groups. The phenethyl alcohol scintillator yields 62% of the light of the best p-xylene solution[4] and in addition is a good solvent for indium trifluoroacetate. The scintillation efficiency of this solution falls roughly exponentially with increasing In concentration reaching e^{-1} at 80 g In/l. At this concentration the scintillator liquid of a neutrino detector containing 3.7×10^6 g In would fill the volume of a cube 3.5 m on a side. We have observed no deterioration in the scintillation efficiency of these In-loaded solutions over periods of many months.

Figure 1 shows the measured spectra from three sources (^{207}Bi, ^{113}Sn, and ^{51}Cr) taken with a 1.25-l fused-silica cell containing 51.2 g In/l in the phenethyl alcohol scintillator. Photomultiplier tubes (5 in. diam) were coupled to the ends of the cylindrical cell and the energy pulses summed in coincidence with $2\tau = 100$ nsec. The ^{51}Cr spectrum illustrates the photopeak efficiency of the detector for a 320-keV γ ray. The Bi^{207} spectrum shows the Pb x-ray photopeak at 75 keV and the weak (8%) conversion (sum) peak at 1.063 MeV. The ^{113}Sn spectrum shows the In-x-ray photopeak (24 keV) and the strong (49%) conversion (sum) peak at 393 keV. These conversion-electron sources, enclosed in thin-walled (10 μm) glass tubes were placed in the liquid at the center of the cell.

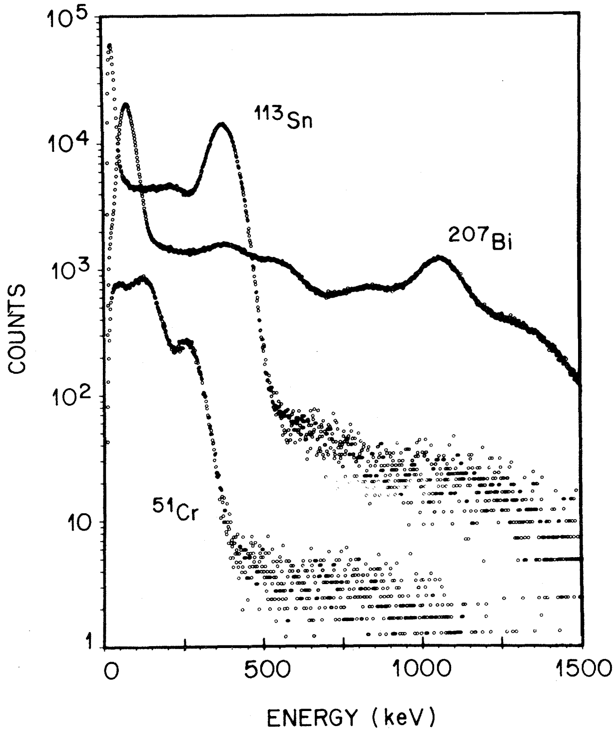

FIG. 1. Measured spectra using a 1.25-l cell with 51.2-g-In/l scintillator. This solution has a density 1.142 g/cm^3 and contains the proportions 1319.1 g phenethyl alcohol, 69.9 g ethylene-glycol, 301.1 g indium trifluoroacetate, 8.0 g PPO (2,5-diphenyl-oxazole), and 0.8 g *bis* MSB [*p*-*bis*(*o*-methylstyryl) benzene].

To evaluate the background expected from the natural radioactivity of In, we have measured the ^{115}In β spectrum. The cell filled with 51.2-g-In/l solution was placed in a 4-ton Pb enclosure. The summed photomultiplier pulses were counted in anticoincidence with a large plastic detector to veto events associated with cosmic rays. Figure 2 shows the energy spectrum obtained with the In-loaded solution along with a background spectrum obtained with a 51.2-g-Sn/l loaded scintillator. The difference of these two spectra is a measure of the In radioactivity. Indium is known to have a high neutron cross section. Separate experiments showed that ambient neutrons which were present caused an extra background by activating the In. This background was removed from the data by subtracting a spectrum proportional to that obtained with an external Pu-Be neutron source (Fig. 3). The area of the β spectrum is 16.0(9) counts/sec from 64.0 g ^{115}In. This implies a half-life $T_{1/2} = 4.41(25)\times 10^{14}$ y for ^{115}In which is con-

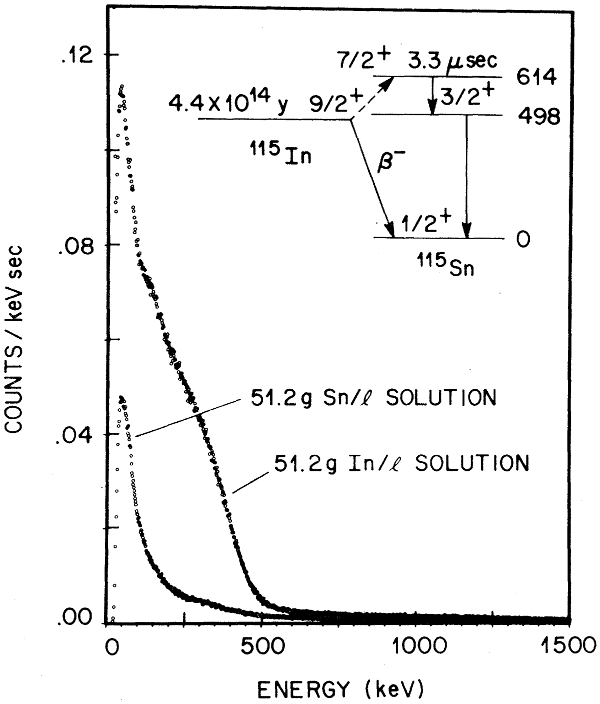

FIG. 2. Raw β spectrum obtained with 51.2-g-In/l scintillator and background spectrum obtained with 51.2-g-Sn/l loaded scintillator. Inset shows the ^{115}In-^{115}Sn nuclear energy levels.

sistent with the result of Watt and Glover[5] but lower than that of Beard and Kelly.[6] The dashed line in Fig. 3 is a polynomial fit to the data after unfolding the measured energy resolution, $\Delta E(\text{keV}) = 5.16\sqrt{E}$ where E is the energy in keV. The β^- endpoint obtained is 482(15) keV, in good agreement with the adopted tabular value,[7] 486(9).

In a practical solar-neutrino detector the principal contribution to the background will be due to the natural β decay of ^{115}In ($N = 10^6$/sec singles rate). The magnitude of this background problem can be appreciated by noting that for a signal-to-noise ratio $S/N = 1$, background reduction of 10^{11} must be achieved. Raghavan has shown[2] that this could be done, in principle, by means of a modular neutrino detector and by using a triple-coincidence signature. Following this, the detector volume must be divided into many cells. An event in one of the n cells can be considered a neutrino-capture candidate if it is followed within $\Delta t_1 \simeq 10$ μsec by a second pulse in the same cell, corresponding to the detection of the 116-keV γ ray of $^{115}\text{Sn}^*$. The total rate of such events due to random coincidences is $A \simeq N^2 \Delta t_1/n \simeq 10^7/n$ per second. The cell size is chosen to be just large enough to ensure the local detection of the 116-keV γ ray. We then require that the cascading 498-keV γ ray be detected in a neighboring cell within a resolving time $\Delta t_2 = 5$ nsec which is typical for these liquid scintillators. This requirement reduces the rate A by a factor $\simeq 30N' \times \Delta t_2/n$, assuming that the 498-keV γ ray is detected in one of the ~30 neighboring cells. N' is the counting rate near 500 keV and Fig. 3 shows $N' \simeq 0.01N$ at the most; the reduction factor is then $1.5\times 10^{-3}/n$. Therefore the effective random rate $A' \simeq A\, 1.5\times 10^{-3}/n \simeq 1.5\times 10^9/n^2$/day. With $n = 4 \times 10^5$ we can achieve $S/N \simeq 100$. This estimate is actually pessimistic since the detection of the 498-keV γ ray will be largely (~85%) by Compton scattering in two or more cells and the requirement of a fast sum coincidence of these pulses would yield reduction factors much larger than those used here. Thus the background from the In β decay can be suppressed entirely.

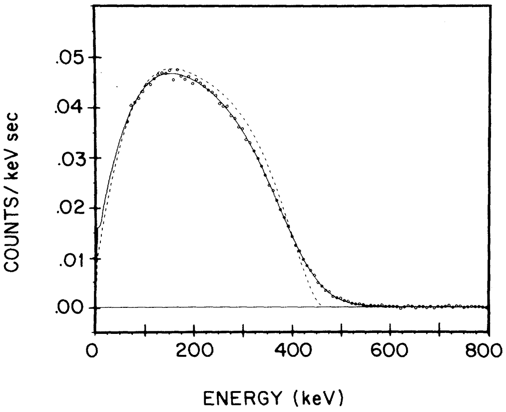

FIG. 3. Background-corrected ^{115}In β spectrum. The solid line is a polynomial fit to the data; the dashed line is the fit with the energy resolution of the In-loaded scintillator unfolded.

A straightforward geometry to carry out this experiment is a stack of 40 000 tubes (1 m long × 5 cm diameter) containing 50-g-In/l liquid scintillator and stacked in a hexagonal array with photomultipliers on the ends of each tube. It appears possible to divide the 1-m tubes electronically into 10 sections using the ratio of pulse amplitudes seen by the paired photomultipliers.[8] Such an array would have an overall detection efficiency ~50%, because of the requirement that the 498-keV γ ray be detected in a different cell from the one where the electron and the 116-keV γ ray are detected. Thus a 3.7-ton indium detector would count 0.5 events per day due to solar $p+p$ neutrinos. Techniques of light collection from large-volume scintillators using wavelength-shifter light guides[9] are expected to reduce the number of photomultipliers needed to as few as 5000. These possibilities and detector geometries suitable to these methods are being actively studied.

While the random background associated with the In β decay can be rejected by the triple-coincidence requirement, this is not possible for other types of background[3] such as chance coincidences between In β-decay pulses and multiply scattered background γ rays. Such background events could arise from internal or external bremsstrahlung or from Compton-scattered γ rays from various sources internal or external to the detector. Bremsstrahlung from the In β spectrum can be excluded by the requirement that the γ-cascade energies sum to 614 keV, since the β endpoint is only 482 keV. A consideration of the bremsstrahlung energy spectrum shows[3] that this is possible if the detector energy resolution is better than ~200 keV. The results of Fig. 1 show that this requirement is more than satisfied. Compton scattering of a background γ ray could simulate the $^{115}\text{Sn}^*$ γ cascade produced by a ν capture; this requires that the energy of the background γ ray be at least 614 keV, that it deposit 614 keV in two Compton events of ~116 and ~498 keV in two different neighboring cells, and that the energy in excess of 614 keV be lost from the sensitive volume of the neutrino detector. Such exact simulations of a 614-keV cascade must be $<0.2/\mathrm{sec}$ in a full-scale detector. If the sources of background γ rays are internal to the active detector volume, this limit could be achieved since the ensemble of cells acts as an efficient total-energy detector and thus γ rays with $E>614$ keV can be discarded. Sources of γ rays located external to the detector are amenable to active and passive shielding. To make a simulation, an ~1 MeV γ ray from an external source must undergo at least one forward scattering [to produce a low-energy (~100 keV) event] and one large-angle scattering to allow the escape of ~400 keV from the detector. This probability is a few percent and decreases with increasing energy of the γ ray. Further, these events are likely to be observed only in the outer parts of the neutrino detector. Thus we expect that γ-ray background events could be suppressed below the limits mentioned above.

The discussion of background requirements given above is made with p-p neutrinos in mind. Neutrinos from ^{7}Be (860 keV) are monoenergetic and occur well above the In β-decay endpoint. At these energies the background rate would be smaller by a factor of 10^{-2} and thus detection of these neutrinos, even though only 20% as abundant as the p-p neutrinos, is relatively less difficult.

In summary, we have constructed a radiation detector with the required energy- and time-resolution properties for low-energy solar-neutrino spectroscopy using Reaction (1). The background from the In decay can be adequately suppressed. Further experimental work is in progress to study the γ-ray background.

We take pleasure in thanking T. Kovacs for his valuable aid in the computer analysis of the data and W. L. Brown and W. F. Brinkman for their continuing interest and encouragement.

---

[1] J. N. Bahcall and R. Davis, Jr., Science 191, 264 (1976).

[2] R. S. Raghavan, Phys. Rev. Lett. 37, 259 (1976).

[3] R. S. Raghavan, in Proceedings of a Conference on the Status and Future of Solar Neutrino Research, Brookhaven National Laboratory, January 1978, edited by G. Friedlander (to be published).

[4] J. B. Birks, *Theory and Practice of Scintillation Counting* (Pergamon, Oxford, 1964).

[5] D. E. Watt and R. N. Glover, Philos. Mag. 7, 105 (1962).

[6] G. B. Beard and W. H. Kelly, Phys. Rev. 122, 1576 (1961).

[7] S. Raman and H. J. Kim, Nucl. Data Sheets 16, 195 (1975).

[8] J. L. Alberi and R. L. Chase, Brookhaven National Laboratory Report No. 22791, 1977 (unpublished); A. Benvenuti *et al.*, Nucl. Instrum. Methods 125, 447 (1975); N. A. Mullani *et al.*, Nucl. Instrum. Methods 125, 447 (1975); N. A. Mullani *et al.*, IEEE Trans. Nucl. Sci. NS-25, 180 (1978).

[9] W. A. Shurcliff, J. Opt. Soc. Am. 41, 209 (1951); R. L. Garwin, Rev. Sci. Instrum. 31, 1010 (1960).

ERRATA

PRODUCTION OF $\Upsilon(9.5)$ IN e^+e^- ANNIHILATION AND PHOTOPRODUCTION. Gordon J. Aubrecht, II, and Walter W. Wada [Phys. Rev. Lett. 39, 978 (1977)].

Equation (10) should read

$$\frac{\Gamma_l}{\Gamma_h}=\frac{81\pi}{10(\pi^2-9)}\,\frac{\alpha^2 e_Q{}^2}{\alpha_s{}^3}=0.43 e_Q{}^2.$$

STIMULATED PHONON EMISSION. W. E. Bron and W. Grill [Phys. Rev. Lett. 40, 1459 (1978)].

The seventh and eighth lines of column 2 on page 1461 should read "... yields a branching ratio of the transitions (3 → 1)/(3 → 2) of ~10."