nucleus. The cross section for the production of such a coherent state should be enhanced by a factor of the order of the number of contributing states. The extreme assumption of perfect unitary symmetry implies an equivalence of nucleons and hyperons such that it costs the same energy to change a neutron to a Λ in any orbit. The SU(3) multiplets contain coherent linear combinations of all these states and also include states in which a nucleon is transformed into a Σ as well. Because of symmetry breaking, the Σ component of the SU(3) analog state must clearly be rejected in view of the large Σ-Λ mass difference, while the Λ component of the SU(3) state must be split by the difference between Λ-nucleon and nucleon-nucleon interactions. However, some coherence and enhancement may still remain if there are groups of states which are approximately degenerate. One should then expect to see some kind of a peak, possibly with some structure, in the pion spectrum at low momentum transfer in Reaction (1). The observed cross section should be smaller and the observed width greater than that predicted from pure SU(3) symmetry.

Another reaction which might be of interest is

$$K^- + (Z,A) \to \pi^+ + \pi^- + {}_\Lambda(Z-1,A). \qquad (2)$$

This reaction has two outgoing charged particles which can be measured. This is analogous to the $(p, 2p)$ experiments for probing nuclear structure.[5] The advantage of this type of reaction is that the angles and energies of the outgoing pions can be set at values corresponding to zero momentum transfer to the residual nucleus.

The author would like to thank R. H. Dalitz and H. W. Wyld, Jr., for stimulating discussions.

---

*Work performed under the auspices of the U. S. Atomic Energy Commission.

†On leave from the Weizmann Institute of Science, Rehovoth, Israel.

[1]R. H. Dalitz, Proceedings of the Athens Topical Conference on Recently Discovered Resonant Particles, Athens, Ohio, 1963 (unpublished), p. 234.

[2]A. Deloff and H. H. Wyld, Phys. Letters 12, 245 (1964).

[3]Such states have been examined by R. J. Oakes, Phys. Rev. 131, 2239 (1963); V. I. Ogievetskij and H. Ting-Chang, Phys. Letters 9, 354 (1964); Y. Tomozawa, Phys. Rev. Letters 13, 512 (1964).

[4]J. B. French, Argonne National Laboratory Report No. ANL-6878, 1964 (unpublished), p. 181.

[5]H. Tyren, P. Hillman, and Th. A. J. Maris, Nucl. Phys. 7, 10 (1958); H. J. Lipkin, Argonne National Laboratory Report No. ANL-6878, 1964 (unpublished), p. 481.

NEW APPROACH TO THE DETECTION OF SOLAR NEUTRINOS VIA INVERSE BETA DECAY*

F. Reines and R. M. Woods, Jr.
Department of Physics, Case Institute of Technology, Cleveland, Ohio
(Received 9 November 1964)

Theoretical calculations for the energy generation processes in the sun predict[1] the production of B^8 in such quantities that a neutrino flux at earth of $(2.5 \pm 1)10^7$ ν_e/cm^2 sec and end point of 14.06 MeV results from beta decay of this nuclide. It is of great interest to check this prediction since it relates to the entire theoretical picture of the sun's deep interior condition. To date, two methods of detection have been suggested, that of Davis[2] which employs a radiochemical technique to observe inverse beta decay of Cl^{37}, and the direct counting approach of Reines and Kropp[3] in which it is proposed to detect the recoil electron from elastically scattered solar neutrinos. The point of this communication is to discuss yet another approach to the problem, using inverse beta decay.

It is desirable to measure the neutrino spectrum and the direction from which the signals emanate in order to label separately the source and the responsible reaction. The radiochemical approach is limited in that it gives the response averaged over a spectrum and with a time constant determined by the half-life of the product nucleus. Also in the radiochemical approach the direct association with the sun can only be made by use of the 7% annual inverse-square variation of intensity. The elastic-scattering experiment, although capable of fairly precise[4] (~15°) directional and energy determination (e.g., by using a multiplate spark

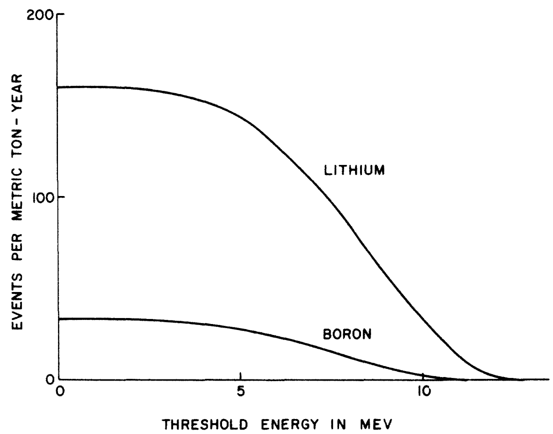

FIG. 1. Product electron spectrum vs threshold electron energy for Li and B neutrino targets.

chamber), has the logical difficulty that it is not complete because a negative result in itself could be attributed either to a different solar mechanism or to the absence of the elastic scattering process.[5]

A search of the nuclides reveals two which look promising as neutrino targets in a direct counting experiment, B^{11} and Li^7. The reactions[6] under consideration are

$$B^{11}+\nu_e \rightarrow C^{11}+e^-,$$
$$Li^7+\nu_e \rightarrow Be^7+e^-. \quad (1)$$

Figure 1 shows the reaction rate due to solar neutrinos in units of events/ton year for normal boron (81.2% B^{11}, 18.8% B^{10}) and lithium (92.6% Li^7, 7.4% Li^6) as a function of the lower limit chosen for the energy of the product electron. The curves are deduced from the predicted ν_e flux and spectrum and the known ft values[7] for B^{11} and Li^7, allowing only for transitions to the ground state of the product nuclei.[8] The interaction cross section used in the calculation is[9]

$$\sigma(E_\nu)=\mathcal{C}(E_\nu-a)[(E_\nu-a)^2-1]^{1/2}, \quad (2)$$

where

$$\mathcal{C}=\frac{2\pi^2}{c}\left(\frac{\hbar}{mc}\right)^3\frac{\ln 2}{ft_{1/2}}=\frac{2.62\times10^{-41}}{ft_{1/2}}(\mathrm{cm}^2),$$

and

$$a=Q-1.$$

Q is the threshold energy in mc^2 units for the nuclide under consideration and the other familiar quantities are in cgs units. Table I lists the relevant values for $ft_{1/2}$, $\mathcal{C}$, and Q.

Table I. Constants for evaluation of interaction cross sections.

Target nuclide	Threshold energy, Q (mc^2 units)	$(ft_{1/2})^{-1}$	$\mathcal{C}$ (cm^2)
Li^7	1.69	5.0×10^{-4}	1.30×10^{-44}
B^{11}	3.89	2.5×10^{-4}	0.66×10^{-44}

An additional feature of these reactions, the extent of the angular correlation $f(\theta)$ between the direction of the incident neutrino and the product electron, is also of interest and merits careful study. The form of the angular correlation is[9]

$$f(\theta)=1+\alpha\cos\theta. \quad (3)$$

In discussing our experimental technique we will set a limit on the value of α which can be useful in correlating the signal with the neutrino direction.[10]

Proposed experimental arrangement.—Consider a thin, large-area slab of target material (Li or B) surrounded on both sides by a detector. We assume here that the detector is an organic scintillator. It is evident in such an arrangement that the number of target nuclei visible to the scintillator is limited by the range of the product electrons and hence that the detection efficiency varies inversely as the charge of the target nucleus.

Figure 2 shows the total number of events

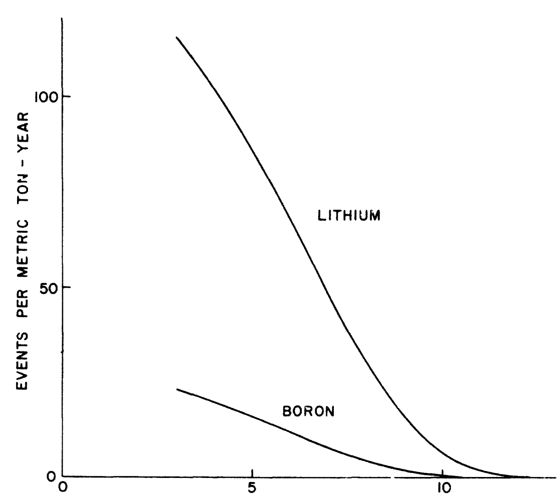

FIG. 2. Count rate for flat slab (2.5 cm Li, 0.5 cm B) vs threshold energy for product electron.

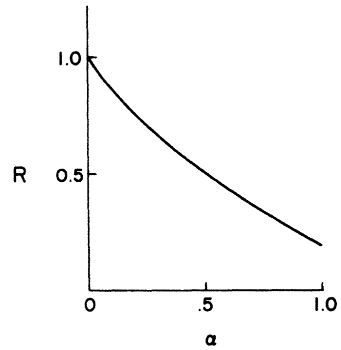

FIG. 3. Ratio of backward to forward signal as a function of the asymmetry parameter α.

per metric ton year in which the energy deposited in the scintillator is $>E$ (MeV). For energies >6 MeV deposited in the scintillator, it is estimated that a slab thickness of 2.5 cm for the Li target and 0.5 cm for the B target (on which Fig. 2 is based) gives results reasonably close (within 15%) to those for slabs with a thickness equal to the maximum product electron range.

Figure 3 shows the results of a calculation in which the slab is taken as oriented broadside to the sun. In this figure, the ratio, R, of counts on the side nearest the sun to those on the side furthest from the sun is plotted against the asymmetry parameter, α, of Eq. (3). The results for boron and lithium are identical because the slabs chosen have equal energy thicknesses.

The information in Figs. 2 and 3 can be combined with statistical considerations to relate, as a function of α, the mass of detector required to associate the result with the direction of the sun. So, for example, if we wish to establish, in one year, the direction of the

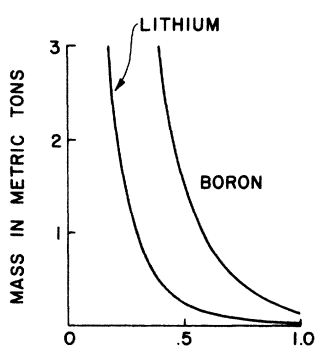

FIG. 4. Target mass needed to detect direction of the sun.

sun by a value of R which differs from unity by two standard deviations, then the required mass is shown in Fig. 4 as a function of the asymmetry parameter α. In this example, the minimum energy deposited in the scintillator is taken to be 6 MeV; background is neglected so the curve represents only a lower limit.

Setting aside for the moment the question of directional discrimination, Fig. 2 will give the total target mass required for the two target materials considered if we choose any desired signal level. Figure 5 shows a conceptual schematic of the detector which is at present under detailed design. Detectors in which the optical requirements are more radical have been built and successfully operated in this laboratory.

The liquid thickness is chosen to absorb an 8-MeV β^- travelling normal to the target sheet. A variant of the above scheme is one in which every third sheet is made of target material. In this case, signals should be expected in alternate layers. If it is desired to make a directional test, the target sheets would be placed in every other position and the ratio of counts in alternate layers measured.

In the actual detector we will separate the photomultiplier tubes from the scintillating liquid with a nonscintillating optically matching medium so as to flatten the detector response. Furthermore, all the sheets will be immersed in a common scintillating liquid and the entire unit enclosed in an anticoincidence shield. For

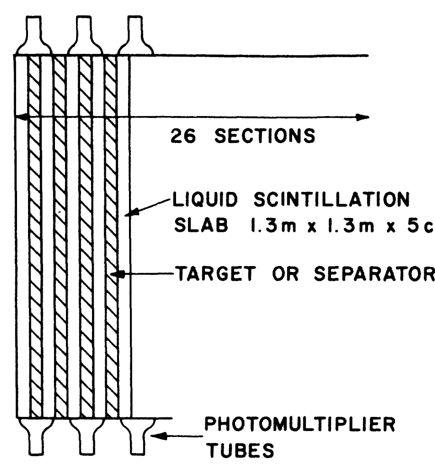

FIG. 5. Schematic of detector. The target or separator sheets will be coated white and wrapped in thin plastic, the latter to produce total internal reflection of the scintillation light.

a directional array we would plan to mount the entire detector on an appropriate turntable so as to maintain its face broadside to the sun.

Backgrounds.—The backgrounds in the detector arrangement under discussion arise from cosmic rays and natural radioactivity. The most drastic measures planned to reduce these backgrounds are to locate the detector 2000 ft underground in an area reasonably free of radioactivity (salt mine), and surround the entire detector with the anticoincidence detector mentioned earlier. For the purpose of discussion we assume the detector to be made of 25 Li plates arranged as shown in Fig. 5. Such a detector would give 70 counts/year with product electron energy >6 MeV.

Cosmic rays.—Based on measurements[11] in our underground laboratory, the number of cosmic rays 2000 ft down which penetrate the detector is expected to be ~1/min. This can be reduced with the anticoincidence blanket[12] by a factor of at least 10^4, or to <50/year. However, this rate includes pulses ranging over the entire spectrum and it is estimated that $\sim\frac{1}{10}$ of the spectrum should be in the region of interest, i.e., 6-13 MeV, leaving a background <5/year. This background is quite acceptable in view of the expected signal. It is, of course, always possible to go deeper underground if it should turn out that the signal is less than expected and it might even be desirable to do so as a further check on the cosmic rays as a source of background.

Neutrons.—Neutrons from any source could, if they were captured by the target nuclei (Li^7 or B^{11}), give rise to a high-energy electron via beta decay, so masking the neutrino signal. (Li^8 decays with an end-point energy of 12 MeV; B^{12} has an end point of 13.4 MeV.) Fortunately, the thermal neutron capture cross sections are very small for Li^7 and B^{11} (36 mb, 5 mb) and quite large for Li^6 and B^{10} (945 b, 4000 b). Furthermore, Li^6 and B^{10} do not produce energetic scintillation pulses as a result of neutron capture. This means that in normal lithium metal the background produced by capture of a neutron in Li^7 is reduced by a factor of 2000 because of the shielding provided by the Li^6. For normal boron the self-shielding factor is 15 000. These figures are conservatively low because of the neutron trapping which can be expected in the layered scintillator.

Various sources of neutrons have been considered: spontaneous fission, muon capture, photoneutrons—and none appear to be troublesome. Spontaneous fission of U^{238} gives rise[13] to 6.5×10^{-3} fission/g U^{238}/sec. The mass of U^{238} in a gram of moderately clean material is $<10^{-9}$ gram.[14] On this basis 5 metric tons of detector material (1 ton Li, 4 tons other) will contain $<5\times10^{-3}$ g of U^{238} and, if we assume two neutrons/fission, will produce $<6.5\times10^{-5}$ neutron/sec. If we consider the self-shielding and the fraction ($\sim\frac{1}{2}$) of the resultant decay electrons from Li^8 which falls in our energy region (6-13 MeV), we can expect $<\frac{1}{2}$/year due to activation of Li^7 by neutrons from spontaneous fission.

The neutrons from nuclear absorption of negative cosmic-ray muons can be estimated from data taken with the 3-ton underground detector of reference 11. The total number of stopping muons was seen to be $\sim\frac{1}{2}$ hr^{-1}. Taking $\frac{1}{2}$ the muons to be negative, assuming them all to be captured producing 2 neutrons/capture, and estimating the probability of a neutron giving a background count as in the spontaneous fission case, we should therefore expect in a 5-ton detector a background from this source of 2/year. Since only a fraction of the stopped muons are captured before decaying in the actual materials of which the detector would consist, 2/year represents an overestimate. Neutrons produced in cosmic-ray stars and by gamma rays can be similarly shown to give an unimportant contribution to the background. It is noteworthy that if it were not for the self-shielding of the Li^7 by the Li^6, some of these sources of background would present a serious problem.

Gamma rays.—ThC$''$ is the most serious source of gamma-ray background due to natural radioactivity since it produces a cascade[15] totaling as much as 3.96 MeV. In order to estimate the expected background rate in the energy region 6-13 MeV, we scale the rate of 6/sec >3 MeV measured[11] with our 3-ton detector located in the salt mine, assuming it all to be due to ThC$''$. The problem is to deduce the twofold pileup in our proposed 25-plate, 5-ton detector. Assuming total absorption in each section, the >3-MeV singles rate/section is $\frac{1}{2}$ sec^{-1} $[=6\times(5/3)\times(1/26)]$ and the twofold pileup for the entire detector is calculated to be 230/year. The resolving time is taken as 10^{-6} second. This number represents a gross overestimate because it is based on the assumption of total absorption. Since the media are low Z, the Compton mean free path measures the localization of energy loss. For gammas >1 MeV the mean free path in scintillator is ~15 cm, a number to be compared with the scintillator slab thickness of 5 cm. This suggests that, unlike the energetic electron which constitutes the ν_e signal, the energy of the several gammas will be deposited in more than one detector section. It is estimated that the detection efficiency of a slab for the ThC'' cascade is <10%. This means that the expected twofold pileup is <3/year.

Another possible source of gamma rays is that from the capture of cosmic-ray–produced neutrons in the detector case or its environment.

If the detector shell is made of low-Z nuclei such as H^1, C^{12}, O^{16}, it will not produce either neutrons from stopped muons or high-energy capture gammas from these or any other source of neutrons. The environment under consideration (NaCl) can be expected to give rise to neutrons and capture gammas[16] and it may therefore be necessary to enclose the detector in a hydrocarbon or water shield. The magnitude of the background which might be expected from these neutron sources can be estimated by taking the detector mass of 5 tons and recalling the previous numbers for spontaneous fission, 6.5×10^{-5} neutron/sec (~2000/year) and for muon-capture neutrons, $\frac{1}{2}$/hr (~4400/year). Since the detector efficiency/slab is ~10% for a cascade of high-energy gammas, the total neutron-associated background is ~700/year for a NaCl environment. This number can be reduced to arbitrarily low levels by means of the aforementioned hydrocarbon or water enclosure. It is to be pointed out that the system is partially self-shielded from such neutrons because of the associated muons.

It is a pleasure to thank Dr. D. K. Froman for a suggestion which led to the design of the directional system. The continued hospitality of the Morton Salt Company in their Fairport Harbor Mine is gratefully acknowledged.

---

*Work done under the auspices of the U. S. Atomic Energy Commission.

[1]J. N. Bahcall, W. A. Fowler, I. Iben, Jr., and R. L. Sears, Astrophys. J. 137, 344 (1963); J. N. Bahcall, Phys. Rev. Letters 12, 300 (1964); R. L. Sears, Astrophys. J. 140, 477 (1964).

[2]R. Davis, Jr., Phys. Rev. Letters 12, 302 (1964).

[3]F. Reines and W. R. Kropp, Phys. Rev. Letters 12, 457 (1964).

[4]J. N. Bahcall, Phys. Rev. 136, B1164 (1964).

[5]Given independent evidence of the solar neutrino flux, such an experiment could then be used to study the elastic scattering process. It may well be that the sun is the best source for this purpose!

[6]The use of Li^7 as a target was independently suggested by J. N. Bahcall to whom we are indebted for communication prior to publication.

[7]Nuclear Data Sheets, edited by C. L. McGinnis (National Research Council), No. 5-5-113.

[8]This is a conservative assumption in the case of Li^7 because the low-lying excited state in Be^7 can be expected to make a significant contribution to the interaction cross section. These and other relevant questions of nuclear structure are under active consideration.

[9]E. J. Konopinski, Ann. Rev. Nucl. Sci. 9, 99 (1958).

[10]G. Marx and N. Menyhard, Science 137, 299 (1960).

[11]L. V. East, T. L. Jenkins, and F. Reines, unpublished.

[12]M. K. Moe, T. L. Jenkins, and F. Reines, Rev. Sci. Instr. 35, 370 (1964).

[13]E. Segrè, Phys. Rev. 86, 21 (1952).

[14]This number is consistent with the amount of U^{238} in the detector of reference 6 as deduced from the assumption that all the counts >3 MeV were due to the U^{238} decay chain. No special precautions were taken in the construction of this detector.

[15]D. Strominger, J. M. Hollander, and G. T. Seaborg, Rev. Mod. Phys. 30, 585 (1958).

[16]B. B. Kinsey, in Beta- and Gamma-Ray Spectroscopy, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955).