LIMITS ON SOLAR NEUTRINO FLUX AND ELASTIC SCATTERING*

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The calculations of Bahcall, Fowler, Iben and Sears[1] on the flux at the earth of neutrinos from the decay of ^{8}B produced in the interior of the sun predict a value of $(2.5\pm 1)\times 10^7$ ν_e/cm^2 sec. Since the ^{8}B decay neutrinos have energies up to 13.7 MeV, i. e., well in excess of natural radioactivity, we are able to interpret results of an underground experiment performed in another connection[2] in terms of an upper limit on the flux of solar neutrinos providing we assume an elastic scatter of ν_e by electrons as predicted by Feynman and Gell-Mann[3] and Marshak and Sudarshan[4]:

$$\nu_e + e^- \rightarrow \nu_e + e^-.$$

Our data can also be interpreted as an upper limit on the elastic scattering process[5] assuming the flux calculations cited by Bahcall to be correct. We describe these arguments in this Letter following a discussion of the complementary relationship between the present approach and that of Davis.[1] Davis proposes to detect solar ν_e by using the inverse beta decay of ^{37}Cl,

$$^{37}\mathrm{Cl} + \nu_e \rightarrow {}^{37}\mathrm{Ar} + \beta^-.$$

The cross section for this reaction is predictable so that the only unknown factor is the ^{8}B ν_e flux, f. Therefore, given the results of the projected experiment of Davis, f can be deduced, assuming of course that the reaction which is responsible is known from other considerations—the projected Davis experiment is expected to give not f but the product of f times the cross section integrated over the relevant neutrino spectrum.

The direct counting experiment utilizing the elastic scattering process has the additional feature that it is in principle capable of giving information regarding the neutrino energy distribution, so helping to identify the responsible reaction. A negative result here in the face of a positive result from the Davis experiment could be interpreted either as due to the absence of the elastic scattering process or as an indication that the ^{8}B reaction is not responsible for the anticipated Davis results and does not occur in the sun as predicted.

A modest experiment was performed which enabled us to set some limits and helps assess the full-scale effort. It consisted of looking for unaccompanied counts in a 200-liter liquid scintillation detector (5×10^{28} electrons) which was surrounded by a large Cherenkov anticoincidence detector and located 2000 feet underground in a salt mine. The experimental details will be published elsewhere.[2] In a counting time of 4500 hours only three events were observed in the energy range 9 to 15 MeV, unaccompanied by pulses in the anticoincidence guard. If we ascribe these events to recoil electrons produced by the elastic scattering of solar neutrinos from the ^{8}B or ^{4}Li decays we obtain the conservative upper limits

$$f(^8\mathrm{B}) < 10^9\ \nu_e/\mathrm{cm}^2\ \mathrm{sec},\ (< 2\times 10^8\ \nu_e/\mathrm{cm}^2\ \mathrm{sec}).$$

The number in the brackets is the corresponding flux limit set by Bahcall and Davis. Table I summarizes the calculation of limits assuming the ^{8}B reaction. The results are seen to depend on the lower limit of the recoil electron energy E, which is considered. Figure 1 shows the calculated cross-section, σ_e per incident ^{8}B ν_e for

Table I. Elastic scattering of ^{8}B neutrinos.

E MeV	$\sigma_e(>E)$ ($\times 10^{45}$ cm^2)	Calculated rate[a] R_1 ($\times 10^4$ day^{-1})	Present experimental limit R_2 ($\times 10^2$ day^{-1})	R_2/R_1	Upper limit on solar ν_e flux (ν_e/cm^2 sec)
8.0	4.7	6.3			
8.5	4.2	4.6	1.6	35	$9\ \times 10^8$
9.0	3.1	3.4	1.6	50	1.2×10^9
9.5	2.1	2.3	1.1	50	1.2×10^9
10.0	1.4	1.5	1.1	75	

[a] $R_1 = \sigma_e(>E)Nf$, $N = 5\times 10^{28}$ target electrons, $f = 2.5\times 10^7$ ν_e/cm^2 sec.

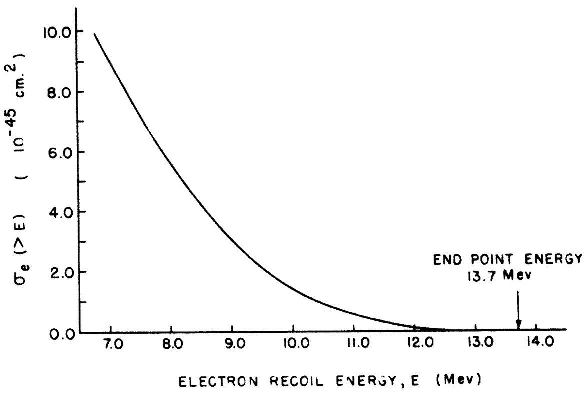

FIG. 1. Cross section, $\sigma_e(>E)$, per target electron, per incident ^{8}B neutrino, for the production of recoil electrons with energy in excess of E.

the production of recoil electrons above the energy E. On this basis, the elastic scattering cross section is seen from the table to be <35 times the expected value, a better limit by ~10 than that previously set for $\tilde{\nu}_e$'s from a fission reactor.[6]

It is interesting to inquire how large a detector would be required to see the predicted ^{8}B solar neutrino and then to consider the question of backgrounds. If the flux is taken to be 2.5×10^7 ν_e/cm^2 sec and the lower limit on electron recoil energy is set at 8 MeV, then we predict a rate of 1.5 events per year in a metric ton of scintillator. Since it is within our current experience with large detectors to consider a sensitive volume of 10^4 gallons we could build a system with a predicted rate $\sim$50/yr. The background which appears most serious is that resulting from the "pileup" of pulses due to natural radioactivity. The most troublesome natural gamma emitter is ThC$''$ which[7] produces a cascade of gammas of energy totalling from 2.62 to 3.96 MeV. Assuming a threefold pileup is required to give an apparent pulse >8 MeV and a resolving time of 10^{-7} sec (modest) in a detector made up of $N(=24)$ identical elements, the singles rate per element, n sec^{-1}, consistent with a total background rate, R, of 10/yr is given by

$$R=2n^3\tau^2\times3.1\times10^7N.$$

Inserting numbers we find

$$n=88/\mathrm{sec\ per\ element}.$$

If the resolving time is reduced a correspondingly larger value of n becomes acceptable.

As an example of attainable backgrounds[8] a scintillation detector of ~10 m^2 surface area and located 2000 feet underground in a salt mine exhibits an integral count rate above 3 MeV of only 6 sec^{-1}, an order of magnitude below the required limit per detector element estimated above.

The twofold pileup background in the complete detector array, using the integral rate above 4 MeV in the 10-m^2 test detector to make an estimate, is ~50/yr, again assuming a resolving time of 10^{-7} sec. It therefore seems reasonable that the background problem due to natural radioactivity can be reduced to acceptable levels.

A second source of background can result from the passage of cosmic rays through the detector. It is improbable that a detector located near the earth's surface can be sufficiently well shielded by a charged-particle anticoincidence detector from cosmic rays which deposit energy in the range, 8-18 MeV, of interest here. It therefore appears necessary to locate such a detector deep underground where the cosmic radiation is penetrating muons and their secondaries. If, to assess the situation, we assume a detector of 25 m^2 surface area as seen by the cosmic rays, then at a location 2000 feet underground, allowing an anticoincidence factor[9] >10^4, the residual rate due to all cosmic rays is estimated to be <300/yr. Considering only those cosmic rays which deposit between 7 and 18 MeV it appears possible that the rate would be reduced by as much as an order of magnitude or more. There always remains the possibility of going deeper underground.

We wish to thank the Morton Salt Company for continued hospitality in their Fairport Harbor Mine and Dr. M. Crouch and Dr. T. L. Jenkins for interesting discussions.

Note added in proof. – It has been called to our attention by L. Heller that Azimov and Schekhter[10] and Heller[11] have recalculated the elastic scattering process according to the conserved vector current theory and find a cross section twice as large as previously quoted. On this basis our limits on the elastic scattering process are closer by a factor of two to prediction and a detector smaller by a factor of two would suffice to detect solar neutrinos.

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[1]J. N. Bahcall, C. W. Fowler, I. Iben, Jr., and R. L. Sears, Astrophys. J. 137, 344 (1963). We are indebted to Dr. R. Davis, Jr., and Dr. J. N. Bahcall for calling our attention to the latest estimates of the ^{8}B rates as well as preprints of their publications on

the subject of solar neutrinos.

[2]A paper by the present authors is in preparation. It will contain a discussion of the various limits which can be set on nucleon stability and neutrino fluxes by a consideration of the unaccompanied counts. The earlier stages of this work are described in a paper by C. C. Giamati and F. Reines, Phys. Rev. 126, 2178 (1962).

[3]R. P. Feynman and M. Gell-Mann, Phys. Rev. 109, 193 (1958).

[4]R. E. Marshak and E. C. G. Sudarshan, Phys. Rev. 109, 1860 (1958); Proceedings of the Padua-Venice Conference on Mesons and Newly Discovered Particles, September, 1957 (Società Italiana di Fisica, Padua-Venice, 1958).

[5]Our results can also be used to set an upper limit on the product of the elastic scattering cross section averaged over the upper end of the ^{4}Li decay spectrum (on the unlikely assumption that it is particle stable) times the solar ^{4}Li-produced ν_e flux at the earth. The flux limit so obtained is $<2\times10^8$ ν_e/cm^2 sec. This is to be compared with the Bahcall-Davis limit of $<1\times10^8$ ν_e/cm^2 sec.

[6]C. L. Cowan, Jr., and F. Reines, Phys. Rev. 107, 528 (1957). This experiment was interpreted in terms of an upper limit on the neutrino magnetic moment. We here reinterpret these data in terms of the conserved vector current predictions.

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

[8]L. V. East, T. L. Jenkins, and F. Reines (unpublished).

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

[10]Ya. I. Azimov and V. M. Shekhter, Zh. Eksperim. i Teor. Fiz. 41, 592 (1961) [translation: Soviet Phys.—JETP 14, 424 (1962)].

[11]L. Heller, Los Alamos Scientific Laboratory Report LAMS-3013, 1964 (unpublished).

ABSOLUTE DECAY RATE FOR $K_2^0 \to \pi^+ + \pi^- + \pi^0$ AND THE $|\Delta I| = 1/2$ RULE*

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In this Letter we describe a measurement of the absolute decay rate $\Gamma_2(+-0) \equiv \Gamma(K_2^0 \to \pi^+ + \pi^- + \pi^0)$. Our result is based on 16 events of the type $\pi^- + p \to \Lambda + K^0$ followed by $\Lambda \to p + \pi^-$ and $K_2^0 \to \pi^+ + \pi^- + \pi^0$, and 2608 double-vee events $\pi^- + p \to \Lambda + K^0$ with $\Lambda \to p + \pi^-$ and $K_1^0 \to \pi^+ + \pi^-$. We find

$$\Gamma_2(+-0) = (2.90 \pm 0.72) \times 10^6 \text{ sec}^{-1}. \quad (1)$$

This result can be compared with the prediction of the $|\Delta I| = 1/2$ rule for nonleptonic decays, that $\Gamma_2(+-0)$ and $\Gamma(+00) \equiv \Gamma(K^+ \to \pi^+ + \pi^0 + \pi^0)$ are related by

$$\Gamma_2(+-0) = 2(1.032)\Gamma(+00), \quad (2)$$

where the factor 1.032 corrects for small mass differences. Equation (2) holds for any linear combination of the three $I = 1$ three-pion states.[1,2] Taking $\Gamma(+00)$ from a compilation of K^+ branching ratios and lifetimes,[3] one obtains the prediction of the $|\Delta I| = 1/2$ rule,

$$\Gamma_2(+-0) = (2.87 \pm 0.23) \times 10^6 \text{ sec}^{-1}. \quad (3)$$

The excellent agreement between our experimental result (1) and the prediction (3) shows that the $|\Delta I| = 1/2$ rule is well satisfied.[4]

The ratio $\Gamma_2(+-0)/\Gamma(+00)$ affords a sensitive test of the $|\Delta I| = 1/2$ rule. To exhibit this sensitivity we parametrize the effect of a small $|\Delta I| = 3/2$ amplitude $A_{3/2}$ for $K \to 3\pi$ under the assumption that the dominant $|\Delta I| = 1/2$ amplitude leads to the symmetrical $I = 1$ three-pion state, but with no such restriction on the $|\Delta I| = 3/2$ amplitude. Then, if $|A_{3/2}/A_{1/2}|^2$ is neglected, our experimental result expressed in the notation of reference 2 becomes

$$\sqrt{2}\,\mathrm{Re}\left(\frac{A_{3/2}}{A_{1/2}}\right) = \frac{2(1.032)\Gamma(+00) - \Gamma_2(+-0)}{4(1.032)\Gamma(+00) + \Gamma_2(+-0)} \quad (4)$$

$$= 0.00 \pm 0.09. \quad (5)$$

The remainder of this paper is concerned with experimental details.

The Alvarez 72-in. hydrogen bubble chamber was exposed to π^- beams with momenta between 1034 and 1325 MeV/c. All film was scanned for single and double vees which were analyzed using the least-squares fitting program KICK. For the present experimental events of the type $\pi^- + p^+ \to \Lambda + K^0$ were used; $\pi^- + p \to \Sigma^0 + K^0$ events were