Detecting solar boron neutrinos with Čerenkov and scintillation detectors

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(Submitted 30 January 1990)
Pis'ma Zh. Eksp. Teor. Fiz. **53**, No. 3, 129–132 (10 February 1991)

The use of Čerenkov and scintillation detectors to detect solar neutrinos is discussed. An intense background is created by the interactions between the detector nuclei and the cascade neutrons generated in nuclear showers triggered by muons. Methods for suppressing this background are proposed. The replacement of the water in the Čerenkov counters by a substance containing carbon should make it possible to detect solar neutrinos with a background level one or two orders of magnitude lower than at present.

The solar-neutrino puzzle arose after the chlorine-argon experiment by Davis.[1] The radiochemical experiments such as SAGE[2] and Gallex,[3] which are being carried out in an effort to solve this puzzle, are now being supplemented with experiments (in the planning stage or actually being carried out) which are based on electronic neutrino detection methods.

Čerenkov and scintillation detectors are used to detect solar neutrinos.[4–7] These instruments are capable of measuring the fluxes of neutrinos produced in the reaction $^8\mathrm{B}(e^+,\nu)^8\mathrm{Be}^*$. The energy spectrum of these neutrinos extends to 14 MeV, peaking at 7 MeV. In Čerenkov counters filled with water, the reaction $\nu e^- \to \nu e^-$ is used, while in heavy-water detectors the reaction $\nu + d \to p + p + e^-$ is used.[5] In a scintillation counter, a neutrino can be detected by virtue of both νe^- scattering and the reactions $^{19}\mathrm{F} + \nu \to {}^{19}\mathrm{Ne} + e^-$ and $^{11}\mathrm{B} + \nu \to 11_\mathrm{C} + e^-$, for scintillators containing fluorine and boron.[6,7] The energy evolution in the interior of the detector above a detection threshold is measured. This threshold is set in such a way that one can discriminate the signal from the background.

0021-3640/91/030135-04$01.00

Solving the problem of detecting solar neutrinos is a matter of solving the background problem. There are two primary sources of background: (1) the natural radioactivity in the detector itself, the structural materials, and the surrounding rock; (2) the cosmic-ray muons and the particles that they generate.

I would like to call attention to an important source of background which has heretofore been ignored. This is the interaction of the detector nuclei with the fast neutrons ($E_n \sim 10$–150 MeV) which are generated in nuclear showers triggered by cosmic-muons in the detector itself, in the soil, or in the shielding around the apparatus.

As a fast isolated neutron—one which has moved far away from the axis of the shower—enters the main volume of the detector, it triggers the following reactions, which are background reactions:

I. Elastic scattering by a proton resulting in the formation of a recoil proton.

II. Inelastic scattering by nuclei accompanied by the emission of γ rays. For the nucleus ^{12}C, for example, the most probable energies are $E_\gamma = 4.49$ MeV and 4.95 MeV; for ^{16}O they are $E_\gamma = 6.13$ MeV, 6.92 MeV, and 7.12 MeV. The cross sections for the reactions at $E_n \sim 10$ MeV are[8] 200 mb.

III. An inelastic interaction with nuclei. Reactions of this type are most dangerous when long-lived isotopes which decay in processes accompanied by the emission of high-energy β particles or γ rays are produced. An example is the (n,p) reaction at ^{12}C and ^{16}O:

$$^{16}\mathrm{O} + n \to {}^{16}\mathrm{N} + p$$

$$^{16}\mathrm{N} \to {}^{16}\mathrm{O} + e^- + \nu, \quad \tau_{1/2} = 7.14\ \mathrm{s};\ E_e^{max} = 10.44\ \mathrm{MeV}\ \ (26\%);$$

$$E_e^{max} = 4.3\ \mathrm{MeV}\ ,\ \ E_\gamma = 6.13\ \mathrm{MeV}\ \ \ (68\%); \tag{1}$$

$$E_e^{max} = 3.3\ \mathrm{MeV}\ ,\ \ E_\gamma = 7.1\ \mathrm{MeV}\ \ (6\%);$$

$$^{12}\mathrm{C} + n \to {}^{12}\mathrm{B} + p$$

$$^{12}\mathrm{B} \to {}^{12}\mathrm{C} + e^- + \nu, \quad \tau_{1/2} = 0.03\ \mathrm{s},\ E_e^{max} = 13.37\ \mathrm{MeV}\ \ (98.3\%)\ ^{9}. \tag{2}$$

The cross section for reaction (1) has a threshold of 10 MeV and reaches a maximum (85 mb) at 12 MeV. At energies above 20 MeV it is $\sigma_1\,(n,p) \sim 20$ mb. Reaction (2) goes at higher energies, $E_{\mathrm{thr}} \sim 15$ MeV, and the cross section $\sigma_2\,(n,p)$ is smaller than $\sigma_1\,(n,p)$ by a factor of about four over the entire energy range.[8] Reaction (1) creates a background in Čerenkov detectors which use ordinary or heavy water, and reaction (2) does the same in scintillation counters using organic liquid scintillators. The thermal neutrons which are produced as a result of the moderation of the fast neutrons constitute a background in boron and fluorine detectors. For scintillators containing fluorine the neutron-capture reaction completely simulates the reaction

$\nu_e{}^{19}F$:

$$^{19}\mathrm{F} + n \rightarrow {}^{20}\mathrm{F} + \gamma, \quad E_\gamma = 6.83\,\mathrm{MeV}$$

$$^{20}\mathrm{F} \rightarrow {}^{20}\mathrm{Ne} + e^- + \nu, \quad \tau_{1/2} = 12\ \mathrm{s}, \quad E_e^{max} = 6,7\,\mathrm{MeV}. \tag{3}$$

The reactions of elastic and inelastic scattering of neutrons coincide in time with the development of the showers, and a good anticoincidence system can eliminate them. It should be kept in mind here that the hard spectrum of neutrons in the substance ($E_n \sim dE_n/E_n^{0.5-0.6}$ up to $E_n \sim 150$ MeV; Refs. 10 and 11) requires shielding calculated for neutrons with $E_n \sim 100$ MeV. Inelastic-scattering reactions of the type in (1) and (2) and the capture of slow neutrons give rise to charged particles a certain time after the shower passes the detector or the shielding. Additional measures will have to be taken, therefore, to suppress the background of this type.

The energy spectrum and fluxes of neutrons associated with nuclear and electromagnetic showers were measured in Refs. 10 and 12–15; the neutron generation frequency was also studied as a function of the depth in the soil. It was found that any nuclear effects associated with muons (other than muon capture) depend on the average muon energy at the depth in accordance with $[E_\mu(H)]^{0.75}$. Table I, which was compiled on the basis of Refs. 10–15, shows the fluxes of isolated neutrons with $E_n > 10$ MeV incident on the lateral surface of the detector at various depths (line 1) and the average number of neutrons which are generated by one muon per 1 g/cm^2 of the detector (line 2).

As an example let us estimate the background from reaction (1) in the Kamiokande II (K II) detector. The number of cascade neutrons formed in the working volume of K II over the course of a year ($T = 3.15 \times 10^7$ s) is $N_n(E_n > 10\ \mathrm{MeV}) = \overline{N_n^{\prime}} K I_\mu \bar{h} T = 189\,000$, where $\bar{h} = 600$ g/cm^2 is the average range of the muons, $I_\mu \sim 0.1\ \mathrm{s}^{-1}$ is the intensity of muons, and $\mathrm{K} = 0.2$ represents the fraction of cascade neutrons.

Neutrons with energies of 20–150 MeV which collide with oxygen nuclei undergo either an elastic scattering or an inelastic interaction. In the latter case, there is a certain probability for ^{16}N production in the reaction $^{16}\mathrm{O}(n,p)^{16}\mathrm{N}$. In the case of elastic scattering, the neutron loses only a small fraction of its energy (< 10% on the average) and is capable of interacting again with ^{16}O, etc. After a collision with hydrogen, a neutron, with an energy reduced by an average factor of two, can interact with either H or ^{16}O. When the multiple interactions and the energy spectrum of the neutrons are taken into account, one finds that, on the average, 3–3.5% of $N_n(E_n > 10\ \mathrm{MeV})$ generate ^{16}N. Taking the efficiency with which the K II Čerenkov

TABLE I.

H, hg/cm^2	2700	3300	6000
I_n, m$^{-2}\cdot$yr^{-1}	160	45	1,1
$\overline{N'}$, g$^{-1}\cdot$cm^2/g	4.9×10^{-4}	5.2×10^{-4}	6.5×10^{-4}

detector detects the energy evolution resulting from the β decay of ^{16}N to be 25–30% for $E_{\text{thr}} = 7.5$ MeV and 6–8% for $E_{\text{thr}} = 9.3$ MeV, we find that over a year the numbers of counts due to this process are $N_p(E_{\text{thr}} = 7.5\ \text{MeV}) = 1500\text{–}2000$ and $N_p(E_{\text{thr}} = 9.3\ \text{MeV}) = 350\text{–}450$. The error of these estimates is 50%. It follows from Ref. 16, which was a report of K II experimental data over ~3 yr of operation, that the average background over the year corresponds to the values

$$N_{\text{expt}}(E_{\text{thr}} = 7.5\ \text{MeV}) \sim 1800, \quad N_{\text{expt}}(E_{\text{thr}} = 9.3\ \text{MeV}) \sim 390.$$

The surprising agreement of the estimates and the measured values suggests that essentially the entire background at K II is due to specifically the effect which we are discussing here. Calculations[17] show that more than 60% of the neutrons are generated in nuclear showers with energies above 10 GeV. Consequently, if a dead time of 20–30 s is imposed after an energy evolution above 10 GeV in the detector, one can reduce the background by a factor of 2.5–3.

One way to avoid false events of this sort might be to replace the water in the Čerenkov detector by, for example, liquid paraffin (C_nH_{2n+2}). The interaction of neutrons with ^{12}C gives rise to short-lived isotopes [see reaction (2)] with a cross section smaller than $\sigma_1(n,p)$ by an average factor of 3–4. The introduction of a dead time of 0.2 s would reduce the background to essentially zero. Liquid paraffins with $\bar{n} = 10\text{–}12$ are inexpensive, can be purified to a transparency of 30–40 m at a wavelength of 420 nm, and have a low level of natural radioactivity.

I am deeply indebted to G. T. Zatsepin, V. L. Dadykin, V. A. Kudryavtsev, A. S. Mal'gin, S. P. Mikheev, and V. G. Ryasnyĭ for useful and stimulating discussions of this question.

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Translated by D. Parsons