Solar Flares and Neutrino Detectors

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Solar flares have been suggested as the cause of occasional high counting rates in the ^{37}Cl solar-neutrino experiment. The sensitivity of neutrino detectors to flares is evaluated. Several neutrino detectors will show large signals when prominent flares are observed electromagnetically, if flares are detected in the chlorine experiment.

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Davis[1] has suggested that solar flares may have produced neutrino pulses that showed up in his ^{37}Cl detector as unusually high observations. This result is of great potential importance since conventional theoretical calculations indicate that there is not enough energy available in neutrinos produced by flares to cause a significant signal in the ^{37}Cl detector.[2,3] Moreover, many of the suggested theoretical interpretations of the ^{37}Cl experiment would have to be revised if it turned out that part of the observed event rate of 2 solar-neutrino units (SNU) was due to neutrinos produced by solar flares on the surface of the Sun, rather than by neutrinos produced by nuclear fusion in the solar interior.

The purpose of this Letter is to point out that other neutrino detectors, existing[4-7] and in progress,[8-10] should register large characteristic signals if solar flares are detected in the ^{37}Cl experiment.

The following discussion summarizes the observational evidence[1] on the relation between solar flares and the ^{37}Cl neutrino capture rate. Run 27, the highest experimental run, corresponded in time with the great solar flares of August 1972. Unfortunately, the flares occurred early in the exposure interval and therefore most of the ^{37}Ar atoms that might have been produced by that event would have decayed before the extraction was completed. However, Bazilevskaya, Stozhkov, and Charakch'yan[11] pointed out that run number 71 might also be high because a burst of high-energy protons was produced by the Sun in October 1981. The extraction for this period indeed indicated an enhanced capture rate. In his Table 2, Davis[1] lists several other solar flares for which there was an excess of observed ^{37}Ar atoms in the tank. However, not all major solar flares yielded an excess of ^{37}Ar and the uncertainties in the number of atoms is large in all cases. If flare events were responsible for the increase in the capture rate above the average rate, the approximate numbers of ^{37}Ar atoms produced in the detector in runs 27, 51, and 71 were 250 ± 130, 20 ± 15, and 56 ± 30, respectively. According to Davis,[1] Monte Carlo simulations of the data indicate that approximately 1 or 2 runs as high as these are expected in 60 experiments.

A simple calculation is sufficient to confirm the result of Lingenfelter *et al.*[2] that neutrinos from the solar flares are not expected to produce a significant number of events in the ^{37}Cl detector. The total energy in the great flares of August 1972 was about 10^{33} ergs.[12] If this amount of energy is assumed, as an upper limit, to be present all in neutrinos from π and μ decay, then approximately $10^{9.5}$ cm^{-2} ν_e would have been incident on the Earth. This fluence corresponds[13] to only ~ 1 ^{37}Ar atom produced in the ^{37}Cl tank, down by more than 2 orders of magnitude from the number estimated by Davis to be required to explain the high result of run 27. A more detailed calculation based upon the current understanding of solar flares gives a much smaller predicted fluence of neutrinos.[2]

Could the chlorine experiment be responding to the production of mesons or energetic positron emitters in the Earth's atmosphere that are produced by flare particles? A conceivable mechanism is that the cosmic rays are modulated by the solar wind encountered on the way to the Earth. However, quantitative estimates of the implications of this mechanism show that it is inadequate to explain high runs in the chlorine experiment. Gaisser and Stanev[14] showed that cosmic-ray secondaries that decay in flight to produce high-energy neutrinos are insufficient to account for the suggested effect by at least 3 orders of magnitude. de la Zerda Lerner and O'Brien[15] calculated the neutrino emission from positrons produced by cosmic rays as they strike the Earth's atmosphere and showed that the positron neutrino emission falls short of explaining the correlation by 9 orders of magnitude.

Is some unknown mechanism operating in the Sun or in the Earth's atmosphere? Further observations are necessary to clarify whether the suggested enhancement in neutrino rates is real and, if so, how it depends upon the characteristics of the flares that are observed by photon observations. Fortunately, there are existing and planned neutrino detectors that will have a greater sensitivity to flare neutrinos than the ^{37}Cl experiment. Observations with these other experiments, when combined with continuing studies using the ^{37}Cl detector, will settle the question of whether flares contribute to the observed event rate in solar-neutrino detectors.

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The basic assumption used in this paper is that the source of flare neutrinos is collisions that produce pions and muons whose decays produce the neutrinos of interest. For specificity, the meson decays are assumed to occur at rest. This assumption minimizes the calculated ratio of predicted counts in nonradiochemical experiments [such as Kamiokande II, IMB (Irvine-Michigan-Brookhaven), Baksan, and LVD (large-volume detector)] compared to the ^{37}Cl experiment, since the ^{37}Ar nucleus is torn apart by very-high-energy neutrinos. Independent of the source of the neutrinos, other detectors must observe at least as many events as calculated here if the ^{37}Cl high runs are explained by neutrinos from π and μ decay.

Table I summarizes the sensitivity of several different neutrino detectors to neutrinos from pion and muon decay. The cross sections are taken from Ref. 13. The small effects of the finite detection thresholds were taken account of in calculating the effective scattering cross sections (with use of the thresholds cited in the experimental papers[4–8]). If the threshold for detecting positrons produced by $\bar{\nu}_e$ absorption is as high as 25 MeV, the decrease in absorption cross section is only 10%. The effective scattering cross sections given in the table are the sum of the scattering cross sections for the three neutrinos that are produced in the π^+-μ^+-e^+ decay chain. This prescription yields the appropriate cross section to use in comparing expected rates of scattering events with the number of absorption events that may be observed by radiochemical detectors, provided that the neutrinos are created by relatively low-energy pp collisions which mainly produce π^+'s and μ^+'s. If equal numbers of mesons of both charges are produced, then the effective scattering cross section per ν_e is increased by about 55%, which is the reason for the inequality signs in Table I. The largest cross section given in the table is for the reaction $\bar{\nu}_e + p \rightarrow e^+ + n$. The $\bar{\nu}_e$'s are produced by μ^- decay and occur in significant numbers if the colliding protons (or other baryons) that produce the decaying mesons have energies in excess of a few GeV.

TABLE I. Sensitivity of detectors to neutrinos from pion and muon decay. Here N is the number of target particles (electrons or nuclei), σ is the cross section, and N_{events} is the number of events expected assuming 250 events occurred in Davis's ^{37}Cl tank. The number of events for a given detector is proportional to $N\sigma$ for that detector times N_{events} for the ^{37}Cl detector.

Detector	N (10^{30})	σ (10^{-40} cm^2)	N_{events}
^{37}Cl (Davis)	2.16	0.7	250 ± 130
^{71}Ga (SAGE)	0.21	0.9	30
Kamiokande II [a]			
ν-e	7.0×10^2	≥ 0.0039	4.5×10^2
$\bar{\nu}_e + p$	1.4×10^2	0.95	2×10^4
IMB [b]			
ν-e	2.3×10^3	≥ 0.0037	1×10^3
$\bar{\nu}_e + p$	4.5×10^2	0.95	7×10^4
Baskan [c]			
ν-e	7.0×10^1	≥ 0.0039	45
$\bar{\nu}_e + p$	1.9×10^1	0.95	3×10^3
LVD [d]			
ν-e	6.3×10^2	≥ 0.0039	4×10^2
$\bar{\nu}_e + p$	1.7×10^2	0.95	3×10^4

[a] 2.1 kton water.
[b] 6.8 kton water.
[c] 0.2 kton scintillator.
[d] 1.8 kton scintillator.

Table I shows that an extraordinary signal should be recorded in the Kamiokande II,[4,5] IMB,[6] Baksan,[7] and LVD[8] detectors if a ^{37}Cl run was high because of a flarelike event. The last column of the table shows the expected number of neutrino events that should occur in each of the detectors assuming that, as suggested by Davis[1] for the great flares of August 1972, 250 ± 130 ^{37}Ar atoms are produced in the ^{37}Cl detector. The number of events ranges from a minimum of 30 in the SAGE[10] (Soviet-American Gallium Experiment, 60 tons of gallium) ^{71}Ga detector (approximately 15 events would be produced in the GALLEX detector[9]) to a maximum of about 10^5 events in the IMB detector,[6] presuming that the neutrinos are produced by collisions at sufficiently high energy that $\bar{\nu}_e$'s are produced in comparable numbers with ν_e's.

Solar neutrinos provide the main background in the radiochemical experiments with ^{37}Cl and ^{71}Ga. The saturation (i.e., maximum) number of radioactive atoms produced in equilibrium with the solar-neutrino flux is about 20 for both the ^{37}Cl detector and the GALLEX ^{71}Ga detector. A large flare would produce of order $10^{2.0 \pm 0.5}$ radioactive atoms, many of which might decay before the tanks were purged.

The direct-counting experiments, Kamiokande II, IMB, and LVD, are more sensitive to flares than are the radiochemical experiments. The total signal is expected to be larger in the direct-counting experiments, of order 10^2 to 10^5 events, because of their large masses. For comparison, the 1987A supernova produced only 11 events in the Kamiokande II detector[5] and 8 events in the IMB detector.[6] Also, the direct-counting experiments provide accurate time measurements, which could be correlated with electromagnetic observations of flares.

Zhang *et al.* (Kamiokande II collaboration)[16] have reported on a relevant search for relic antineutrinos from past supernovae. The search with Kamiokande II data is based upon 357.4 detector days between the period of 6 January 1986 and 31 December 1987. For this study, a reduced fiducial volume of 0.6 kg was used and recoil positron energies between 19 and 35 MeV were considered. For these conditions, the number of counts given in Table I should be multiplied by 0.062.

If a flarelike process had produced during this period 250 events in the ^{37}Cl tank, then it would have produced in the Kamiokande II detector between 28 events (from scattering of neutrinos from μ^+ and π^+ decay) and 1300 events (if $\bar{\nu}_e$ from μ^- decay were incident in equal number with ν_e from μ^+ decay). Only 2 widely separated events were observed in the entire ~1 yr of observation. Unfortunately, no strong solar flares were observed in any form during the period of observation since the epoch under consideration was near the minimum in the solar cycle. However, this observation shows that a continued search with Kamiokande II during the more active phases of the solar cycle, especially near solar maximum in 1990, should provide information on flares of between 10^{-1} and 10^{-3} the strength of the August 1972 flares, depending upon what one assumes about the production of $\bar{\nu}_e$'s. Of course, all of the calculated event rates in this Letter assume that the great flares of 1972 produced 250 ^{37}Ar atoms in Davis's ^{37}Cl tank.

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[1] R. Davis, Jr., in *Proceedings of Seventh Workshop in Grand Unification (ICOBAN '86),* edited by J. Arafune (World Scientific, Singapore, 1987), p. 237.

[2] R. E. Lingenfelter, R. Ramaty, R. J. Murphy, and B. Kozlovsky, in *Solar Neutrinos and Neutrino Astronomy,* edited by M. L. Cherry, W. A. Fowler, and K. Lande, AIP Conference Proceedings No. 126 (American Institute of Physics, New York, 1985), p. 121.

[3] J. N. Bahcall, G. B. Field, and W. H. Press, Astrophys. J. **320**, L69 (1987).

[4] E. W. Beier, in Ref. 1, p. 79.

[5] K. Hirata *et al.*, Phys. Rev. Lett. **58**, 1490 (1987).

[6] R. M. Bionta *et al.*, Phys. Rev. Lett. **58**, 1494 (1987).

[7] E. N. Alekseev, L. N. Alekseev, V. I. Volchenko, and I. V. Krivosheina, Pis'ma Zh. Eksp. Teor. Fiz. **45**, 461 (1987) [JETP Lett. **45**, 589 (1987)].

[8] C. Bari, Nucl. Instrum. Methods Phys. Res., Sect. A **264**, 5 (1988).

[9] T. Kirsten, in *Massive Neutrinos in Astrophysics and in Particle Physics,* edited by O. Fackler and J. Tran Thanh Van (Editions Frontieres, Paris, 1986), p. 119.

[10] I. R. Barabanov *et al.*, in Ref. 2, p. 175.

[11] G. A. Bazilevskaya, Yu. I. Stozhkov, and T. N. Charakhch'yan, Pis'ma Zh. Eksp. Teor. Fiz. **35**, 273 (1982) [JETP Lett. **35**, 341 (1982)].

[12] P. B. Lin and H. S. Hudson, Sol. Phys. **50**, 153 (1976).

[13] J. N. Bahcall, Rev. Mod. Phys. **59**, 505 (1987); J. N. Bahcall and R. K. Ulrich, Rev. Mod. Phys. **60**, 297 (1988); J. N. Bahcall, "Neutrino Astrophysics" (Cambridge Univ. Press, Cambridge, to be published), Chap. 8.

[14] T. K. Gaisser and T. Stanev, Phys. Rev. Lett. **58**, 1695 (1987).

[15] A. de la Zerda Lerner and K. O'Brien, Nature (London) **330**, 353 (1987).

[16] W. Zhang *et al.*, Phys. Rev. Lett. **61**, 385 (1988).