Search for Correlation of Neutrino Events with Solar Flares in Kamiokande

K. S. Hirata, T.Kajita, T. Kifune, K. Kihara, M. Nakahata, K. Nakamura, S. Ohara, Y. Oyama, N. Sato, M. Takita, Y. Totsuka, and Y. Yaginuma
Institute for Cosmic Ray Research, University of Tokyo, Tokyo 188, Japan

M. Mori, A. Suzuki, K. Takahashi, T. Tanimori, and M. Yamada
National Laboratory for High Energy Physics (KEK), Ibaraki 305, Japan

M. Koshiba
Department of Physics, Tokai University, Kanagawa 259-12, Japan

T. Suda
Department of Physics, Kobe University, Hyogo 657, Japan

K. Miyano, H. Miyata, and H. Takei
Department of Physics, Niigata University, Niigata 950-21, Japan

K. Kaneyuki, Y. Nagashima, and Y. Suzuki
Department of Physics, Osaka University, Osaka 560, Japan

E. W. Beier, L. R. Feldscher, E. D. Frank, W. Frati, S. B. Kim, A. K. Mann, F. M. Newcomer, R. Van Berg, and W. Zhang
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104

M. Fukugita
Research Institute for Fundamental Physics, Kyoto University, Kyoto 606, Japan
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A search has been made for a correlation between large solar flares and neutrino events observed in Kamiokande for the period of July 1983–July 1988. No significant neutrino signal was found at the time of a solar flare, giving a limit on the time-integrated "solar-flare" ν_e flux $<3.7\times 10^7$ (2.5×10^9) cm^{-2} per flare at 90% confidence level, for $E_\nu = 100$ (50) MeV. These limits are 2000 (60) times smaller than the value required for neutrinos with those energies to account for the excess of signal in the ^{37}Cl solar-neutrino experiment at some of the corresponding solar-flare times.

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The solar-neutrino experiment which has been carried out by Davis[1] and his collaborators over two decades with a chlorine detector has provided a number of interesting puzzles that need to be understood better both theoretically and experimentally. Besides the very significant solar-neutrino-deficit problem,[1] one such puzzle that deserves further elucidation is the possibility of association of high neutrino-capture rates in the chlorine detector with the occurrence of large solar flares.[1,2] Three runs (run Nos. 27, 51, and 71) with unusually high neutrino-capture rates have been recorded during which large solar flares occurred.[1] One additional run (No. 86), not obviously correlated with a solar flare, was in coincidence[1] with a strong γ-ray burst observed by the Solar Maximum Mission satellite.[3]

Associating the excess events with solar flares, Davis[1] estimated 20–250 excess neutrino captures per flare corresponding to the times of occurrence of the solar flares in the 615-ton C_2Cl_4 detector at Homestake. If the excess is not due to statistical fluctuations, it is natural to consider ascribing the origin of such neutrinos to the decay of pions and muons produced by energetic protons accelerated in solar magnetic fields. Neutrinos from such decays would carry significant energy, perhaps in the 100-MeV region,[1,4] and would readily be detected with a water Čerenkov detector. In fact, corresponding to 50 ^{37}Ar excess production in the ^{37}Cl detector at the solar-flare times, more than 4500 (130) neutrino events are expected in the Kamiokande detector[5] if the energy of neutrinos involved is ≥ 100 (50) MeV.[6]

In this Letter we report the result of a search for a correlation between solar flares and neutrino events in the Kamiokande detector during the five years from July 1983 to July 1988. The characteristics of the neutrino events have been reported elsewhere.[7] Three flares nominally associated with excess events in the ^{37}Cl detector came before the start of operation of the Kamiokande detector, and we cannot examine a possible correlation at those times. There occurred, however, fifteen large solar flares during the above period,[8] and it is interesting to see whether there exist any correlations with the Kamiokande neutrino data. During run No. 86 of the ^{37}Cl experiment, in which an event excess[1] was observed, the Kamiokande detector was in operation and we can directly test for a possible coincidence.

The Kamiokande experiment[5] is divided into two phases, KAM-I (6 July 1983–3 October 1984, live time 342 days, fiducial mass 880 tons; 29 December 1984–9 November 1985, 222 days, 780 tons) and KAM-II (21 November 1985–14 July 1988, 750 days, 1040 tons). The detection thresholds (50% efficiency) of KAM-I are 30 MeV/c for electrons and 205 MeV/c for muons. For KAM-II the thresholds are 7.6 MeV/c for electrons and 165 MeV/c for muons, but the analysis thresholds are set at the detection thresholds of KAM-I to treat all the data in a consistent way. An adopted momentum interval in the analysis corresponds to 30–1330 and 205–1500 MeV/c for electrons and muons, respectively. During the live time of 1314 days a total of 326 fully contained events were observed, out of which 225 single-ring [122 e-like ($e^{\pm},\gamma$) and 103 μ-like ($\mu^{\pm},\pi^{\pm}$)] events are used to search for "solar-flare neutrinos." Additionally, we also analyzed low-energy neutrinos (recoil electron momentum 19–50 MeV/c) in KAM-II with a fiducial mass of 680 tons.[9] One additional e-like event was found in this analysis, besides those of the supernova 1987A origin.[5]

The magnitude of solar flares, as determined from the observed strength of the H_α line (6563 Å), is categorized in "importance" from 1 to 4 (Ref. 8) with subclasses denoted by B (brilliant), N (normal), and F (faint). Fifteen flares are recorded as importance ≥ 3 in the period of July 1983–July 1988,[8] which are listed in Table I. The importance as seen with soft x rays (1–8 Å) is also shown in column 5. The last column gives the number of neutrino events recorded in the Kamiokande detector during the interval of (start of flare -1 h, end of flare $+1$ h). Only one event, which is of ν_μ type, is recorded in coincidence with a large solar flare. This is statistically consistent with the background level of 0.35 event expected from the random distribution of neutrino events during the flare periods. We have also searched for a coincidence of neutrino events with hard-x-ray (25–440 keV) observations by the hard-x-ray-burst spectrometer on the Solar Maximum Mission satellite.[10] Eleven large hard-x-ray flares (for details, see Ref. 10) are recorded in the period of detector operation, but we find no neutrino events in correlation with these hard x rays.

Probably more important in the study of the correlation of neutrino events with the solar flare is the strength of the proton flux associated with a flare,[8] as measured at a geosynchronous satellite orbit. The largest flux 2500 cm^{-2} s^{-1} sr^{-1} for the flare on 24 April 1984 (see Table I) is as large as that[8] of the flare on 12 October 1981 (2000 cm^{-2} s^{-1} sr^{-1}), to which the excess neutrino capture of run No. 71 of the ^{37}Cl experiment was as-

TABLE I. Correlation between large solar flares (importance ≥ 3) and single-ring neutrino events.

Importance[a]	Date	Start[b] (UT)	End[b] (UT)	X ray[c]	Proton flux[d]	ν events
3B	25 Feb 1984	03:12	03:55	M2.5		0
4B	14 Mar 1984	03:23	04:45	M2.0	100	0
3B	01 Apr 1984	21:37	23:20	C7.6		0
4B	21 Apr 1984	01:58	03:33			1[e]
3N	22 Apr 1984	04:20	04:56	C5.6		0
3N	24 Apr 1984	03:46	04:44	X1.0		0
3B	24 Apr 1984	23:56	25:35	X13.0*	2500	0
3B	01 May 1984	01:38	03:25	M4.0		0
4B	04 Feb 1986	07:32	08:35	X3.0*		0
3B	04 Feb 1986	10:26	10:44			0
3B	06 Feb 1986	06:18	07:36	X1.7*	130	0
3B	11 Feb 1986	03:30	04:50			0
3B	01 Feb 1987	14:00	15:50			0
3B	02 Jan 1988	21:11	24:09	X1.4	92	0
3B	02 Jul 1988	00:41	02:02	M3.0		0

[a]The maximum importance is adopted if a solar flare is recorded by more than one observatory.

[b]The earliest start time and the latest end time are given in the case that several observatories give different start or end times with the same importance.

[c]Importance of the flares as seen in soft x rays (1–8 Å). The symbols X, M, and C stand for the importance in decreasing order and the number is a relative importance in the class (Ref. 8). The asterisk in this column means that intense hard x rays (25–440 keV) are also observed (Ref. 10).

[d]Proton flux (cm^{-2} s^{-1} sr^{-1}) measured at > 10 MeV at a geosynchronous satellite orbit (Ref. 8).

[e]ν_μ detected on 21 April 1984, at 3:31 UT with a muon energy of 411 MeV.

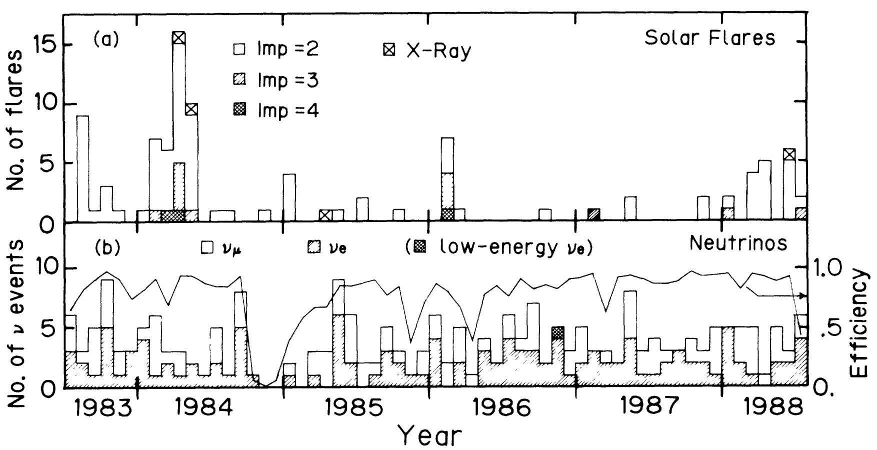

FIG. 1. The sensitivity of the Kamiokande detector to the solar-flare ν_e flux plotted as a function of ν_e energy, corresponding to one neutrino event in the detector. The curves are plotted for KAM-I with a fiducial mass of 880 tons and for KAM-II low-energy events with a fiducial mass of 680 tons. The shaded region indicates the solar-flare ν_e flux estimated from the results of the ^{37}Cl experiment.

cribed.[1]

The sensitivity of our experiment is presented in Fig. 1,[11] which exhibits the ν_e flux on Earth corresponding to one neutrino event in the Kamiokande detector as a function of the incident neutrino energy. We have also shown the flux suggested by the ^{37}Cl experiment[1] from the provisional identification of the ^{37}Ar excess events with solar-flare neutrinos. In calculating the sensitivity, we used the neutrino reaction cross section on ^{16}O as given in Ref. 6 for $E_\nu > 50$ MeV, and that given by Haxton[12] for $E_\nu \leq 50$ MeV, with efficiency of event selection and the computer dead time taken into account. To draw the sensitivity curve we considered two cases: one is only for ν_e and the other for $\nu_e:\bar{\nu}_e:\nu_\mu:\bar{\nu}_\mu = 1:1:2:2$. The limits derived from the ν_e flux alone are regarded as conservative limits. From this analysis it may be concluded that the 90%-confidence-level upper limit for the time-integrated ν_e flux per flare which might have arisen from a solar flare is 3.7×10^7 (2.5×10^9) cm^{-2} at $E_\nu = 100$ (50) MeV.

We may also extend our analysis to flares of optical importance ≥ 2 or maximum x-ray importance (X) with optical importance ≤ 1, which were observed 99 times in the same period. No ν_e events are in coincidence with these flares, and only three ν_μ came during the interval of (start of flare -1 h, end of flare $+1$ h), which is statistically consistent with an expected background of 1.8 events.

We also consider the possibility that the strong neutrino flux arises from flares on the side of the sun opposite to Earth, which is not visible by the optical observation. For such flares we cannot define an exact coincidence, but we may look for a correlation between the numbers of flares and neutrino events summed over long periods. We plot monthly numbers for flares and neutrino events in Fig. 2, where no correlation between the two event types is seen.

Finally, we have searched for neutrino events during the period of run No. 86 of the ^{37}Cl detector at Homestake, in which an excess of 40 ± 16 ^{37}Ar events was reported.[1] It has been pointed out[1] that this run occurred at the same time as a γ-ray burst observed by the Solar Maximum Mission satellite on 5 August 1984 at 23:48:00 UT (the duration is about 45 s) in the constellation Hydra.[3] Corresponding to the 40 excess events in

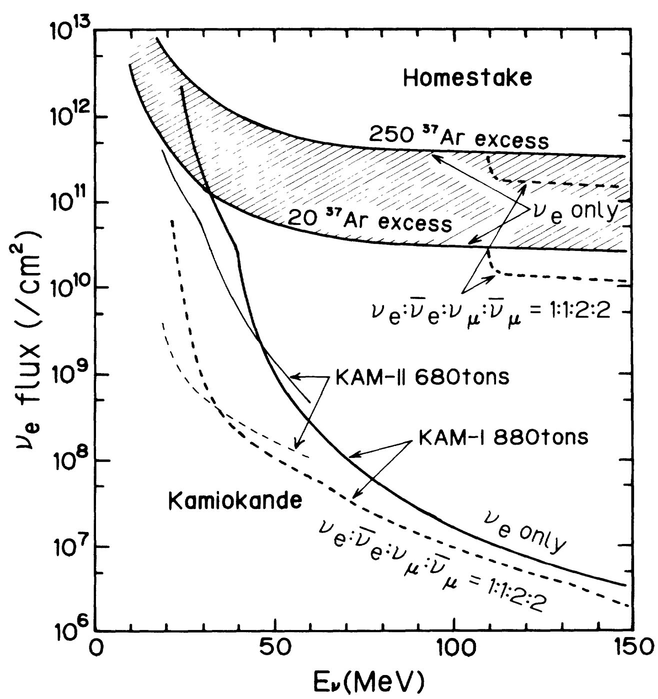

FIG. 2. (a) Number of solar flares with optical importance ≥ 2 or maximum x-ray importance (X) with optical importance ≤ 1. (b) Number of single-ring ν_e and ν_μ events observed by the Kamiokande detector. The monthly data-taking efficiency is also shown by the solid line (right vertical scale).

the ^{37}Cl detector, the Kamiokande detector, which was operative at the time, should have observed $\gtrsim 3600$ (100) events, if $E_\nu \gtrsim 100$ (50) MeV. No neutrino events, however, were recorded in Kamiokande at the time and consequently the possible neutrino flux associated with this γ-ray burst is at most $\frac{1}{100}$ times that estimated from the ^{37}Cl data, provided that $E_\nu \gtrsim 50$ MeV.

We also search for ν_e and ν_μ events during the entire period of run No. 86 (20 July 1984–2 September 1984[13]). We recorded two ν_e events, which is again consistent with the expected background of 3.0 ν_e and 2.6 ν_μ events. No anomalous clustering of neutrino events is found during the period of run No. 86, while we anticipate at least 60 events in Kamiokande for $E_\nu \gtrsim 50$ MeV from the residual ^{37}Ar of the ^{37}Cl experiment. (This number is obtained by the assumption that the excess events occurred on the last day of run No. 86). We conclude that the excess capture of run No. 86 of the ^{37}Cl experiment was not due to the interaction of neutrinos with an energy in excess of 50 MeV.

In summary, the data of the Kamiokande detector do not support the hypothesis[1,4] that there is an increase of neutrino flux with $E_\nu \gtrsim 50$ MeV at the time of solar flares, which were correlated with the excess events observed in the ^{37}Cl solar-neutrino detector.[14] However, the sensitivity of the Kamiokande detector to solar-flare neutrinos with $E_\nu \gtrsim 100$ MeV already reaches[6] an optimistic theoretical estimate of the neutrino flux which might arise from a flare,[15] which corresponds to 5–10 events in the Kamiokande detector for a large flare. In addition, a possible neutrino flux at solar maximum in 1990 ± 1 yr, with the energy loss in the Sun as its source,[15] translates into ~ 20 events/day in the Kamiokande detector. Accordingly, it remains interesting and possibly important to seek neutrino events in coincidence with very large solar flares, or with the period of maximum solar activity toward the peak of solar cycle 22 expected to come in a few years.

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