Experimental Limit on the Flux of Relic Antineutrinos from Past Supernovae

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We report the result of a search in the Kamiokande II detector for the interactions of electron-type antineutrinos in the energy level 19 to 35 MeV. We measure directly a 90%-C.L. upper limit of 226 $\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$ on the flux of electron antineutrinos with energies in that interval. An upper limit on the total flux of relic antineutrinos from past supernovae is obtained as a function of the effective equilibrium temperature of the relic antineutrino sea.

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The recent observation[1,2] of a neutrino burst emitted by SN1987A provided direct experimental evidence in support of the basic elements of the current model of type-II supernovae.[3] The inferred total number ($\sim 10^{57}$) and energy ($\sim 3\times 10^{53}$ ergs) of the emitted neutrinos fix the temperature of the radiating neutron star to be in the vicinity of 4 MeV. With this experimental and theoretical insight, it becomes possible to make a meaningful search for the relic neutrinos which originated from past supernovae. These relics, unlike those from the "big bang,"[4] may have detectable energies because reasonable models of stellar evolution[5] suggest that the integrated red-shift factor for all past supernova neutrinos is unlikely to have lowered the mean neutrino energy by a factor much smaller than 0.5. Estimates of the total relic antineutrino flux from past supernovae[5] vary widely from 1 to 10^5 $\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$, with the mean energy of the roughly Fermi-Dirac distribution of those antineutrinos in the vicinity of 10 MeV.

In this paper we report the result of a search in the data of the Kamiokande II detector for the interactions of relative low-energy electron-type antineutrinos ($\bar{\nu}_e$). In the energy interval of particular interest here, 19 to 35 MeV, the dominant (by a factor of at least 20) neutrino interaction probability is for the reaction $\bar{\nu}_e p_{\mathrm{free}} \to e^+ n$. Furthermore, above the lower limit of that interval, the residual background from $^8\mathrm{B}$ solar neutrinos, from β decays of nuclei produced by inelastic interactions of cosmic-ray muons in the detector, and from $\bar{\nu}_e$ from reactors and the Earth itself, all of which peak below 10 MeV, is small, as is the event rate resulting from the flux of atmospheric ν_e ($\bar{\nu}_e$) and ν_μ ($\bar{\nu}_\mu$).

Kamiokande II is an imaging water Cherenkov detector of useful water mass 2140 tons, viewed by the photocathodes of 948 photomultiplier tubes (PMT's), each 0.5 m in diameter, which cover 20% of the surface area of the cylindrical tank containing the water. The detector is surrounded by a 4π-solid-angle water Cherenkov counter which serves as both an absorber and anticounter. Kamiokande II has been described in detail elsewhere.[6] The salient properties relevant here are the following: (a) it has greater than 90% geometrical detection efficiency for electrons of 15 MeV and above in the total volume; (b) the vertex of an interaction producing an electron with $E_e \geq 19$ MeV is determined with a 1σ error of 0.7 m in each of the three coordinates; (c) the uncertainty on the direction of an electron with $E_e = 19$ MeV is 20°; and (d) $\Delta E_e/E_e = 0.15$ for $E_e = 19$ MeV, where E_e is the electron total energy.

The data reported here were taken during the period 6 January 1986 to 31 December 1987, yielding a total of 357.4 live detector days.[7] Events were accepted satisfying the following criteria: (i) The total number of photoelectrons detected in the anticounter was less than 20, indicating containment of the event. (ii) The number of PMT discriminators per event yielding a signal was equal to or greater than 30, corresponding[6] to approximately 10 MeV. This served as a coarse energy threshold. (iii) The time interval between an accepted event and the event immediately preceding it was greater than 100 μsec; this requirement eliminated the electrons and positrons from all muon decays. (iv) The ratio of the number of PMT signals within 100 nsec to the total number of PMT signals in the 400-nsec event gate was greater than 0.75. This cut eliminated occasional electric noise events for which the uncorrected PMT times were excessively spread. (v) The time interval between an accepted event and the previous cosmic-ray muon passing through the detector was greater than 100 msec; this requirement eliminated the short-lived β decays from spallation products induced by cosmic-ray muons. (vi) The χ^2 per degree of freedom specifying the quality of reconstruction of an event was less than 1.5.

The event-selection process began with 162623 events satisfying the criteria (i)-(vi) above, and proceeded through a subsample of 37071 events which met the further condition that all event origins were at least 1.0 m from the surface of the nearest PMT. The vertical (z) and radial (r^2) distributions of the 37071-event sample are shown in Figs. 1(a) and 1(b). These distributions dictated the use of a smaller fiducial volume, i.e., $-3.9 < z \leq 3.0$ m and $r \leq 5.2$ m. Within this fiducial volume there remains 3985 events, and the exposure then amounts to 0.58 k-y.

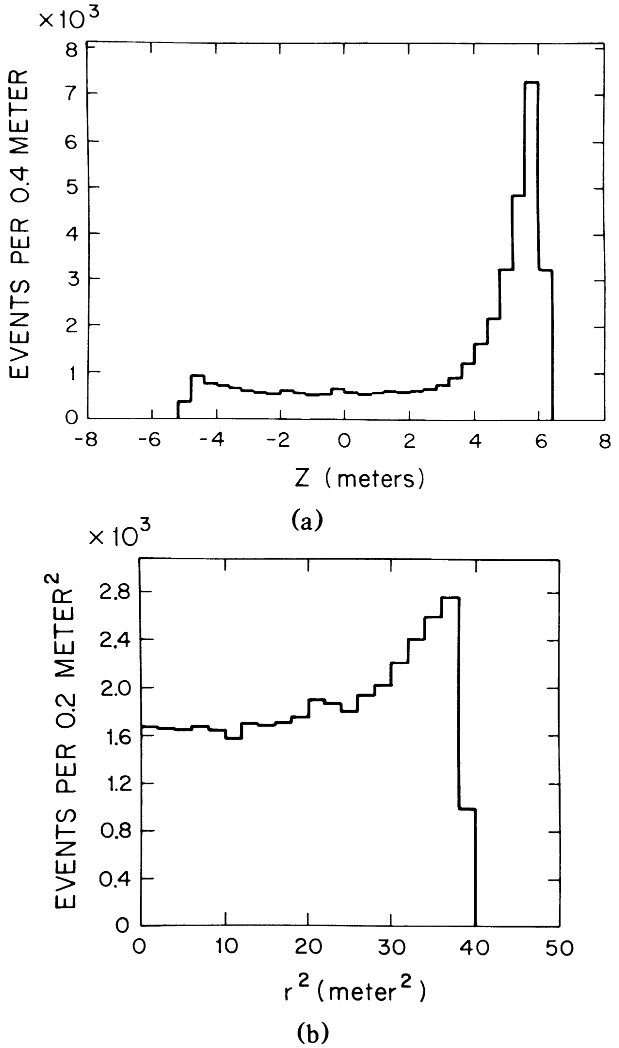

FIG. 1. (a) The vertical (z) distribution of the 37071 events remaining after application of the criteria (i)-(vi) in the text, and the further condition that all event origins lie at least 1.0 m from the nearest PMT. (b) The radial (r^2) distribution of the 37071-event sample.

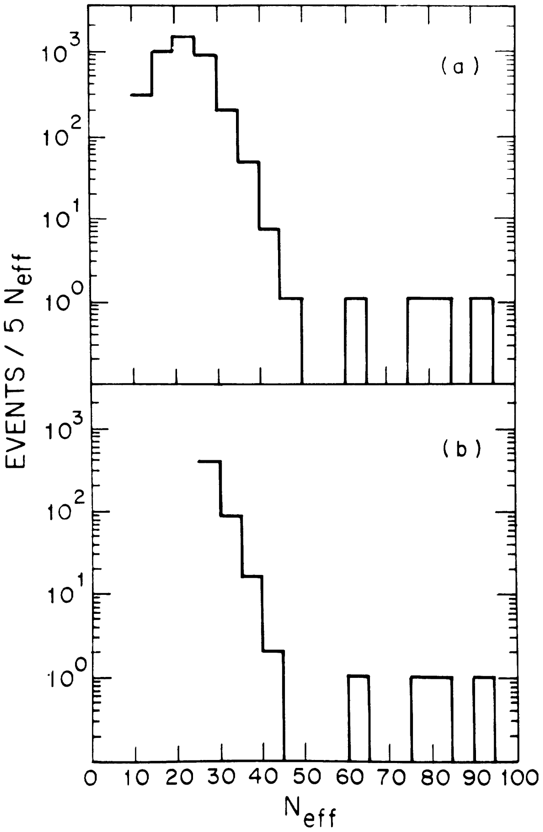

FIG. 2. (a) The N_{eff} distribution of the 3985 events in the final fiducial volume, where N_{eff} is the corrected number of hit PMT's, approximately proportional to electron or positron energy. (b) The spectrum of 535 events with $N_{\mathrm{eff}} \geq 25$ that remain after all cuts.

The distribution in $N_{\rm eff}$ of the 3985 events in the fiducial volume is shown in Fig. 2(a), where $N_{\rm eff}$ is the corrected number of PMT's yielding a signal, and is approximately proportional to the total energy of the electron or positron.[6] Above $N_{\rm eff}=25$ ($E_e \simeq 11$ MeV), there are 1156 events which are subjected to a further cut to remove β decays from long-lived spallation products.[8] The spectrum of the 535 events with $N_{\rm eff} \geq 25$ that remain after the long-lived spallation product cut is shown in Fig. 2(b). The exponentially decreasing spectrum of the final sample in the interval $25 \leq N_{\rm eff} < 50$ in Fig. 2(b) is almost entirely due to (i) the tail of penetrating background radiation from outside the fiducial volume, e.g., from the walls of the cavity that houses the detector, and (ii) the long-lived spallation-produced events which survived the applied cut. The $N_{\rm eff}$ dependence of each of the background components is similar, and each contributes roughly one-half of the events in the intervals $25 \leq N_{\rm eff} < 50$ in Fig. 2(b).

To extract the number of candidates in the interval $N_{\rm eff}-40$ ($E_{\bar\nu_e} \simeq 19$ MeV) to $N_{\rm eff}=70$ ($E_{\bar\nu_e} \simeq 35$ MeV), we take the number of events in that energy interval directly from the spectrum of Fig. 2(b). In addition, the atmospheric ν_e ($\bar\nu_e$) and ν_μ ($\bar\nu_\mu$) flux is estimated to contribute one event in the interval $19 \leq E_e \leq 35$ MeV through quasielastic and single-pion production reactions. This arises because a fraction of the reactions produce muons with energies below the threshold for Cherenkov radiation (53 Mev) which decay to the observed electrons. Hence with three observed events, between $N_{\rm eff}=40$ ($E_{\bar\nu_e} \simeq 19$ MeV) and $N_{\rm eff}=70$ ($E_{\bar\nu_e} \simeq 36$ MeV), if we subtract the contribution of the atmospheric neutrinos, and include event selection efficiency and dead time, the directly measured, model-independent, 90%-C.L. upper limit on the flux of relic supernovae antineutrinos in the energy interval 19 to 35 MeV is

$$\int_{19\,\rm MeV}^{35\,\rm MeV} \frac{d\Phi_\nu(E_\nu)}{dE_\nu} dE_\nu = 9.61\times 10^{-40} \sum [\sigma_i(E_{\bar\nu_e})\epsilon_i(E_{\bar\nu_e})]^{-1} \leq 226\ {\rm cm}^{-2}{\rm sec}^{-1}, \tag{1}$$

where $E_{\bar\nu_e}=E_e+1.3$ MeV, $\sigma(E_{\bar\nu_e})=\sigma_0 E_{\bar\nu_e}^2$ is the cross section for $\bar\nu_e p \rightarrow e^+ n$, and $\epsilon(E_{\bar\nu_e})$ is the event-selection efficiency. In the numerical calculation of Eq. (1), the cross section for all three events was conservatively evaluated at 19 MeV.

The recent observation and current model neutrino emission from a type-II supernova suggest that the antineutrino energy spectrum of a single supernova is roughly consistent with a Fermi-Dirac spectrum corresponding to the initial temperature T of the newly formed neutron star. By parametrization of the relic antineutrino spectrum as a Fermi-Dirac distribution, the number of observed events may also be used to determine an upper limit on the total antineutrino flux $\Phi_0(\bar\nu_e)$, without our invoking a specific model of stellar evolution. Thus, we write

$$L\sigma_0\Phi_0(\bar\nu_e)\int_{19\,\rm MeV}^{35\,\rm MeV} \epsilon(E_{\bar\nu_e})dE_{\bar\nu_e} \left(\int_0^\infty F(E,T_{\rm eff})E^2 G(E-E_{\bar\nu_e})dE\right] \leq 5.68\ \text{events}, \tag{2}$$

where $F(E,T_{\rm eff})$ is the normalized Fermi-Dirac distribution, $G(E)$ is a Gaussian resolution function with rms$=0.67E^{1/2}$, L is the total exposure in units of free protons times seconds, $T_{\rm eff}$ is the effective equilibrium temperature of the relic antineutrino sea, and 5.68 events yield the 90%-C.L. upper limit according to Poisson statistics when three events are observed with one event expected from background. This is shown in Fig. 3, which gives the 90%-C.L. upper limit on $\Phi_0(\bar\nu_e)$ from the observation reported here in terms of the single variable, $T_{\rm eff}$. The curve in Fig. 3 is dependent on the accuracy with which the value of the lower limit of the integrals of Eqs. (1) and (2) is known ($\pm 5\%$); at $T_{\rm eff}=2$ MeV, for example, the limiting value of $\Phi_0(\bar\nu_e)$ is increased by approximately 60% and decreased by approximately 30% for a 1-MeV increase and decrease, respectively, of the lower limit on the integrals.

It is seen that the limiting values of $\Phi_0(\bar\nu_e)$ in Fig. 3, for example, $\Phi_0(\bar\nu_e) \leq 4.5\times 10^4$ cm^2 sec^{-1} at $T_{\rm eff}=2$ MeV, are large but perhaps within the range of values of interest in some models of stellar evolution.[5] We anticipate that a specific model which provides a rate of supernova occurrence and a corresponding integrated red-shift factor will in turn lead to numerical values of $T_{\rm eff}$ and

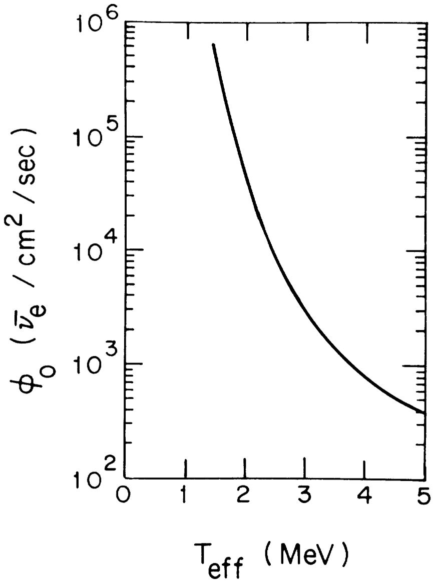

FIG. 3. The 90%-C.L. upper limit on the total relic-supernova-antineutrino flux $\Phi_0(\bar\nu_e)$ as a function of the effective equilibrium temperature $T_{\rm eff}$ of the relic-antineutrino sea.

$\Phi_0(\bar{\nu}_e)$. These values may then be compared with the 90%-C.L. upper limit on $\Phi_0(\bar{\nu}_e)$ at that $T_{\rm eff}$ in Fig. 3.[9]

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[7] Only data taken during nonholiday weekdays were used. These data include complete information about each cosmic-ray muon, which was required to evaluate spallation background.

[8] Muon-induced spallation of ^{16}O has been studied in detail because it is a background source in the Kamiokande II solar-neutrino measurement. The short-lived ($T_{1/2}=18.2\pm1.8$ msec, $E_{\rm max}\sim16$ MeV) radioisotope decays were removed by cut (v) in the text. The longer-lived ($T_{1/2}=0.77\pm0.13$ sec, $E_{\rm max}\sim14$ MeV) isotopes require a more elaborate rate cut: A low-energy event is rejected if the distance between its vertex and the muon trajectory is less than 2.0 m and the time elapsed between the two is less than a certain value depending on the energy deposition of the muon. The dead time introduced by this cut is 7%.

[9] Clearly, if a different form of $d\Phi_0(\bar{\nu}_e)/dE_{\bar{\nu}_e}$ is preferred for the $\bar{\nu}_e$ spectrum from SN1987A, it may be substituted for the Fermi-Dirac distribution of Eq. (2), and a new upper limit curve of $\Phi_0(\bar{\nu}_e)$ vs $T_{\rm eff}$ obtained.