Nuclear response of water Cherenkov detectors to supernova and solar neutrinos

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I present a careful examination of the nuclear cross sections of low-energy neutrinos and antineutrinos in water Cherenkov detectors, and consider the implications for neutrinos from SN1987A. For thermal sources with $T \gtrsim 4$–5 MeV (depending on the detector threshold) the reaction $\mathrm{O}(\nu_e,e^-)\mathrm{F}$ becomes the dominant mechanism for ν_e interactions, and at $T \gtrsim 7$–9 MeV its rate exceeds that for (ν_e,e) elastic scattering by at least an order of magnitude. This has important implications for proposed mechanisms for prompt emission of energetic ν_e's following neutronization. The $\mathrm{O}(\bar{\nu}_e,e^+)\mathrm{N}$ contribution remains a small correction to the dominant $\bar{\nu}_e+p \to e^+ + n$ rate, accounting for less than 10% of the events even at $T=10$ MeV. Thus delayed β^- emission by $^{16}\mathrm{N}(\tau_{1/2}=7.1$ sec) cannot distort event timing. Observable neutral-current nuclear excitations are absent in water, but can be strongly excited in carbon-bearing liquid-scintillation detectors. Arguments are given that a burst poor in electron neutrinos and antineutrinos, but otherwise similar to those derived from standard supernovae theory, might produce comparable signals in the Mt. Blanc, Kamioka, and Irvine-Michigan-Brookhaven detectors. For solar neutrinos generated by $^8\mathrm{B}$ β decay, reactions with trace quantities of $^{18}\mathrm{O}$ (two atoms per 10^4 electrons in natural water) account for approximately 10% of electron events. If it proves feasible to enhance the $^{18}\mathrm{O}$ content of a water Cherenkov detector, the hard spectrum of produced electrons would make an attractive charged-current signal.

I. INTRODUCTION

We are extremely fortunate to have two large water Cherenkov detectors functioning as observatories of low-energy neutrinos. The Kamioka and Irvine-Michigan-Brookhaven (IMB) Collaborations recently observed[1,2] neutrino bursts of 11 and 8 events, respectively, occurring approximately 18 h before the first optical sighting of supernova 1987A. From the flux, timing, and energy distribution of these events, one hopes to learn a great deal about the dynamics of stellar collapse and neutron-star formation, and about the properties of neutrinos that have traveled galactic distances. In addition, the sensitivity of the Kamioka detector to low-energy neutrinos has been improved to the point that an important measurement of the $^8\mathrm{B}$ solar-neutrino spectrum may soon result.[3] Because of level-crossing enhancements in matter,[4] the shape of the $^8\mathrm{B}$ spectrum could provide an important test of neutrino oscillations for $\delta m^2 \sim 10^{-4}$–10^{-8} eV^2 and $\sin^2 2\theta \gtrsim 10^{-3}$.

Most analyses of events from SN1987A have assumed that the principal neutrino reactions in water are $\bar{\nu}_e+p \to e^+ + n$ off free protons and (ν,e) elastic scattering. The purpose of this paper is to consider the effect of charge-current (and neutral-current) scattering off the oxygen nuclei. These cross sections can be calculated accurately because of constraints from measured β-decay rates, (p,n) calibrations of Gamow-Teller strength, and electron scattering form factors. To help experimentalists, double differential cross sections are given for thermal neutrino sources with 3 MeV $\leq T \leq 10$ MeV, and both angular distributions and total cross sections are presented for triggering efficiencies characteristic of the Kamioka and IMB detectors. I also consider the relation between the responses of liquid-scintillator and water Cherenkov detectors in view of the large neutral-current signal in the former (an energetic γ ray following excitation of the 15.11 MeV level in $^{12}\mathrm{C}$).

Because of the rapid progress made by the Kamioka Collaboration in detecting low-energy neutrinos, I also consider possible nuclear contributions in the detection of solar neutrinos.

For those readers interested primarily in the qualitative results of this analysis, the main conclusions are summarized below.

(a) For thermal sources with $T \gtrsim 4$–5 MeV (depending on the detector threshold) the reaction $\mathrm{O}(\nu_e,e)\mathrm{F}$ becomes the principal mechanism for ν_e interactions, and at $T \gtrsim 7$–9 MeV its rate exceeds that for (ν_e,e) elastic scattering by an order of magnitude. Fits to the Kamioka and IMB SN1987A events favor a temperature (presumably of the $\bar{\nu}_e$'s) of $T \sim 4$–5 MeV, though a wider range ($T \sim 3$–7 MeV) probably cannot be ruled out.[5] The enhanced sensitivity to high-energy neutrinos is important because ν_e's produced by neutronization in the hot stellar core would then produce a larger, prompt ($\sim$10-msec duration) signal if neutrino trapping fails to occur. The angular distribution of these events is somewhat backward-peaked. Thus, for ν_e's produced thermally (after neutronization) at $T \gtrsim 5$ MeV, it is unfortunate that the dominant reaction mechanism is difficult to distinguish from $\bar{\nu}_e+p \to e^+ + n$.

(b) The $\mathrm{O}(\bar{\nu}_e,e^+)\mathrm{N}$ rate is a small correction to that for $\bar{\nu}_e+p \to e^+ + n$, accounting for less than 8% of the e^+ events even at $T=10$ MeV. Transitions to bound states of $^{16}\mathrm{N}$ do not exceed 1% of the $\bar{\nu}_e+p \to e^+ + n$

rate. This rules out delayed β^- and $\beta^-\gamma$ emission by ^{16}N ($\tau_{1/2}=7.13$ sec) as a significant mechanism for spreading event times in water Cherenkov detectors. (The observed spreads in the Kamioka and IMB bursts, 13 and 6 sec, respectively, are comparable to the ^{16}N half-life.)

(c) Possible neutral-current transitions to bound states in ^{16}O are both low in energy and forbidden in the allowed approximation. In contrast, the transition to the 1^+ 1 15.11 MeV level in ^{12}C is strong, and the branching ratio for subsequent γ decay to the ground state is 96%. Thus carbon-based liquid-scintillation detectors, such as that in use at the Mt. Blanc laboratory, have enhanced sensitivities to muon and taon neutrinos. This suggests a possible scenario to explain the Mt. Blanc events, and the absence of corresponding Kamioka and IMB signals, that does not assume an unrealistically large neutrino luminosity.

(d) A nuclear contribution of approximately 10% to ^8B solar-neutrino capture results from trace quantities of ^{18}O (0.204% abundant) in water. The large cross section can be calculated very accurately from known β-decay rates, and the resulting electron spectrum is unusually hard. If large quantities of ^{18}O-enriched water can be obtained, an attractive charged-current detector could be built.

II. NEUTRINO REACTIONS

The nuclear cross section for charged-current neutrino reactions is given by[7]

$$\frac{d\sigma}{d\Omega}\begin{bmatrix}\nu_e\\ \bar{\nu}_e\end{bmatrix}=\frac{2}{\pi}G_F{}^2\cos^2\theta_c F(Z,\epsilon)\frac{\epsilon^2}{2J_i+1}\cos^2\frac{\theta}{2}$$
$$\times\left[\sum_{J=0}^{\infty}\left|\left\langle J_f\left|\left|\mathcal{M}_J+\frac{\omega}{|\mathbf{q}|}\mathcal{L}_J\right|\right|J_i\right\rangle\right|^2+\left[\frac{1}{2}\frac{q^2}{\mathbf{q}^2}+\tan^2\frac{\theta}{2}\right]\sum_{J=1}^{\infty}\left(|\langle J_f\|\mathcal{T}_J^{\mathrm{el}}\|J_i\rangle|^2+|\langle J_f\|\mathcal{T}_J^{\mathrm{mag}}\|J_i\rangle|^2\right)\right.$$
$$\left.\mp 2\tan\frac{\theta}{2}\left[\frac{q^2}{\mathbf{q}^2}+\tan^2\frac{\theta}{2}\right]^{1/2}\sum_{J=1}^{\infty}\mathrm{Re}(\langle J_f\|\mathcal{T}_J^{\mathrm{mag}}\|J_i\rangle\langle J_f\|\mathcal{T}_J^{\mathrm{el}}\|J_i\rangle^*)\right], \quad (1)$$

where $G_F\cos\theta_c$ is the weak coupling constant, θ is the angle between the electron and neutrino, ω and $\mathbf{q}$ are the nuclear excitation energy and three-momentum transfer, $q^2=\mathbf{q}^2-\omega^2$, and ϵ is the energy of the outgoing electron. The function $F(Z,e)$ corrects the electron phase space for the effects of Coulomb distortion in the field of the daughter nucleus of charge Z. Equation (1) assumes that $\epsilon \gg m_e$ and that the nucleus is infinitely heavy. The operators $\mathcal{M}_J$, $\mathcal{L}_J$, $\mathcal{T}_J^{\mathrm{el}}$, and $\mathcal{T}_J^{\mathrm{mag}}$ are the usual charge, longitudinal, transverse-electric, and transverse-magnetic projections of the weak charge-changing hadronic current

$$J_\mu^{\pm}=J_\mu^1 \pm iJ_\mu^2 , \quad (2)$$

where $J_\mu^i, i=1,2,3$, are the three components of an isovector. The reduced matrix elements appearing in Eq. (1) are functions of the three-momentum transfer $|\mathbf{q}|$. In the limit of long wavelengths and nonrelativistic nucleons, the only nonvanishing matrix elements involve the Fermi and Gamow-Teller operators (only the one-body currents are retained)

$$M_F=\left\langle J_f\left|\left|\sum_{i=1}^{A}\tau_{\pm}(i)\right|\right|J_i\right\rangle , \quad (3a)$$

$$M_{\mathrm{GT}}=\left\langle J_f\left|\left|\sum_{i=1}^{A}\sigma(i)\tau_{\pm}(i)\right|\right|J_i\right\rangle . \quad (3b)$$

Excitation of the giant resonances can also be important for relatively low-energy neutrinos. These operators depend on $|\mathbf{q}|\mathbf{r}(i)$.

The analogous expression[7,8] for neutral-current scattering of neutrinos off nuclei can be obtained from Eq. (1) by replacing ϵ by $\epsilon_{\nu'}$, the energy of the scattered neutrino. The multipole operators now involve the hadronic neutral current

$$J_\mu^{\mathrm{NC}}=J_\mu^3-2\sin^2\theta_W J_\mu^{\mathrm{em}} . \quad (4)$$

J_μ^3 is the third isospin component of the current introduced in Eq. (2), and J_μ^{em} is the electromagnetic current. I use $\sin^2\theta_W=0.22$ as the value of the Weinberg angle. In the limits of long wavelengths and nonrelativistic nucleons the only matrix element that can generate inelastic transitions is

$$M_{\mathrm{GT}}^{\mathrm{NC}}=\left\langle J_f\left|\left|\sum_{i=1}^{A}\sigma(i)\tau_3(i)\right|\right|J_i\right\rangle . \quad (5)$$

To evaluate inclusive neutrino reaction cross sections one must formulate a reasonable description of the spectrum of states in ^{16}O. The simplest model of the ^{16}O ground state, a closed core, is clearly inadequate: the Gamow-Teller matrix elements [Eqs. (3) and (5)] would then vanish. This contradicts experiment, as three $J^\pi T=1^+1$ states are known to reside at approximately 19 MeV in ^{16}O with appreciable M1 strength to the ground state $(0.3\mu_N{}^2)$.[9] The corresponding Gamow-Teller transitions have been measured in forward-angle (p,n) reactions and are weaker,[10] suggesting that the orbital contributions to the M1 matrix elements are strong.

I have thus chosen to describe the low-lying positive-parity states for $A=16$ in a full $2\hbar\omega$ shell model. The interaction adopted was that of Cohen-Kurath ($1p$ shell),[11] Millener-Kurath (cross shell $2s\,1d$-$1p$),[12] and Kuo-Brown ($2s\,1d$).[13] The remaining matrix elements were taken from the bare G-matrix elements of Kuo.[13] Since the basis contains all $2\hbar\omega$ configurations, spurious center-of-mass excitations can be trivially removed from the calculations. In this regard these shell-model calculations can be viewed as an extension of the work of Snover *et al.*,[9] who diagonalized a similar Hamiltonian in a truncated $2\hbar\omega$ basis (no excitations into or out of the $1s$ and $2p\,1f$ shell were allowed).

As in that earlier calculation, the resulting Gamow-Teller strength near 5 MeV in ^{16}F (~ 19 MeV in ^{16}O) is underestimated. The transition density matrices for the

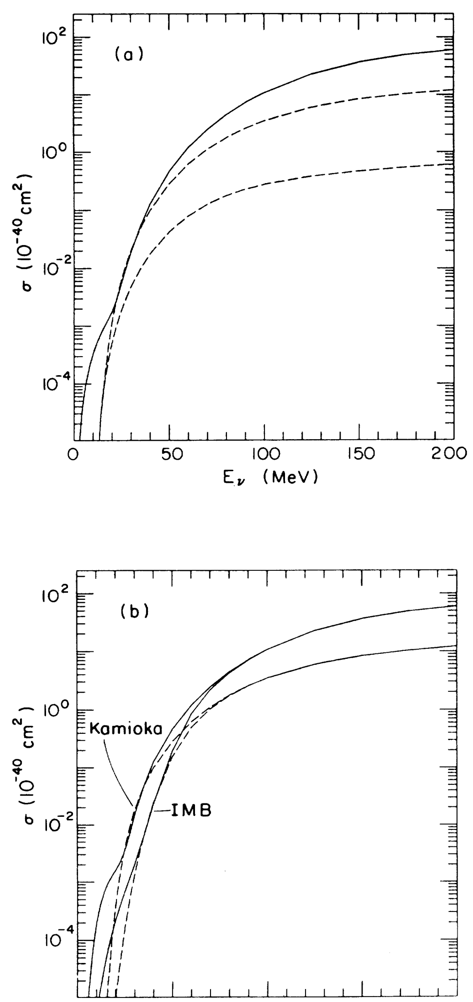

FIG. 1. Total cross sections off natural oxygen: O(ν_e,e^-)F (solid line) and O($\bar{\nu}_e,e^+$)N (dashed line). (a) assumes a perfect triggering efficiency. (b) shows the effect of Kamioka and IMB triggering efficiencies, as described in the text. The second dashed line in (a) gives the cross section to particle-bound states in ^{16}N.

three 1^+1 states in this complex (3.76, 4.65, and 6.23 MeV in ^{16}F) were multiplied by scale factors to reproduce the B(GT) values extracted from (p,n) measurements. The experimental B(GT) values[14] of these states are 0.007, 0.092, and 0.079, respectively, where

$$B(\mathrm{GT})=\frac{1}{2J_i+1}\left|\left\langle J_f\left|\left|g_A\sum_{i=1}^{A}\sigma(i)\tau_\pm(i)\right|\right|J_i\right\rangle\right|^2 . \qquad (6)$$

In addition, all transitions to higher-lying 1^+1 states were evaluated with $g_A=1.0$, a value that empirically leads to good agreement between shell model B(GT) values and measured $2s\,1d$ shell values.

Effective density matrices were also used to describe transitions to negative-parity states. The starting point[15] is a set of $1\hbar\omega$ transition amplitudes derived in the Tamm-Dancoff approximation for a Serber-Yukawa residual interaction. These coefficients were then scaled by an overall factor $1/\xi$ to reproduce measured form factors from electron scattering. Values of $\xi=1.7$ for ^{16}O states near 13 MeV and $\xi=1.4$ for states at higher energies give quite satisfactory results. These same amplitudes are then used in describing transitions to the analog states in ^{16}F and ^{16}N. This procedure[15] has been used quite successfully in analyses of semileptonic interactions in light nuclei.

Finally, although ^{17}O and ^{18}O are rare isotopes (0.038% and 0.204% abundant, respectively), strong Fermi and Gamow-Teller transitions exist at low excitation energies in these nuclei. Simple $2s\,1d$ shell-model wave functions for the relevant positive-parity states were derived from the Kuo-Brown interaction. With the choice $g_A=1.0$, the very strong Gamow-Teller transition to the 1^+0 ^{18}F ground state is well reproduced.

The complete sets of $1\hbar\omega$ and $2\hbar\omega$ ^{16}O wave functions described here should provide a reliable description of inclusive neutrino reactions for neutrino energies of present interest ($\epsilon_\nu \lesssim 100$ MeV). At such energies the allowed transitions and giant resonances determine the nuclear response. At higher energies and three-momentum transfers additional nuclear modes combine to form the nuclear quasielastic response, a region in which neutrino-induced reactions are also of astrophysical interest.[16]

III. THE NUCLEAR RESPONSE TO SUPERNOVAE NEUTRINOS

Before discussing detailed results, I will describe the qualitative response of the nuclei of interest. The thresholds for charge-current neutrino reactions on the principal isotope ^{16}O are high (15.4 and 11.4 MeV, respectively, for exciting ^{16}F and ^{16}N) and as allowed transitions only arise from core polarization, the Gamow-Teller transitions to excited states ($E_x \gtrsim 3.5$ MeV) are relatively weak. The phase space for exciting such states depends on ϵ^2, where ϵ is the energy of the emitted electron, and the angular distribution is roughly isotropic, $d\sigma/d\Omega \sim 1-\cos\theta/3$. Transitions to the giant resonances are forbidden in the long-wavelength limit, as the amplitudes depend explicitly on $|\mathbf{q}|$. However, their strength grows rapidly with increasing ϵ_ν (and thus increasing $|\mathbf{q}|$), leading to a sharply backward-peaked cross section. Energetic neutrinos will thus preferentially excite these modes. In addition, although ^{18}O has an abundance of only 0.2%, it offers, effectively, two neutrons with which the ν_e's can interact. Thus the cross section is unusually large and the excitation threshold is only 1.66 MeV. The Fermi and Gamow-Teller transitions combine to yield a nearly isotropic cross section for ^{18}O.

The total cross sections for O(ν_e,e^-)F and O($\bar{\nu}_e,e^+$)N as a function of ϵ_ν are given by the solid and dashed lines, respectively, in Fig. 1. [Two dashed lines appear in Fig. 1(a), one giving the total $\bar{\nu}_e$ cross section, the second that portion proceeding to the 2^-, 0^-, 3^-, and 1^- complex of particle-bound states. Excitations of these states are followed by β^- emission to the ground state (26%) or 6.13 MeV excited state (68%) in ^{16}O, with $\tau_{1/2}^{\beta}=7.13$ sec. As the total energy emitted in electrons and photons averages about 8 MeV per transition, this could contribute to the apparent spread of the "neutrino" burst in a low-threshold detector. This effect is always negligible, as will be seen below. No particle-bound states exist in ^{16}F.] The low-energy shoulder due to ^{18}O and ^{17}O is apparent on the solid line. The important feature of this figure is the extraordinarily rapid rise in the cross section in the region between 10 and 50 MeV.

A normalized Fermi-Dirac neutrino number distribution is assumed to describe the spectrum of neutrinos of a given flavor emitted by the supernova

$$n(E)=\frac{0.5546}{T^3}\frac{E^2}{e^{E/T+1}} . \quad (7)$$

Most fits to the events recorded by the water Cherenkov detectors have given $T\sim4-5$ MeV (Ref. 5). The response of a detector to such a spectrum depends critically on the triggering efficiency for low-energy electrons. I have used an approximate efficiency function $F=1-\exp[-(\epsilon/\epsilon_{\rm thresh})^p]$, with $\epsilon_{\rm thresh}=34$ MeV and $p=3.1$ for the IMB detector and $\epsilon_{\rm thresh}=9$ MeV and $p=3.0$ for the Kamioka detector. This parametrization was used earlier by Krauss.[5]

The results for total cross sections are given in Table I for sources with $3\leq T\leq 10$ MeV. As summarized in the Introduction, at $T\sim4$ MeV for the IMB detector and $T\sim5$ MeV for the Kamioka detector the nuclear reaction O(ν_e,e^-)F becomes the principal mechanism for ν_e reactions in water. At $T\sim7$ MeV and $T\sim9$ MeV, re-

TABLE I. Neutrino cross sections off natural oxygen for normalized Fermi-Dirac spectra of temperature T, in units of 10^{-42} cm^2, are compared to those for (ν_e,e) elastic scattering and $\bar{\nu}_e+p\rightarrow e+n$. The latter have been multiplied by 10 and 2, respectively, to account for the different abundances of oxygen nuclei, electrons, and free protons in water. The results marked "full" assume a 100% triggering efficiency. The results for the Kamioka and IMB detectors employ the efficiency functions described in the text. The cross section for ^{12}C(ν,ν')^{12}C (15.11 MeV) is also given.

	T (MeV) 3	4	5	6	7	8	10
			$\nu_e+\mathrm{O}\rightarrow e^-+\mathrm{F}$				
Full	0.0498	0.236	0.880	2.49	5.73	11.4	32.8
Kamioka	0.0391	0.209	0.829	2.41	5.63	11.2	32.6
IMB	0.0049	0.049	0.297	1.16	3.31	7.58	26.1
			$\bar{\nu}_e+\mathrm{O}\rightarrow e^++\mathrm{N}$				
Full	0.0306	0.187	0.650	1.65	3.41	6.15	15.2
Kamioka	0.0229	0.164	0.609	1.59	3.34	6.08	15.1
IMB	0.0029	0.038	0.213	0.74	1.90	3.97	11.8
			$\bar{\nu}_e+\mathrm{O}\rightarrow e^++\mathrm{N}$ (bound)				
Full	0.0103	0.0480	0.139	0.307	0.570	0.940	2.01
Kamioka	0.0084	0.0444	0.134	0.302	0.565	0.936	2.01
IMB	0.0012	0.0121	0.054	0.159	0.355	0.662	1.64
			$\nu_e+e\rightarrow\nu_e+e$ ($\times10$)				
Full	0.853	1.15	1.44	1.74	2.03	2.33	2.92
Kamioka	0.291	0.525	0.785	1.06	1.34	1.63	2.21
IMB	0.017	0.048	0.105	0.189	0.303	0.442	0.786
			$\bar{\nu}_e+p\rightarrow n+e^+$ ($\times2$)				
Full	20.5	36.0	55.7	79.4	107	138	212
Kamioka	16.1	32.4	52.9	77.3	105	137	211
IMB	1.95	7.16	17.8	34.8	58.2	87.6	162
			$\nu+{}^{12}\mathrm{C}\rightarrow\nu+{}^{12}\mathrm{C}^*$ (15.11 MeV)				
Full	0.0519	0.232	0.602	1.18	1.97	2.94	5.32

spectively, the rate for this reaction exceeds that for (ν_e, e) elastic scattering by an order of magnitude. Thus the inclusion of the nuclear contribution qualitatively alters the detector response over the temperature region of interest.

The enhanced sensitivity to high T neutrinos is important because ν_e's produced by neutronization in the hot stellar core ($T \sim 10$ MeV) could produce a large, prompt ($\sim$10-msec duration) signal if neutrino trapping fails to occur. The present result thus imposes a more severe constraint on any mechanisms[17] that lead to a reduced opacity for electron neutrinos.

The $O(\nu_e, e^+)N$ rate is somewhat lower than that for $O(\nu_e, e^-)F$ and is a smaller correction to the dominant process $\bar{\nu}_e + p \rightarrow e^+ + n$, accounting for less than 8% of the e^+ events even at $T = 10$ MeV. Transitions to particle-bound states of ^{16}N never exceed 1% of the $\bar{\nu}_e + p \rightarrow e^+ + n$ rate. This rules out delayed β^- and $\beta^-\gamma$ emission by ^{16}N ($\tau_{1/2} = 7.13$ sec) as a significant mechanism for spreading event times in water Cherenkov detectors.

The numerical results are summarized in Figs. 2–5. Figures 2 and 3 give $d\sigma/d\Omega$ for $C(\nu_e, e^-)F$ and $O(\bar{\nu}_e, e^+)N$, respectively, assuming a normalized neutrino spectrum [(Eq. 17)] for $T = 3$, 4, 5, and 10 MeV. For the solid curves labeled Kamioka and IMB, the spectra of outgoing electrons have been folded with the appropriate efficiency functions discussed earlier. The third curve would be appropriate for an ideal detector ($F = 1$). The dashed curves in Fig. 3 are the corresponding results for exciting only the bound states in N. In all cases, a natural oxygen target has been assumed. The cross sections become increasingly backward peaked with increasing T, reflecting the strong contribution from giant resonances whenever the kinematics permits a large three-momentum transfer to the nucleus.

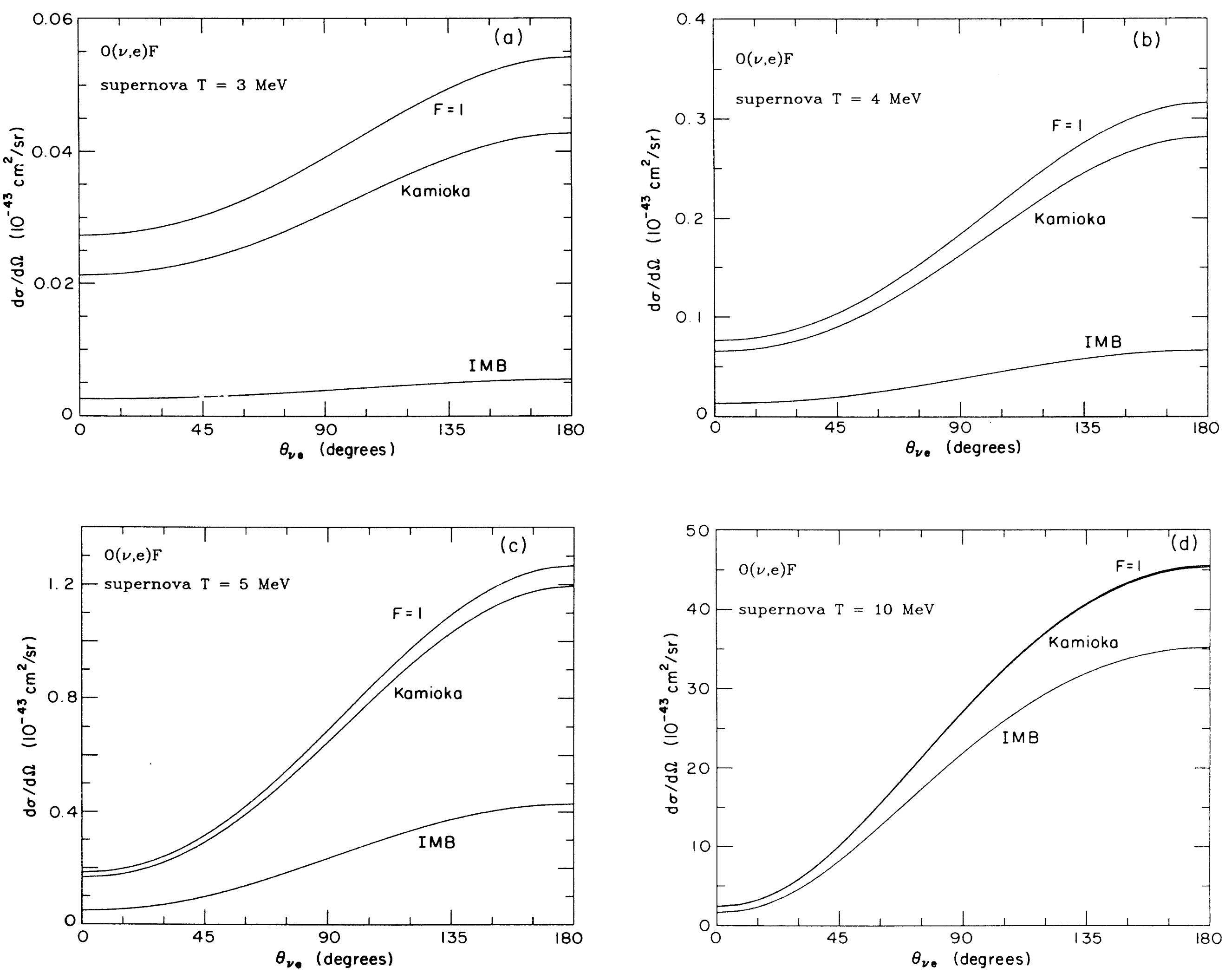

FIG. 2. Differential cross sections for $O(\nu_e, e^-)F$ averaged over Fermi-Dirac distributions with $T = 3$, 4, 5, and 10 MeV. The curves are labeled according to the assumed triggering efficiencies.

Figures 4 and 5 give the double differential cross sections $d\sigma/d\Omega dE_e$, where E_e is the outgoing electron energy, for scattering angles between 15° and 165°, in 15° steps, and for T=4, 5, 6, and 8 MeV. These results should be useful to experimentalists, as they provide the basic information that, when combined with efficiency functions, will determine the nuclear response of any water Cherenkov detector.

So far only charge-current interactions have been discussed. Neutral-current interactions in water Cherenkov detectors should not be significant. Although ^{16}O can be excited in (ν,ν'), no allowed transitions occur to bound states. [The obvious signal for (ν,ν') in a water Cherenkov detector is the subsequent γ decay of the excited nuclear state.] Furthermore, those bound states that could be excited by forbidden transitions are low in excitation energy ($\lesssim$9 MeV), so the subsequent low-energy γ ray would be very difficult to detect. In this respect, it is very interesting to compare water Cherenkov detectors with carbon-based liquid-scintillation detectors (LSD's), such as that operated by the Mt. Blanc Collaboration. There exists a strong allowed transition to the 15.11 MeV 1^+1 in state in ^{12}C that can be excited in inelastic neutrino scattering,[8] and the dominant decay mode of this state (96%) is the emission of a 15.11-MeV γ ray. Thus a reasonably attractive signal exists for the (ν,ν') mode.

This neutral-current asymmetry between LSD's and water Cherenkov detectors is amusing in view of the reported neutrino burst (5 events with energies between 7 and 11 MeV) by the Mt. Blanc Collaboration. This result is widely discounted because no corresponding signal was recorded in the much larger water Cherenkov detectors. (However, see Ref. 20.) For instance, comparing the composition and fiducial volume of the Kamioka (2140 tons) and Mt. Blanc (90 tons) detectors, one would expect $(92\pm41)X(T)$ events in the Kamioka detector if the Mt. Blanc signal is attributed to

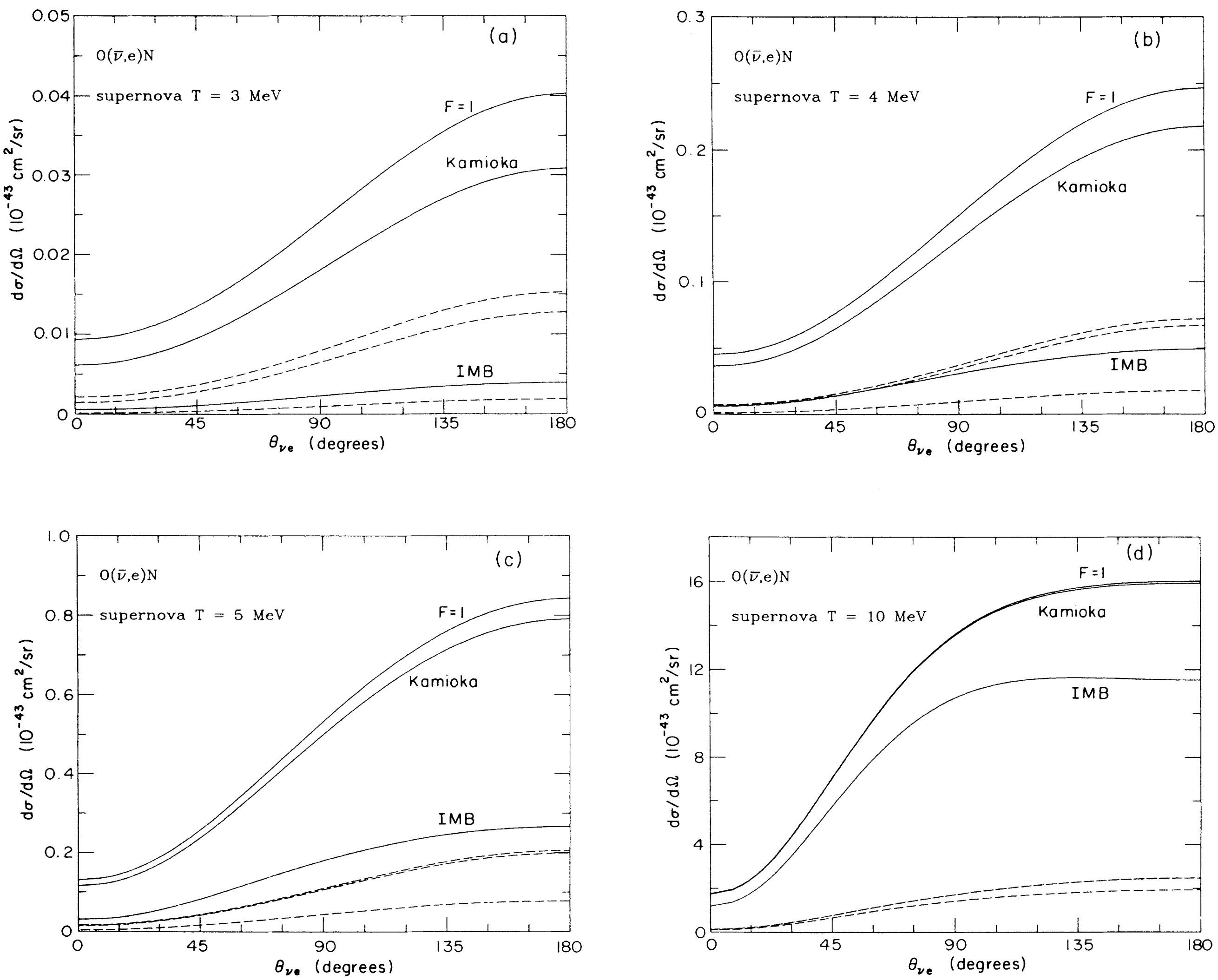

FIG. 3. As in Fig. 2, only for $O(\bar{\nu}_e,e^+)N$. The dashed curves give the cross sections to particle-bound states in ^{16}N.

$\bar{\nu}_e + p \rightarrow n + e^+$, where $\mathcal{X}(T) \sim 1$ is the ratio of efficiencies in the two detectors. The corresponding result for ν_e scattering on electrons is $(116 \pm 52)\mathcal{X}(T)$. Although nuclear contributions have been ignored in these arguments, the qualitative conclusion, that a $\bar{\nu}_e$- or ν_e-induced signal in the Mt. Blanc detector must generate a spectacular number of events in the Kamioka detector, remains valid.

Now consider the neutral-current reactions induced by ν_μ, $\bar{\nu}_\mu$, ν_τ, or $\bar{\nu}_\tau$ neutrinos. The estimated $^{12}C(\nu, \nu')^{12}C$ (15.11 MeV) cross sections given in Table I were calculated for nuclear wave functions generated with the 8–16 2BME interaction of Cohen and Kurath.[11] These wave functions predict $1^+1 \rightarrow 0^+0(gs)\gamma$ decay and β decay rates in good agreement with the measure values in the $A = 12$ nuclei. Wilson and collaborators[18] have recently found, for a collapse of a 25-$M_\odot$ star with a 1.6-$M_\odot$ iron core at a distance of 50 kpc,

$$\phi(\nu) = 0.8 \times 10^{10}\ \text{cm}^2 \text{ for } \nu = \nu_\mu,\ \bar{\nu}_\mu,\ \nu_\tau, \text{ or } \bar{\nu}_\tau\ ,$$

$$\langle T \rangle = 10\ \text{MeV}\ .$$

It follows that 0.63 neutral-current events (i.e., 15.11 MeV γ rays) would be produced from ν_μ, $\bar{\nu}_\mu$, ν_τ, and $\bar{\nu}_\tau$ reactions in the Mt. Blanc detector, assuming a Fermi-Dirac distribution with the above characteristics. The corresponding results for the total neutral-current $\nu - e$ elastic scattering events in the Kamioka (2140 ton) and IMB (5000 ton) detectors are 0.84 and 0.70, respectively. [I use $\sigma_{\nu-e}^{NC} = 1.4 \times 10^{-45}\ (E_\nu/\text{MeV})\ \text{cm}^2$.]

This suggests a possible explanation of the Mt. Blanc events: a $\bar{\nu}_e$-poor (and ν_e-poor[19]) neutrino burst yielding a signal (15.11-MeV γ rays) whose energy is not simply related to the T of the burst. For fixed neutrino luminosity, the predicted Mt. Blanc event rate will increase

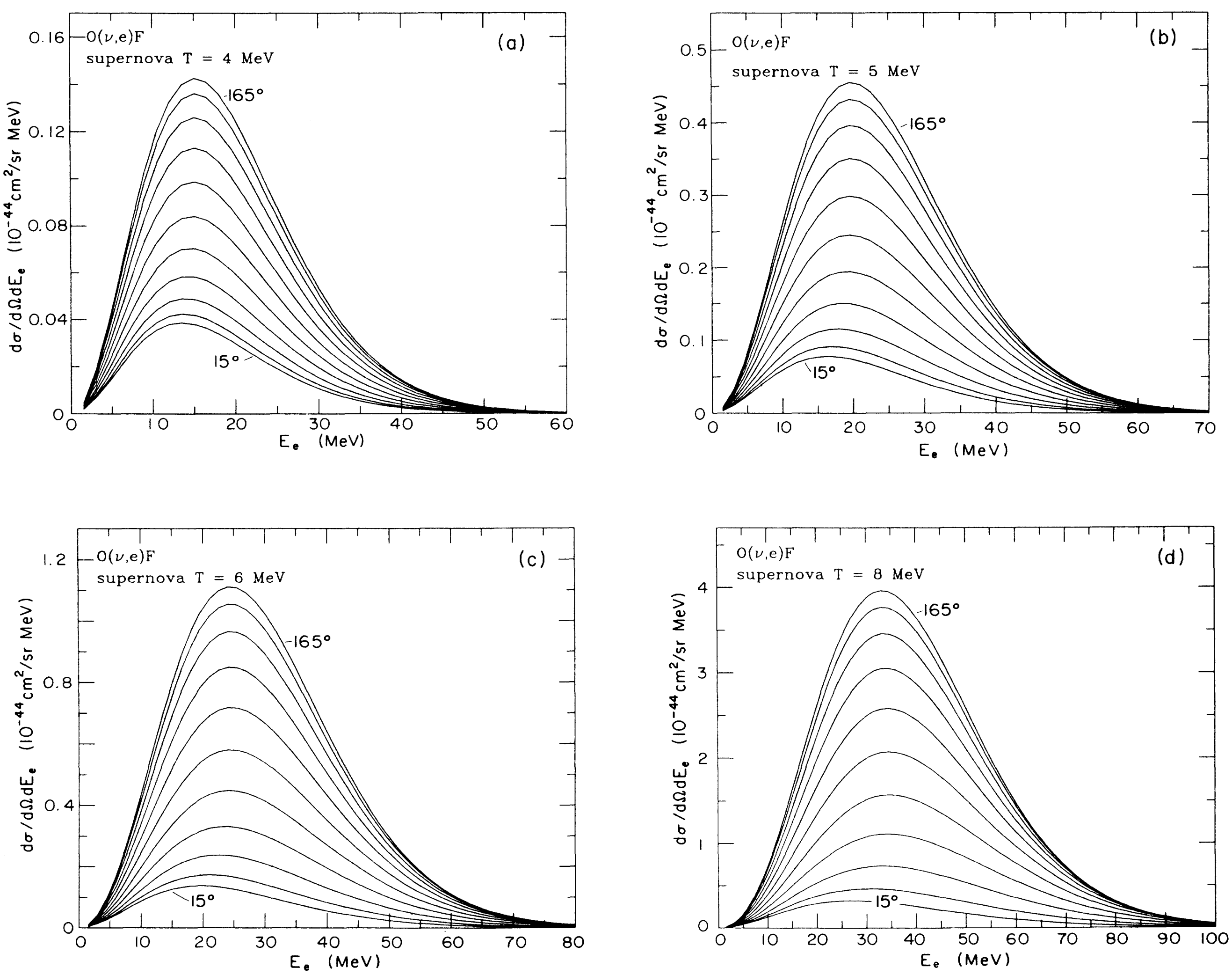

FIG. 4. Double differential cross sections for $O(\nu_e, e^-)F$ averaged over Fermi-Dirac distributions with $T = 4$, 5, 6, and 8 MeV. Results are given for scattering angles between 15° and 165°, in 15° steps. Note the compression of the horizontal scale as T is increased.

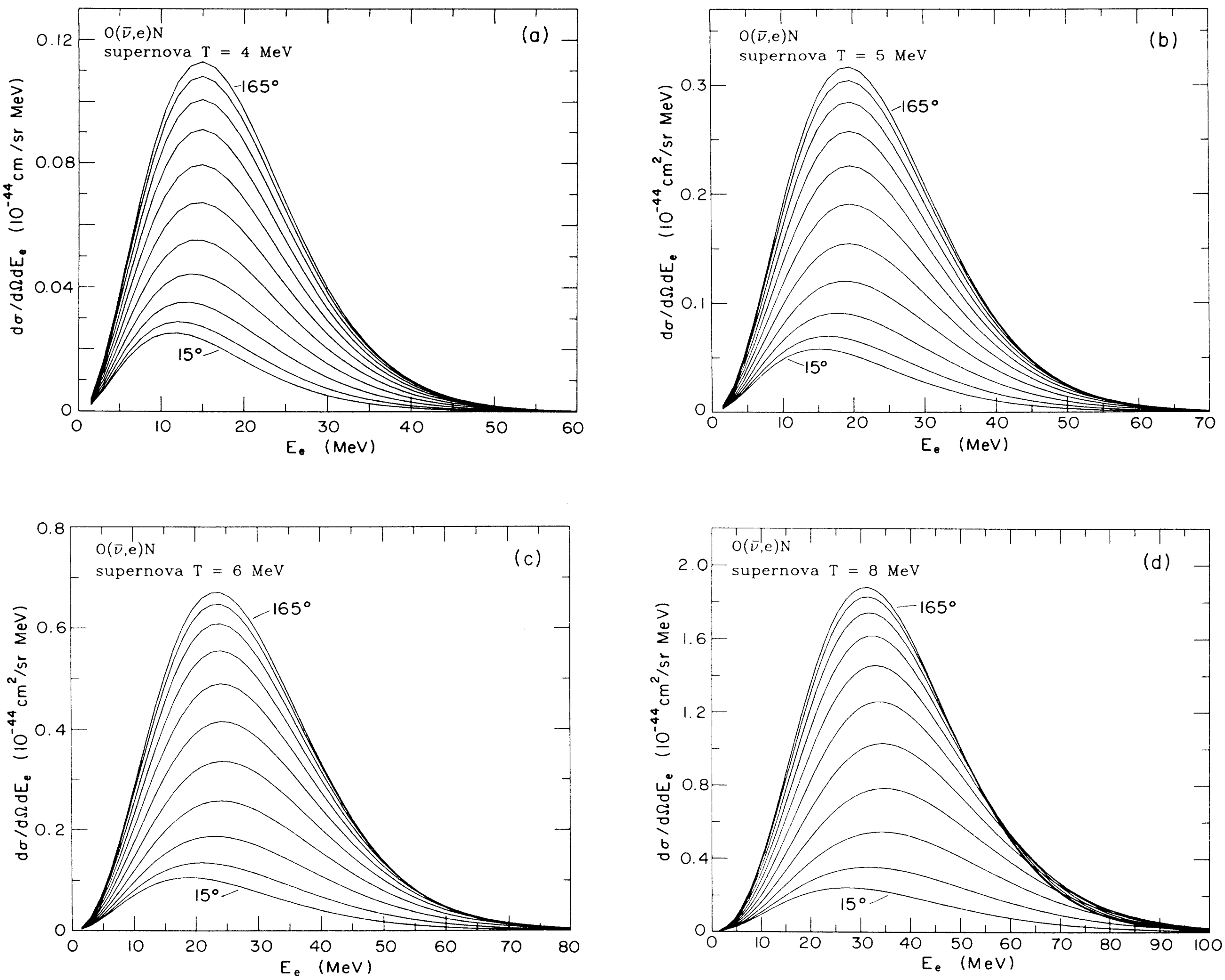

FIG. 5. As in Fig. 4, only for $O(\bar{\nu}_e,e^+)N$.

as $\langle T \rangle$ is raised, and this increase is more rapid than that for the Kamioka and IMB rates. (In fact, the exercise completed above most likely underestimates the Mt. Blanc signal, both absolutely and comparatively, because supernovae simulations predict more high-energy neutrinos than given by the Fermi-Dirac distribution.[18]) Such an explanation for the Mt. Blanc events, and for the absence of strong signals in the Kamioka and IMB detectors, would not necessarily require an unrealistically large luminosity. These issues are considered in more detail elsewhere.[21]

IV. THE NUCLEAR RESPONSE TO ^{8}B SOLAR NEUTRINOS

In the previous section it was noted that the only open nuclear modes for charge-current reactions of low-energy ν_e's in water are absorption on ^{17}O (0.038% abundant) and on ^{18}O (0.204% abundant). Even though only two ^{18}O nuclei are found in natural water for every 10^4 electrons, I will show below that the nuclear contribution to ^{8}B solar-neutrino absorption is not negligible. More importantly, because of both the size of the $^{18}O(\nu_e,e)\,^{18}F$ cross section and the remarkable hardness of the spectrum of produced electrons, a water Cherenkov detector enriched in ^{18}O could potentially provide important information on the shape of the ^{8}B spectrum.

The Kamioka Collaboration has made remarkable progress in reducing backgrounds and lowering the threshold of their detector in order to detect the high-energy ($\sim$15-MeV end-point) ^{8}B neutrinos produced in the Sun.[3] They recently established a limit on the ^{8}B neutrino flux at approximately the level of the standard solar model. Their signal, the recoil electron after ν_e-e elastic scattering, is strongly forward peaked, a feature that is exploited to suppress backgrounds. Because the electron spectrum is quite soft, it is not clear at this point whether information on the shape of the ^{8}B spectrum can be obtained. Enhanced neutrino oscillations due to the Mikheyev-Smirnov-Wolfenstein (MSW) mechanism[4] are expected to distort the spectrum in a characteristic way, with the "level-crossing boundary" solution reducing the higher-energy ^8B neutrinos strongly and the "adiabatic boundary" solutions preferentially suppressing the lower-energy neutrinos. Thus the spectrum shape is a crucial physics issue.

Neutrinos can interact with one and two free neutrons, effectively, in ^{17}O and ^{18}O. For $^{18}O(\nu,e)^{18}F$, only two transitions are important, the $0^+1 \rightarrow 1^+0$ Gamow-Teller transition to the ^{18}F ground state ($\log ft = 3.094$) and the $0^+1 \rightarrow 0^+1$ Fermi transition to the first excited states ($\log ft = 3.456$). A $2s\,1d$ shell-model calculation of the remaining Gamow-Teller strength increases the cross section, averaged over the ^8B neutrino spectrum, by only 1%, to a total of 0.51×10^{-41} cm^2. The calculated ^{17}O cross section (with the $\log ft$ value for the Fermi/Gamow-Teller transition to the ^{17}F ground state taken from experiment) is 0.12×10^{-41} cm^2.

The results for a natural water Cherenkov detector are given in Table II. To conform to the presentation of Ref. 22, I have chosen step-function triggering efficiencies at 5 and 9 MeV. The latter is probably the more reasonable approximation to the Kamioka triggering efficiency discussed in Sec. III. In this case one would expect approximately one $^{18}O(\nu,e)^{18}F$ event for every 10 ν_e-e elastic scattering events occurring in the Kamioka detector. (Almost 98% of the nuclear events are due to ^{18}O). As the distribution of these events is almost isotropic, most will not be counted as solar-neutrino events because of the angular cuts the Kamioka collaboration presently employs. However, in view of efforts to develop very low background water Cherenkov detectors,[22] this contribution could conceivably stand out above backgrounds in future detectors.

However, more interesting is the prospect of a water Cherenkov detector enriched in ^{18}O. A fully enriched detector would produce counting rates of 17 500/kton yr and 5740/kton yr, assuming 5- and 9-MeV step-function thresholds, respectively, and an ^8B neutrino flux of 4×10^6/cm^{2}sec. These rates are 24 to 48 times those due to ν_e-e scattering, and 2.7 to 3.8 times those that would be achieved in a fully enriched D_2O detector,[22] where the dominant charge-current reaction is $D(\nu_e,e)pn$ (see Table II). The spectrum of electrons from ^{18}O is even harder than that from the deuteron and is extraordinarily simple: with a probability of 77% (22%) the produced electron carries off an energy of $E_\nu - 1.14$ MeV ($E_\nu - 2.18$ MeV).

TABLE II. Expected elastic scattering and $O(\nu,e)F$ event rates/kiloton-year for a natural water Cherenkov detector, assuming a ^8B neutrino flux of 4×10^6/cm^{2}sec. ^{2}s and sharp detector thresholds of 5 and 9 MeV. The last column gives the results for a D_2O detector, where the charge-current signal is $\nu_e + D \rightarrow n + p + e^-$. Results for water detector fully enriched in ^{18}O can be obtained by multiplying the third column by 490.

Threshold (MeV)	$\nu_e - e$	$O(\nu,e)F$	$D(\nu,e)np$
5	730	35.7	6490
9	119	11.7	1530

Unfortunately, unlike D_2O, there is no present source of ^{18}O-enriched water in the quantities that would be needed. The cost of building the necessary refinery appears to be quite high, perhaps in excess of $50 000 000 (Ref. 23). Nevertheless, SN1987A has clearly underscored the potential importance of ν_e observatories than can match the effectiveness of present water Cherenkov $\bar{\nu}_e$ detectors.

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The expected number of elastic scattering and $O(\nu_e,e^-)F$ events in the Kamioka and IMB detectors are $0.83+0.65=1.48$ and $0.23+0.46=0.68$, respectively. Thus these contributions cannot be increased significantly without producing a conflict with the Kamioka results [Kamioka may have seen two counts within 8 sec of the Mt. Blanc burst (Ref. 20)]. Of course, this assumes that the ν_e and $\bar{\nu}_e$ temperatures have values similar to those in Wilson's calculations. Alternatively, one could tolerate higher ν_e and $\bar{\nu}_e$ fluxes if the temperatures for these species were markedly lower.

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