Signal for Supernova ν_μ and ν_τ Neutrinos in Water Čerenkov Detectors

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We suggest that photons with energies between 5 and 10 MeV, generated by the $(\nu,\nu' p\gamma)$ and $(\nu,\nu' n\gamma)$ reactions on ^{16}O, constitute a signal which allows a unique identification of supernova ν_μ and ν_τ neutrinos in water Čerenkov detectors. We calculate the yield of such γ events and estimate that a few hundred of them would be detected in Superkamiokande for a supernova at 10 kpc distance.

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Neutrinos play a decisive role in various stages of supernova evolution [1]. In particular, the gravitational binding energy of the nascent neutron star is released by neutrino-pair production [2]. It is the neutrinos generated during this cooling and deleptonization phase of the hot remnant core which will be mainly observed in Earth-bound detectors. Although pairs of all three flavors are generated with equal luminosity [3], due to their smaller opacities ν_μ and ν_τ neutrinos and their antiparticles decouple at smaller radii, and thus higher temperatures in the core, than ν_e and $\bar{\nu}_e$ neutrinos. As the neutrinos decouple in neutron-rich matter, which is less transparent for ν_e than for $\bar{\nu}_e$, it is expected on general grounds that the neutrino spectra after decoupling obey the temperature hierarchy [3], $T_{\nu_x} > T_{\bar{\nu}_e} > T_{\nu_e}$, where ν_x stands for ν_μ, ν_τ and their antiparticles, which are assumed to have identical spectra. The neutrino spectra can be approximately described by Fermi-Dirac (FD) distributions with zero chemical potential and $T_{\nu_x} = 8$ MeV, $T_{\bar{\nu}_e} = 5$ MeV, and $T_{\nu_e} = 3.5$ MeV, corresponding to average neutrino energies of $\langle E_{\nu_x}\rangle = 25$ MeV, $\langle E_{\bar{\nu}_e}\rangle = 16$ MeV, and $\langle E_{\nu_e}\rangle = 11$ MeV. More elaborate investigations of neutrino production in supernovae indicate that the high-energy tail of the neutrino spectra is better described by a Fermi-Dirac distribution with a finite chemical potential [4,5].

In what is considered the birth of neutrino astrophysics, neutrinos from supernova SN1987A have been detected by the Kamiokande [6] and IMB [7] water Čerenkov detectors (11 and 8 events, respectively). It is generally assumed that these events originated from the $\bar{\nu} + p \rightarrow n + e^+$ reaction in water. The detection of ν_e and ν_x neutrinos via the $\nu + e \rightarrow \nu' + e'$ scattering or the $^{16}\mathrm{O}(\nu_e, e^-)^{16}\mathrm{F}$ reaction was strongly suppressed by the small effective cross sections of these processes, although the ν_e induced signal can in principle be separated by its angular distribution [8]. The observability of supernova neutrinos will significantly improve when the Superkamiokande (SK) detector becomes operational [9]. This detector, with about 15 times the fiducial volume for supernova neutrinos of Kamiokande and a lower threshold of $E_{\mathrm{th}} = 5$ MeV, will be capable to detect also the recoil electrons from $\nu + e \rightarrow \nu' + e'$. In principle, ν_x induced neutrino-electron scattering events can be separated from everything else in SK using their angular distributions and energy spectra [9]. However, only about one third of the $\nu_x + e$ scattering events will have energies distinctly larger than the recoil electrons from $\nu_e + e$ and $\bar{\nu}_e + e$ scattering. Moreover, these higher energy electron recoils have to be separated by their direction from the much more numerous positrons from $\bar{\nu}_e + p \rightarrow n + e^+$ with the same energy.

In this Letter we suggest another signal in water Čerenkov detectors which allows one to unambiguously identify ν_x induced events. The basis of our proposal is the fact that SK can observe photons with energies larger than 5 MeV [10]. Schematically our detection scheme works as follows (Fig. 1). Supernova ν_x neutrinos, with average energies of $\approx$25 MeV, will predominantly excite 1^- and 2^- giant resonances in ^{16}O via the $^{16}\mathrm{O}(\nu_x, \nu_x')^{16}\mathrm{O}^*$ neutral current reaction [11]. These resonances are above the particle thresholds and will mainly decay by proton and neutron emission. (Decay into the α channel, although energetically allowed, is strongly suppressed by isospin conservation [11].) Although the proton and neutron decays will be mainly to the ground states of ^{15}N and ^{15}O, respectively, some of these decays will go to excited states in these nuclei. If these excited states are

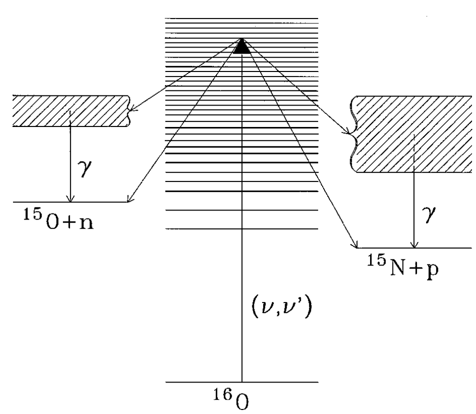

FIG. 1. Schematic illustration of the detection scheme for supernova ν_μ and ν_τ neutrinos in water Čerenkov detectors.

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below the particle thresholds in ^{15}N ($E^* < 10.2$ MeV) or ^{15}O ($E^* < 7.3$ MeV), they will decay by γ emission. As the first excited states in both nuclei ($E^* = 5.27$ MeV in ^{15}N and $E^* = 5.18$ MeV in ^{15}O) are at energies larger than the SK detection threshold, all of the excited states in ^{15}N and ^{15}O below the respective particle thresholds will emit photons which can be observed in SK.

Of course, it is important to estimate the effective $^{16}\mathrm{O}(\nu_x, \nu_x' p\gamma)$ and $^{16}\mathrm{O}(\nu_x, \nu_x' n\gamma)$ cross sections for SK and to compare it to the effective "background" cross sections, stemming from the $\bar{\nu}_e + p \rightarrow n + e^+$ and $\nu + e \rightarrow \nu' + e'$ events with energy release similar to the energy of the photons. Assuming equal luminosities for all neutrino species ($i = \nu_e, \bar{\nu}_e, \nu_x$) leaving a supernova, the relative event rate (σ_{eff}) for a specific neutrino-induced process in a water Čerenkov detector is [3]

$$\langle\sigma_{\mathrm{eff}}\rangle \sim \frac{n}{\langle E\rangle} \int dE\, f(E)\sigma(E), \qquad (1)$$

where f is the neutrino energy spectrum and the factor $1/\langle E\rangle$ accounts for the ratio of fluxes for the different neutrino flavors. $\sigma(E)$ is the total cross section for the neutrino-induced process and n is the number of targets for an individual neutrino process in a single water molecule ($n = 10$ for neutrino-electron scattering, $n = 2$ for $\bar{\nu}_e + p \rightarrow n + e^+$ and $n = 1$ for neutrino reactions on ^{16}O).

To calculate the $^{16}\mathrm{O}(\nu_x, \nu_x' p\gamma)$ and $^{16}\mathrm{O}(\nu_x, \nu_x' n\gamma)$ cross sections we assume a two-step process. In the first step we calculate the $^{16}\mathrm{O}(\nu_x, \nu_x')^{16}\mathrm{O}^*$ cross section as a function of excitation energy in ^{16}O within the continuum random phase approximation (CRPA). In the second step we calculate for each final state with well-defined energy, angular momentum, and parity the branching ratios into the various decay channels using the statistical model code SMOKER [12], considering proton, neutron, α, and γ emission. As possible final states in the residual nucleus the SMOKER code considers the experimentally known levels supplemented at higher energies by an appropriate level density formula [12]. If the decay leads to an excited level of the residual nucleus (e.g., to $p + {}^{15}\mathrm{N}^*$), we calculate the branching ratios for the decay of this level in an analogous way. Keeping track of the energies of the ejected particles and photons during the cascade, and weighting them with appropriate branching ratios and the corresponding differential $^{16}\mathrm{O}(\nu_x, \nu_x')^{16}\mathrm{O}^*$ cross section, we determine the various particle (proton, neutron, or α) and photon spectra for the (ν_x, ν_x') reaction on ^{16}O. We performed a similar calculation also for the $(\bar{\nu}_x, \bar{\nu}_x')$ reaction on ^{16}O. The contribution of various neutrino energies was weighted according to a (normalized) distribution $f(E)$. Note that the same CRPA approach has been successfully applied to the muon capture on ^{16}O [13]. The model is described in detail in Refs. [11,14]. As residual interaction we adopt the finite-range force based on the Bonn potential [15]. A similar two-step approach (combining CRPA and the statistical model) has been tested successfully against the integrated $(\gamma p)/(\gamma n)$ data on ^{16}O [11].

The total and partial cross sections for ν_x and $\bar{\nu}_x$ induced neutral current reactions on ^{16}O were evaluated first using the Fermi-Dirac neutrino spectrum with zero chemical potential μ and temperature $T = 8$ MeV (FD1) [16]. The results are listed in Tables I and II. The total (ν_x, ν_x') and $(\bar{\nu}_x, \bar{\nu}_x')$ cross sections are roughly the same as the vector-axial vector interference term is rather unimportant. As expected, the partial cross sections for decay into proton and neutron channels dominate the total cross section. The proton channel is favored over the neutron channel by the lower threshold in ^{16}O. We find that a significant fraction of these decays goes to excited states in ^{15}N and ^{15}O below particle thresholds and thus decay by γ emission. The relatively larger importance of this decay mode in ^{15}N ($\approx$24%) than in ^{15}O ($\approx$6%) reflects the larger number of final states in ^{15}N due to the higher particle threshold. We find 3.2×10^{-42} cm^2 for the total γ producing cross section for each flavor of ν_x plus $\bar{\nu}_x$ in the neutral current reactions on ^{16}O, obtained by adding the $(p\gamma)$ and $(n\gamma)$ partial cross sections.

As discussed above, the ν_x and $\bar{\nu}_x$ induced reactions will produce γ events in the energy range $E \approx 5$–10 MeV. The other events at these energies (a background for our

TABLE I. Total and partial cross sections for ν_x and $\bar{\nu}_x$ induced reactions on ^{16}O, calculated for a Fermi-Dirac neutrino spectrum with temperature and chemical potential ($T = 8$ MeV, $\mu = 0$) (upper part) and ($T = 6.26$ MeV, $\mu = 3T$) (lower part).

Reaction	σ_{tot} (10^{-42} cm^2)	Reaction	σ_{tot} (10^{-42} cm^2)
$^{16}\mathrm{O}(\nu_x, \nu_x')\mathrm{X}$	5.90	$^{16}\mathrm{O}(\bar{\nu}_x, \bar{\nu}_x')\mathrm{X}$	4.48
$^{16}\mathrm{O}(\nu_x, \nu_x' p)^{15}\mathrm{N}$	3.75	$^{16}\mathrm{O}(\bar{\nu}_x, \bar{\nu}_x' p)^{15}\mathrm{N}$	2.93
$^{16}\mathrm{O}(\nu_x, \nu_x' n)^{15}\mathrm{O}$	1.76	$^{16}\mathrm{O}(\bar{\nu}_x, \bar{\nu}_x' n)^{15}\mathrm{O}$	1.29
$^{16}\mathrm{O}(\nu_x, \nu_x' p\gamma)^{15}\mathrm{N}$	1.41	$^{16}\mathrm{O}(\bar{\nu}_x, \bar{\nu}_x' p\gamma)^{15}\mathrm{N}$	1.09
$^{16}\mathrm{O}(\nu_x, \nu_x' n\gamma)^{15}\mathrm{O}$	0.37	$^{16}\mathrm{O}(\bar{\nu}_x, \bar{\nu}_x' n\gamma)^{15}\mathrm{O}$	0.28
$^{16}\mathrm{O}(\nu_x, \nu_x')\mathrm{X}$	3.08	$^{16}\mathrm{O}(\bar{\nu}_x, \bar{\nu}_x')\mathrm{X}$	2.50
$^{16}\mathrm{O}(\nu_x, \nu_x' p)^{15}\mathrm{N}$	2.02	$^{16}\mathrm{O}(\bar{\nu}_x, \bar{\nu}_x' p)^{15}\mathrm{N}$	1.69
$^{16}\mathrm{O}(\nu_x, \nu_x' n)^{15}\mathrm{O}$	0.90	$^{16}\mathrm{O}(\bar{\nu}_x, \bar{\nu}_x' n)^{15}\mathrm{O}$	0.70
$^{16}\mathrm{O}(\nu_x, \nu_x' p\gamma)^{15}\mathrm{N}$	0.72	$^{16}\mathrm{O}(\bar{\nu}_x, \bar{\nu}_x' p\gamma)^{15}\mathrm{N}$	0.59
$^{16}\mathrm{O}(\nu_x, \nu_x' n\gamma)^{15}\mathrm{O}$	0.18	$^{16}\mathrm{O}(\bar{\nu}_x, \bar{\nu}_x' n\gamma)^{15}\mathrm{O}$	0.14

TABLE II. Combined ν_e and $\bar{\nu}_e$ partial cross sections (in 10^{-42} cm^2) for γ decays via particle-bound excited states in ^{15}N (upper eight rows) and in ^{15}O (lower four rows). The excitation energies E_x are given in MeV. The calculations have been performed for a Fermi-Dirac neutrino spectrum with temperature and chemical potential ($T = 8$ MeV, $\mu = 0$) (second column) and ($T = 6.26$ MeV, $\mu = 3T$) (third column).

E_x	σ	σ
5.27, 5.30	0.73	0.40
6.33	0.84	0.47
7.16, 7.30	0.24	0.12
7.56	0.05	0.02
8.32	0.07	0.03
8.57	0.07	0.04
9.05, 9.16, 9.22	0.31	0.16
9.76, 9.83, 9.93	0.14	0.07
5.18, 5.24	0.28	0.14
6.18	0.21	0.10
6.69, 6.86	0.14	0.07
7.28	0.02	0.01

purpose) will stem mainly from the $\bar{\nu}_e + p \rightarrow n + e^+$ reaction. Adopting the Fermi-Dirac distribution with $T = 5$ MeV and zero chemical potential, we calculate a total cross section for this reaction of 47×10^{-42}cm^2. (This includes the factor $n = 2$ for the two protons in a water molecule. The result is somewhat smaller than that quoted in [3] where minor effects, such as the weak magnetism and recoil were not included.) However, the energy spectrum of positrons as seen by SK is peaked at around 15 MeV and only a small fraction of events is in the energy window $E = 5-10$ MeV. This becomes obvious in Fig. 2, where we compare the positron spectrum with the γ spectrum calculated for the ν_x and $\bar{\nu}_x$ induced reaction on ^{16}O. The latter has been multiplied by a factor of 2 (to account for ν_μ and ν_τ neutrinos) and by 16/25 to consider the ratio of $\bar{\nu}_e$ and ν_x fluxes [$\sim\langle E_{\nu_x}\rangle/\langle E_{\bar{\nu}_e}\rangle$; see Eq. (1)] at the detector. An energy resolution $14\%/(E/10)^{1/2}$ [10], where E is in MeV, i.e., 1 MeV for the energies of interest, has been assumed for the detector. As is obvious from Fig. 2, the γ spectrum constitutes a clear signal at $E = 5-7$ MeV on top of a smooth background from the $\bar{\nu}_e + p \rightarrow n + e^+$ reaction. Our calculation predicts most of the photons to stem from the decay of the three lowest levels in ^{15}N and ^{15}O. Further, in Fig. 2 and Table II we assume that the detector will record all photons in a possible cascade of several γ rays as a single event. Let us stress that each of such multiphoton events will contain at least one photon above the 5 MeV threshold. The ν_e and $\bar{\nu}_e$ induced neutral current reactions on ^{16}O also produce γ events with energies $E \approx 5-10$ MeV. However, due to the lower temperatures of supernova ν_e and $\bar{\nu}_e$ neutrinos and the high threshold of $(\nu, \nu' p\gamma)$ and $(\nu, \nu' n\gamma)$ reactions in ^{16}O, the background signal generated by $(\nu_e + \bar{\nu}_e)$ neutrinos is less than 2% of the ν_x induced γ events.

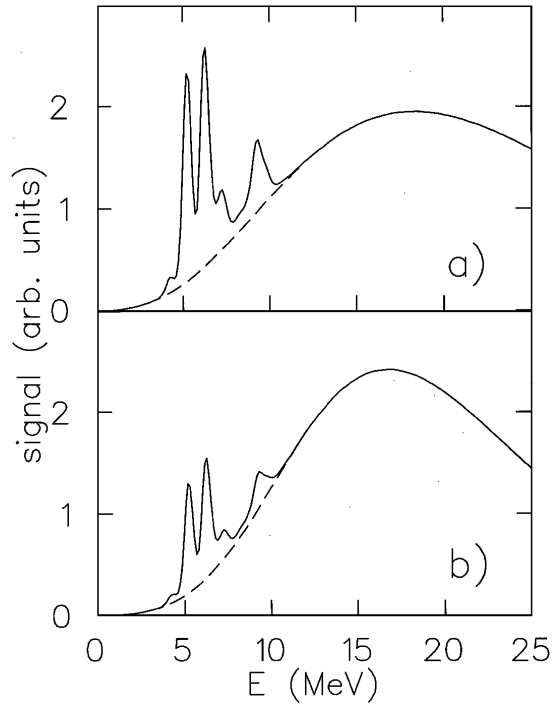

FIG. 2. Signal expected from supernova neutrinos in a water Čerenkov detector. The solid line is the sum of the γ spectrum, generated by ν_x and $\bar{\nu}_x$ reactions on ^{16}O, and of the positron spectrum (dashed line) from the $\bar{\nu}_e + p \rightarrow n + e^+$ reaction. The upper part (a) has been calculated assuming Fermi-Dirac neutrino distributions with ($T = 8$ MeV, $\mu = 0$) and ($T = 5$ MeV, $\mu = 0$) for ν_x and $\bar{\nu}_e$ neutrinos, respectively. In the lower part (b) Fermi-Dirac neutrino distributions with ($T = 6.26$ MeV, $\mu = 3T$) and ($T = 4$ MeV, $\mu = 3T$) have been assumed for ν_x and $\bar{\nu}_e$ neutrinos. The energy E refers to the photon or positron energy, respectively. The spectra are in arbitrary units.

Other possible backgrounds are neutrino-electron scattering and charged current reactions on ^{16}O. For these reactions we find smooth electron or positron spectra, whose cross sections in the interval $E = 5-10$ MeV (normalized with the appropriate flux ratios and target numbers n) are much smaller than the γ signal. Water also contains a tiny amount of ^{18}O and even less ^{17}O. However, their natural abundances ($\approx$0.2% and 0.04%, respectively) are too small for neutrino reactions on ^{18}O to be of importance (see Ref. [8] for the calculated charged current cross sections).

We then repeated our calculation of the ν_x and $\bar{\nu}_x$ induced reactions on ^{16}O, using a Fermi-Dirac neutrino spectrum (FD2) with $T = 6.26$ MeV and $\mu = 3T$ [5],

$$f(E) \sim \frac{E^2}{1 + \exp[(E - \mu)/T]}, \qquad (2)$$

which has the same average neutrino energy as the FD1 distribution. We find that the FD2 total and partial cross sections are smaller by about a factor of 2 when compared to the FD1 results (see Table I). Noting that the main contribution to the cross sections comes from neutrinos with $E_\nu > \langle E_\nu \rangle$, this scaling simply reflects the ratio of the two Fermi-Dirac distributions in that energy region. At the same time, the cross section for the dominant reaction $\bar{\nu}_e + p \rightarrow n + e^+$ is changed only slightly, to 44×10^{-42} cm^2 when the FD spectrum with $T = 5$ MeV and $\mu = 0$ is replaced by a spectrum with $T = 4$ MeV and $\mu = 3T$.

We note that photodissociation data confirm a significant decay rate of the giant dipole resonance in ^{16}O by proton and neutron emission into excited states of ^{15}N and ^{15}O [17]. In agreement with our model these decays mainly lead to the first three excited levels in these nuclei and are relatively larger in ^{15}N than in ^{15}O [18,19]. While the total decay rate appears to be in reasonable agreement with our calculation, the data suggest a preference of the decay to the $3/2^-$ state at $\approx$6.3 MeV over the decay to the positive-parity states at around 5.3 MeV, caused by nuclear structure effects beyond our present model [18,19]. This suggests that a fraction of the signal, predicted by our calculation at $E \approx 5.3$ MeV just above the SK detection threshold, is to be shifted to 6.3 MeV, where it can be detected easier in SK. To clarify this point, a detailed investigation of the photodissociation process on ^{16}O within the current model is in progress.

Superkamiokande is expected to detect about 4000 positrons from the $\bar{\nu}_e + p \rightarrow n + e^+$ reaction [9] for a supernova going off at 10 kpc ($\approx 3 \times 10^4$ light-years or the distance to the galactic center). By scaling the respective effective cross sections, we estimate that such a supernova will produce about 360 (FD1) or 190 (FD2) γ events in the energy window $E = 5$–10 MeV, to be compared with a smooth background of about 270 positron events from the $\bar{\nu}_e + p \rightarrow n + e^+$ reaction in the same energy window. This number of events produced by supernova ν_x neutrinos via the scheme proposed here is larger than the total number of events expected from ν_x-electron scattering (about 80 events [9]). More importantly, the γ signal can be unambiguously identified from the observed spectrum in the SK detector, in contrast to the more difficult identification from ν_x-electron scattering.

In conclusion, we propose a novel signal for the identification of supernova μ and τ neutrinos in water Čerenkov detectors. Our suggestion is based on the fact that the levels in ^{16}O, which are excited by inelastic neutral current scattering of supernova ν_x neutrinos, have decay branches via proton and neutron emission into excited states in ^{15}N and ^{15}O. These states, in turn, decay by emission of photons with $E_\gamma > 5$ MeV, which can be detected in the Superkamiokande water Čerenkov detector. We show that the expected number of γ events in the relevant energy window $E = 5$–10 MeV is noticeably larger than the positron or electron background expected from other neutrino reactions in water. It is amusing to note that the ν_x neutrinos from SN1987A at 50 kpc would have created about ten photons in SK (which did not exist at that time, unfortunately), the same number of events as all of the recorded events in the Kamiokande or IMB detectors then, which launched the era of neutrino astronomy.

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