Detection of muon and tau neutrinos from the gravitational collapse of stars with the help of low-background scintillation detectors

O. G. Ryazhskaya and V. G. Ryasnyĭ
Institute of Nuclear Research, Russian Academy of Sciences, 117334, Moscow, Russia

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The possibility of detecting muon and tau neutrinos in scintillation detectors through excitation of the 1^+ level (15 MeV) of ^{12}C nuclei is discussed. For low-background detectors with a high neutron detection efficiency, $^{12}C(\nu,\nu)^{12}C^*$ events can be reliably distinguished from inverse β decay.

The appearance of Supernova 1987A in the Large Magellanic Cloud (see the reviews[1,2]) revealed the high level of interest in experimental neutrino astrophysics. As we know, neutrinos of all types ($\nu_{e,\mu,\tau}$ and $\bar{\nu}_{e,\mu,\tau}$) carry off most of the gravitational binding energy of a collapsing star (10^{53}–10^{54} erg) over a time of 10–20 s. These rank among the most intense fluxes in the universe and may provide unique information on the dynamics of gravitational collapse and the properties of condensed matter and neutrinos.

A simulation of the collapse of nonrotating, nonmagnetic, spherically symmetric stars yields neutrino spectra[3]

$$\varphi(E_\nu)=\frac{C\epsilon^2}{1+\exp(\epsilon)}\exp(-\alpha\epsilon^2),$$

where

$$\epsilon=E_\nu/(kT); \tag{1}$$

kT (in MeV) is the effective temperature of the neutrinosphere of the newly formed neutron star, having the values $kT=3.5$, 4.5, and 8 MeV for ν_e, $\bar{\nu}_e$, and $\nu_{\mu,\tau}$ $\bar{\nu}_{\mu,\tau}$, respectively; the factor $\exp(-\alpha\epsilon^2)$ reflects the partial nontransmission of layers of the star above the neutrinosphere; we have $\alpha=0.01$, 0.02, and 0 for ν_e, $\bar{\nu}_e$, and $\nu_{\mu,\tau}$, $\bar{\nu}_{\mu,\tau}$, respectively; and the constant C is determined by the energy of the neutrino flux. We take this energy to be 10^{53} erg for $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$, ν_τ, and $\bar{\nu}_\tau$ and 1.1×10^{53} erg for ν_e. The average ν_e and $\bar{\nu}_e$ energies are 10 and 12.6 MeV, respectively, and the average $\nu_{\mu,\tau}\bar{\nu}_{\mu,\tau}$ energy is 25 MeV.

For the generally accepted models of collapse, the inverse β-decay reactions

$$\bar{\nu}_e+p\rightarrow n+e^+=1.8\ \text{MeV}, \tag{2}$$

$$n+p\rightarrow d+\gamma,\quad E_\gamma=2.2\ \text{MeV},\quad \tau\simeq185\ \mu\text{s}, \tag{3}$$

where τ is the average lifetime with respect to capture, would cause the basic response in underground liquid scintillation and Čerenkov detectors.

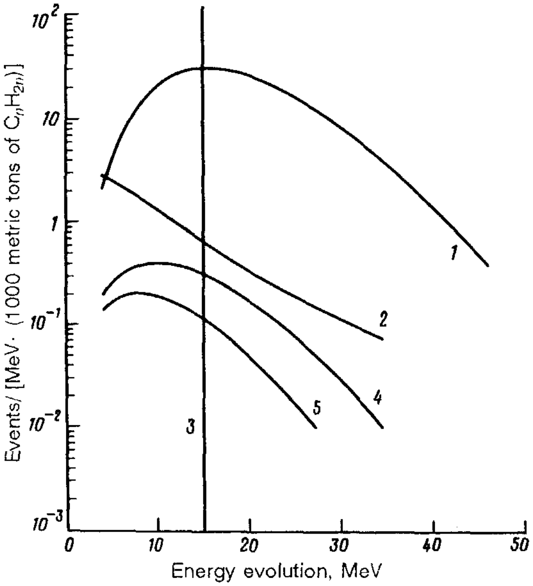

FIG. 1. Spectra of energy evolution in a scintillator based on C_nH_{2n} in the detection of neutrino fluxes from a star collapsing at a distance of 10 kpc. *1*—e^+ from reactions (2); *2*—e^- from νe scattering; *3*—γ rays from reactions (4); *4*—e^+ from $^{12}C(\bar{\nu}_e,e^+)^{12}B$; *5*—$e^-$ from $^{12}C(\nu_e,e^-)^{12}N$.

Because of the large cross section[4,5] for the reaction $^{12}C(\nu,\nu)^{12}C^*$ (15.11 MeV, 1^+), scintillation counters using C_nH_{2n} are capable of detecting neutrinos with energies above[6] 15.1 MeV:

$$\begin{aligned}&\nu+{}^{12}C\rightarrow{}^{12}C^*+\nu, \quad \text{where } \nu=\nu_{e,\mu,\tau},\bar{\nu}_{e,\mu,\tau},\\ &{}^{12}C^*\rightarrow{}^{12}C+\gamma(15.1\text{ MeV}) \quad (96\%),\\ &{}^{12}C^*\rightarrow{}^{12}C+\gamma(4.4\text{ MeV})+\gamma(10.7\text{ MeV}) \quad (4\%).\end{aligned} \tag{4}$$

The efficiency at which γ rays are detected, η_γ, depends on the size of the scintillation counters. For 15.1-MeV γ rays this efficiency is $\eta_\gamma > 40\%$ if the typical dimension of the counter is greater than 1 m, while it is $\eta_\gamma > 80\%$ if the dimensions of the counter are greater than 5 m.

Because of the soft spectra of ν_e and $\bar{\nu}_e$, the number of their interactions amounts to less than 5% of the total number of $^{12}C(\nu,\nu)^{12}C^*$ reactions. Essentially all events of type (4) are thus due to muon and tau neutrinos, and the discrimination of these events makes bolometric estimates possible. Such estimates are difficult to make in the case of water-based Čerenkov detectors, since the excitation of high-lying energy levels of ^{16}O is suppressed.[4]

Figure 1 shows results calculated on the energy-evolution spectra for various neutrino reactions per 1000 metric tons of C_nH_{2n} scintillator ($\bar{n}=9.6$). The total number of interactions is shown in the third column of Table I, for a distance of 10 kpc to the star. It can be seen from these results that the inverse β decay in (2) and νe scattering constitute the background for the detection of muon and tau neutrinos with the help of reaction (4). The signal-to-noise ratio improves if events in the range 11–18 MeV are discarded (see the fourth column in Table I).

TABLE I. Numbers of interactions with an energy evolution greater than 5 MeV in 1000 metric tons of C_nH_{2n} scintillator for the collapse of a star at a distance of 10 kpc.

Reaction	Particle detected	N_{tot}	$N(11-18\ \mathrm{MeV})$		
			$\eta_n = 0$	$\eta_n = 0.6$	$\eta_n = 0.8$
$\bar{\nu}_e p \to n e^+$	e^+, n	547	181	72	36
$\nu e^- \to \nu e^-$	e^-	21	3	3	3
$\nu {}^{12}C \to \nu {}^{12}C^*$	γ	118	118	118	118
$\bar{\nu}_e^{12}C \to^{12} Be^+$	e^+	7	3	3	3
$\nu_e^{12}C \to^{12} Ne^-$	e^-	3	1,5	1,5	1,5

Large-volume, low-background detectors based on C_nH_{2n} can detect both particles from the reaction[10] $\bar{\nu}_e p$, so the background in $\nu_{\mu,\tau}\bar{\nu}_{\mu,\tau}$ detection can be reduced even further. We put the signals from neutrinos in two groups on the basis of the presence or absence of accompaniment pulses with amplitudes of 1–3 MeV over a time of about 800 μs after the pulse which is being considered as a candidate for a neutrino interaction. The ratio of the number of detected $\nu^{12}C$ and $\bar{\nu}_e p$ interactions is thus improved in the group without accompaniment pulses. The other events can be used as a statistically independent sample for estimating the background spectrum. In this case the estimate of the number of carbon-excitation interactions which are detected will evidently be independent of assumptions regarding the shape of the $\bar{\nu}_e$ spectrum.

The last three columns in Table I illustrate the decrease in the background as a function of the neutrino detection efficiency η_n. At an η_n value of about 0.6, the effect due to $\nu_{\mu,\tau}\bar{\nu}_{\mu,\nu}$ becomes comparable to the background, while at $\eta_n = 0.8$ this effect is nearly three times the background (with $\eta_\gamma = 1$).

Table II shows the results of a simulation of ν detection for scintillation detectors with high values of η_γ and η_n. Interestingly, the single-module scintillation detector of

TABLE II. Underground scintillation installations for detecting neutrinos from stellar collapse.

Installation	Mass, metric tons	η_γ	η_n	Number of interactions detected			Signal-to-noise ratio
				$\bar{\nu}_e p$	νe^-	$\nu^{12}C$	
ASS 1)	105	0,85	0,8	57	2,1	11	11/4
LSD 2)	90	0,54	0,6	45	1,8	6	4,2/6
LVD 3)	1840	0,54	0,6	924	36,3	117	87/122
	368	0,54	0,6	185	7,3	23,4	18/24

1)Artemovsk Science Station, Institute of Nuclear Research, Russian Academy of Sciences.[7]

2)Institute of Nuclear Research, Russian Academy of Sciences, Institute of Cosmogeophysics, National Research Center of Italy; and Institute of General Physics. Turin University.[8]

3)See Refs. 6 and 9; 1840 metric tons is the projected figure (for 1995), and 368 metric tons is the working part.

the Artemovsk Science Station, Russian Academy of Sciences, is capable of distinguishing events due to $\nu_{\mu,\tau}\bar{\nu}_{\mu,\tau}$ by virtue of the high efficiency with which neutrons and γ rays are detected (despite the comparatively small mass of this detector). Figure 2 shows the pulse spectra in the counters of the LSD and LVD installations after events with accompaniment pulses have been eliminated.

The best detectors for measuring the fluxes of muon and tau neutrinos from stellar collapse are thus counters with dimensions of greater than 5 m, for which η_γ and η_n are greater than 0.8.

At large masses of the muon and tau neutrinos, one should see a shift of the

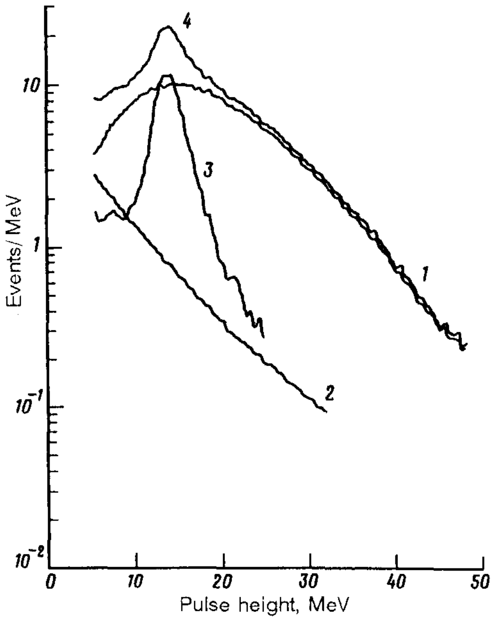

FIG. 2. Spectra of pulses in the counters of the LSD and LVD installations in the detection of neutrinos from a star collapsing at a distance of 10 kpc. *1*—Inverse β decay (pulses from positrons not accompanied by the detection of neutrons); *2*—νe scattering; *3*—15.1-MeV γ rays; *4*—total spectrum.

detection time and an increase in the duration of the packet of 15.1-MeV γ rays. By virtue of the decrease in the background due to $\bar{\nu}_e p$ interactions, the discrimination of this packet will be facilitated by values 100 eV $< m_{\mu,\tau} <$ 1.5 keV, and the pulse delay time can be used to find limitations on the masses of the muon and tau neutrinos. If these masses are greater than about 1.5 keV, the packet of pulses should spread out to the extent that the packet would become difficult to distinguish from the background in the apparatus.

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