Detection of neutrino flavor oscillations during observation of a neutrino burst from a stellar collapse in the galaxy

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The ability of large-volume scintillation counters based on white spirit $[(CH_2)_n]$ to select charged current (CC) $\nu_e,\tilde{\nu}_e$ interactions with ^{12}C, while observing a neutrino burst from a stellar collapse in the Galaxy is discussed. If there exist neutrino flavor oscillations, $\nu_{\mu(\tau)}\leftrightarrow\nu_e$, and the temperature of $\nu_{\mu,\tau}\tilde{\nu}_{\mu,\tau}$ fluxes is higher than that of $\nu_e\tilde{\nu}_e$, then the number of the CC interactions will increase. The scintillation counters have very high sensitivity for detection of these effects.

Neutrino oscillations might change the observable effects during detection of the burst of neutrinos from a stellar gravitational collapse in the Galaxy. If a detector is able to separate interactions of different neutrino types, it might be possible to obtain information on the neutrino itself. The method which we will describe here can be applied to any carbon-containing neutrino detector.

It is expected that $\nu_{\mu,\tau}$ and $\tilde{\nu}_{\mu,\tau}$ fluxes from a stellar collapse have higher temperatures kT with respect to the fluxes of ν_e and $\tilde{\nu}_e$.[1] The $\nu_{\mu,\tau}$ and $\tilde{\nu}_{\mu,\tau}$ energy spectra obtained in various calculations have a Fermi–Dirac shape with $kT\approx 6$–8 MeV and a chemical potential $\mu\approx 0$–$3\ kT$ compared to $kT\approx 3$–3.5 MeV for ν_e and $kT\approx 4$–5 MeV for the $\tilde{\nu}_e$ fluxes at the neutron star cooling stage.[1–4]

The high energy $\nu_{\mu,\tau}$ and $\tilde{\nu}_{\mu,\tau}$ and the high energy tails of the ν_e and $\tilde{\nu}_e$ energy spectra can excite the ^{12}C level (15.1 MeV, 1^+) via their neutral current interactions.[5,6] Because of the difference in the neutrino flux temperatures, about 95% of the carbon excitation events in the detector are attributable to the interactions of $\nu_{\mu,\tau}$ and $\tilde{\nu}_{\mu,\tau}$. The $^{12}C^*$ decays to the ground level, emitting γ rays of energy 15.1 MeV. These γ rays can be selected[7] from the inverse β-decay reactions:

$$\tilde{\nu}_e+p\rightarrow n+e^+, \qquad (1)$$

which for the "standard" collapse models give the main effect in the Čerenkov and scintillation detectors, if the apparatus can detect radiative neutron capture:

$$n+p\rightarrow d+\gamma+2.2\ \text{MeV}, \qquad (2)$$

(the average time of the capture is $\tau\approx 185\ \mu s$).

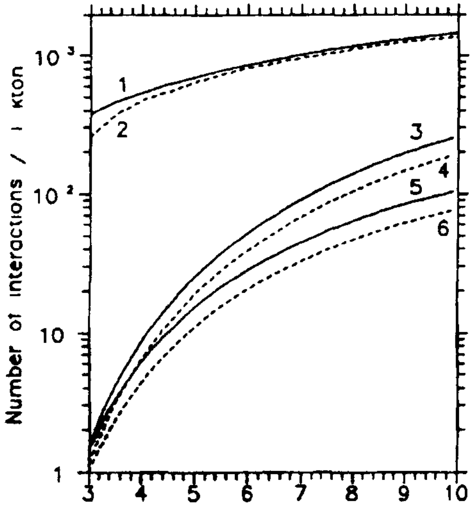

FIG. 1. Dependence of the number of interactions in 1000 tons of $(CH_2)_n$ on the electron neutrino flux temperature. Solid curves—The total number; dashed curves—the number of detected interactions in the LVD counters. Curves 1 and 2 correspond to the interactions (1); 3 and 4 correspond to the CC reactions (3); 4 and 5 correspond to the reactions (5). For reactions (1) the $\tilde{\nu}_e$ spectrum high-energy tail suppression[10] was taken into account. The distance to the collapsing star is $D = 10$ kpc. The reaction cross sections (3) and (5) were taken from Ref. 6.

The selection of the neutral-current carbon excitation events will make it possible to carry out muon and/or tauon neutrino mass measurements[8] and the $\tilde{\nu}_{\mu,\tau},\nu_{\mu,\tau}$ bolometry.

If there exist flavor oscillations $\nu_x \leftrightarrow \nu_e$ $(\nu_x = \nu_\mu, \nu_\tau)$, then the high-energy ν_e and/or $\tilde{\nu}_e$ will participate in the charge current reactions with ^{12}C:

$$\nu_e + {}^{12}C \rightarrow {}^{12}N + e^- \quad \Delta M = 16.83 \text{ MeV}, \tag{3}$$

$$^{12}N \rightarrow {}^{12}C + e^+ + \nu_e \quad \tau = 15.9 \text{ ms}, \tag{4}$$

$$\tilde{\nu}_e + {}^{12}C \rightarrow {}^{12}B + e^+ \quad \Delta M = 13.88 \text{ MeV}, \tag{5}$$

$$^{12}B \rightarrow {}^{12}C + e^- + \tilde{\nu}_e \quad \tau = 29.3 \text{ ms}. \tag{6}$$

Both CC reactions have a good signature because of the subsequent β decays with high-energy electrons and positrons, which can be detected by the existing scintillation counters with an efficiency of about 70–80%, if the apparatus provides a detection threshold of ≈ 5 MeV.

Figure 1 shows the increase in the number of CC interactions (1), (3), and (5) in 1 kton of white spirit due to the rise of the electron neutrino flux temperature (the curves with odd numbers). The large volume detector (LVD)[9] in Gran Sasso Laboratory, Italy, is used as an example of a real installation (the curves with even numbers). If we assume that $kT(\nu_e) \approx 3.5$ MeV, $kT(\tilde{\nu}_e) \approx 4.5$ MeV, and the energy carried by every neutrino-type flux is $\varepsilon^{\mathrm{tot}}_{\nu_e\tilde{\nu}_e} \approx 10^{53}$ erg (Refs. 2 and 10), then in the absence of oscillations the total average number of detected reaction pairs (3), (4) and (5), (6) will be $\bar{N}_{\mathrm{non\text{-}osc}} \approx 5.6$ per 1 kton of the LVD active mass.

If $\mu = 0$, $kT(\nu_x, \tilde{\nu}_x) = 8$ MeV, and $\varepsilon^{\mathrm{tot}}_{\nu_e\tilde{\nu}_e} = 10^{53}$ erg, then in the case of the total oscillation transition $\nu_x \rightarrow \nu_e$ $(\tilde{\nu}_x \rightarrow \tilde{\nu}_e)$ the number of detected reaction pairs will be $\bar{N}_{3,4} \approx 90$ $(\bar{N}_{5,6} \approx 38)$.

It is important that the flavor oscillations do not change the number of neutral current interactions with ^{12}C in the detector.

If the $\tilde{\nu}_x \leftrightarrow \tilde{\nu}_e$ oscillation channel is resonant, then in addition to the CC reactions (5) the transitions $\tilde{\nu}_x \rightarrow \tilde{\nu}_e$ will change the energy spectrum of positrons in the inverse β-decay reactions (1). This effect for vacuum oscillations was first discussed in Ref. 11. The evaluation of neutrino oscillation parameters from the change in the energy spectrum of positrons from reaction (1) was described in Ref. 12.

By selecting pairs of pulses with the amplitudes > 5 MeV in the time gate of 100 ms from the same $1 \times 1.5 \times 1$ m^3 LVD counter the detector background can be made negligible. The interactions (3) and (5) caused by high-energy tails of unconverted ν_e and $\tilde{\nu}_e$ spectra will then be the competing events for the detection of the CC interactions with ^{12}C of ν_e's from the transition $\nu_x \rightarrow \nu_e$.

To imitate the oscillation increase in the number of CC events with the probability of $<1\%$, the number of competing events must be $\leqslant N_{\rm sel}$ ($N_{\rm sel} = 12$ if $\bar{N}_{\rm non\text{-}osc} = 5.6$). Requiring that the detection probability of the true oscillation events be $\geqslant 90\%$, we obtain the lower average detectable event number:

$$\bar{N}_{\rm osc} \geqslant \bar{N}_{\rm osc}^{\rm min} = 17.8 \quad \text{for LVD (1 kton).} \tag{7}$$

For vacuum oscillations both transitions $\nu_x \rightarrow \nu_e$ and $\tilde{\nu}_x \rightarrow \tilde{\nu}_e$ will occur and for MSW matter oscillations one of them will be enhanced and the other will be suppressed, depending on the sign of Δm^2 — mass difference of the neutrino interaction eigenstates. Assume that the $\nu_x \leftrightarrow \nu_e$ channel is resonant and consider two-particle flavor oscillations for simplicity. The minimum vacuum permutation factor is

$$\bar{P}_{\rm min}^{\rm vac}(\nu_x \rightarrow \nu_e) = \frac{1}{2} \sin^2 2\theta_{\rm min} = \frac{\bar{N}_{\rm osc}^{\rm min}}{\bar{N}_{3,4} + \bar{N}_{5,6}},$$

where θ is the vacuum mixing angle. The LVD sensitivity to the CC flavor vacuum oscillations for a 1-kton active mass will then be $\sin^2 2\theta \geqslant 2 \times 17.8/(90+38) \approx 0.28$. Because of the large distance to the collapsing star, the scintillation detectors could reach sensitivities of $\Delta m^2 \approx 10^{-18}$–$10^{-19}$ eV^2.

The neutrino oscillates in the vacuum regime if the oscillation parameters lie in a nonadiabatic region.[12,13] In the region of a strong matter resonance we have $\bar{P}^{\rm ad}_{\nu_x \rightarrow \nu_e} = \cos^2\theta$ and $\bar{P}^{\rm ad}_{\tilde{\nu}_x \rightarrow \tilde{\nu}_e} = \sin^2\theta$. $\bar{P}^{\rm ad}_{\nu_x \rightarrow \nu_e} > \bar{P}_{\nu_x \rightarrow \nu_e} > \bar{P}^{\rm vac}$ and $\bar{P}^{\rm ad}_{\nu_x \rightarrow \tilde{\nu}_e} < \bar{P}_{\tilde{\nu}_x \rightarrow \tilde{\nu}_c} < \bar{P}^{\rm vac}$ at the nonadiabatic edge of a matter oscillation "bath." If

$$\bar{N}_{3,4} \cos^2\theta + \bar{N}_{5,6} \sin^2\theta > \bar{N}_{\rm osc}^{\rm min}, \tag{8}$$

then, adjusting Δm^2 and $\sin^2 2\theta$ in such a way as to achieve the equality in (7), we obtain the sensitivity limit which corresponds to the nonadiabatic edge.

Figure 2 shows the sensitivity region for 1 kton of the LVD active mass. This region includes all proposed neutrino flavor oscillation solutions of a solar neutrino deficit problem.

It is necessary to point out that after the inequality (8) is satisfied, at small $\sin^2 2\theta$ the change of the sensitivity limit due to a decrease in $\bar{N}_{3,4}$ and $\bar{N}_{5,6}$ is determined by the width of the nonadiabatic edge (< 1 order of magnitude along the Δm^2 axis).

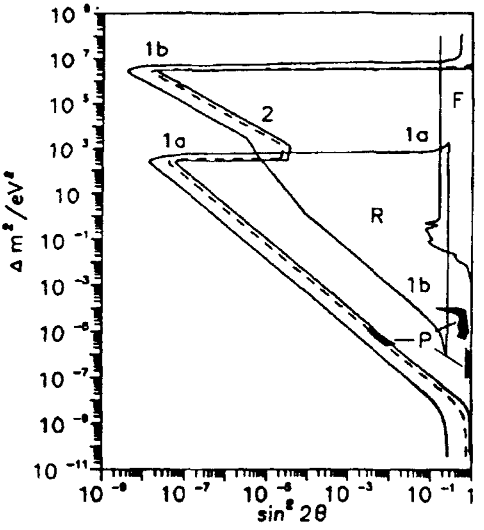

FIG. 2. The sensitivities of the scintillation detectors LSD (90 tons) and LVD (1 kton of active mass) to the neutrino oscillation effects. Curves: 1a,b—LVD (1 kton), $kT=8$ MeV. 1a—Oscillations in the stellar envelope; 1b—oscillations in the stellar core; 2—LSD (90 tons), $kT=8$ MeV; dashed line—LVD (1 kton), $kT=6$ MeV. Regions: F—forbidden by reactor experiments; P—permitted by solar neutrino deficit;[15] R—regeneration in the stellar envelope. If the neutrino oscillation parameters lie in the region R, the neutrino oscillation effects cannot be detected with the desired efficiency.

Take, for example, the liquid scintillation detector (LSD[14]), which is analogous to the LVD scintillation part but with a smaller active mass (90 tons):

$$\bar{N}_{\text{non-osc}}=0.50,\quad N_{\text{sel}}=2,\quad \bar{N}_{\text{osc}}^{\text{min}}=5.3,\quad \bar{N}_{3,4}=8.1,\quad \bar{N}_{5,6}=3.4,\quad \sin^2 2\theta_{\text{min}}=0.92,$$

and for $\sin^2 2\theta \leqslant \sin^2 2\theta_{\text{min}}$ the inequality (8) is satisfied in the region of a strong resonant conversion (see Fig. 2). Evidently the decrease in the mass of the apparatus is equivalent to smaller $\varepsilon_\nu^{\text{tot}}$ or a more distant collapse.

Figure 2 shows also the LVD sensitivity region for the case of $kT(\nu_x, \tilde{\nu}_x)=6$ MeV. It can be seen that a large change in the LVD sensitivity due to a decrease in the neutrino flux temperature or $\varepsilon_\nu^{\text{tot}}$ should not be expected. We can conclude that the proposed method is highly sensitive to the MSW and to vacuum oscillations for a variety of stellar collapse models.

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