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ON THE DETECTION OF NEUTRINO FLAVOUR OSCILLATIONS DURING OBSERVATION OF NEUTRINO BURST FROM 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 flavour oscillations $\nu_{\mu(\tau)} \leftrightarrow \nu_e$ and the temperature of $\nu_{\mu,\tau}\tilde{\nu}_{\mu,\tau}$ fluxes is higher than that of $\nu_e\tilde{\nu}_e$, the number of the CC interactions will increase. The scintillation counters have very good sensitivity to detect these effects.

Neutrino oscillations might change 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 neutrino itself. The approach which we are to describe could be applicable to any carbon-containing neutrino detector.

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

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

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

which for 'standard' collapse models give the main effect in Cherenkov and scintillation detectors, if an installation can detect radiative neutron captures:

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

(average time of the capture $\tau \approx 185$ μs).

The selection of the neutral current carbon excitation events will provide possibilities of muon and/or tauon neutrino mass measurement [8] and the $\tilde{\nu}_{\mu,\tau}\nu_{\mu,\tau}$ bolometry.

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

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

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

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

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

Both CC reactions have good signature due to subsequent β-decays with high energy electrons and positrons, which can be detected by existing scintillation counters with the efficiency of about 70-80%, if the installations provide detection threshold of ≈ 5 MeV.

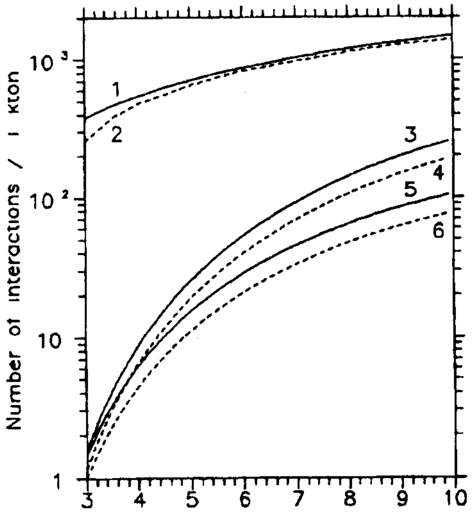

Fig.1

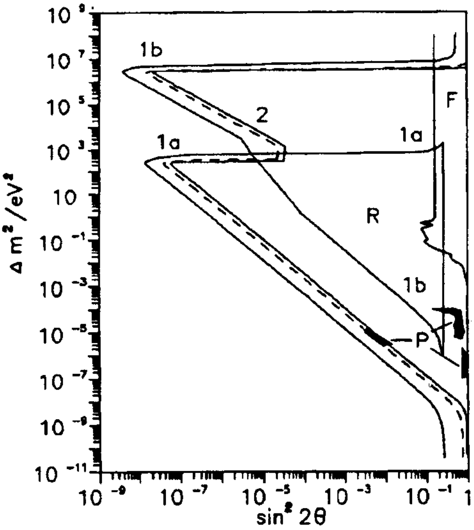

Fig.2

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 - number of detected interactions in the LVD counters. Curves *1* and *2* correspond to interactions (1), *3* and *4* - to CC reactions (3), *4* and *5* - to reactions (5). For reactions (1) the $\tilde{\nu}_e$ spectrum high energy tail suppression [10] was taken into account. Distance to the collapsing star $D = 10$ kpc. The reaction (3) and (5) cross sections were taken from [6]

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

Fig.1 shows the increase of 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 $\mathcal{E}^{tot}_{\nu_e,\tilde{\nu}_e} \approx 10^{53}$ erg [2,10], then in case of absence of oscillations the total average number of detected reaction pairs (3), (4) and (5), (6) $\bar{N}_{non-osc} \approx 5.6$ in 1kton of the LVD active mass.

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

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

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

By selecting the pairs of pulses with the amplitudes of > 5 MeV in the time gate of 100 ms and from the same $1 \times 1.5 \times 1$ m^3 LVD counter the detector background can be made negligible. Then interactions (3) and (5) caused by high energy tails of non-converted ν_e and $\tilde{\nu}_e$ spectra will be competing events for a 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 has to be $\leq N_{sel}$ ($N_{sel} = 12$ if $\bar{N}_{non-osc} = 5.6$). Demanding that the detection probability of the true oscillation events will be $\geq 90\%$, we obtain the lower average detectable event number:

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

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

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

where θ - vacuum mixing angle. Then the LVD sensitivity to CC flavour vacuum oscillations in case of 1 kton active mass is $\sin^2 2\theta \geq 2 \times 17.8/(90+38) \approx 0.28$. Due to a 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 non-adiabatic region [12,13]. In the region of a strong matter resonance $\bar{P}^{ad}_{\nu_x \rightarrow \nu_e} = \cos^2\theta$ and $\bar{P}^{ad}_{\tilde{\nu}_x \rightarrow \tilde{\nu}_e} = \sin^2\theta$. $\bar{P}^{ad}_{\nu_x \rightarrow \nu_e} > \bar{P}_{\nu_x \rightarrow \nu_e} > \bar{P}^{vac}$ and $\bar{P}^{ad}_{\tilde{\nu}_x \rightarrow \tilde{\nu}_e} < \bar{P}_{\tilde{\nu}_x \rightarrow \tilde{\nu}_e} < \bar{P}^{vac}$ on a non-adiabatic edge of a matter oscillation 'bath'. If

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

then, adjusting Δm^2 and $\sin^2 2\theta$ so as to achieve the equality in (7), we will obtain the sensitivity limit, which corresponds to the non-adiabatic edge.

Fig.2 shows the so obtained sensitivity region for 1 kton of the LVD active mass. This region covers all proposed neutrino flavour oscillation solutions of a solar neutrino deficit problem.

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

Take as an example the Liquid Scintillation Detector (LSD, [14]), which is analogous to the LVD scintillation part but with a smaller active mass (90 tons):

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

and for $\sin^2 2\theta \leq \sin^2 2\theta_{min}$ the inequality (8) is satisfied in the region of a strong resonant convertion (see Fig.2). Evidently the decrease of the installation mass is equivalent to smaller $\mathcal{E}_{\nu}^{tot}$ or more distant collapse.

Fig.2 shows also the LVD sensitivity region for the case of $kT(\nu_x, \tilde{\nu}_x) = 6\,\text{MeV}$. It can be seen that great changes in the LVD sensitivity due to decreasing of neutrino flux temperature or $\mathcal{E}_{\nu}^{tot}$ should not be expected and we can conclude that the proposing method has high sensitivity to the MSW and vacuum oscillations for a variety of stellar collapse models.

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