Measuring the masses of μ and τ neutrinos by detecting neutrinos from collapsing stars with hydrocarbon scintillation detectors

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By detecting the neutrino emission from the gravitational collapse of a star by means of low-background underground scintillation detectors one can refine the limit on the ν_e mass. One can furthermore measure ν_μ and/or ν_τ by a time-of-flight method or establish ranges on their values at the level of 50–100 eV.

We have previously[1] discussed the possibility of identifying carbon excitation reactions

$$\nu+{}^{12}\mathrm{C}\rightarrow{}^{12}\mathrm{C}^*+\nu-15.11\ \mathrm{MeV}$$
$$(\nu=\nu_e,\bar{\nu}_e,\nu_\mu,\bar{\nu}_\mu,\nu_\tau,\bar{\nu}_\tau) \qquad (1)$$

against the background of νe scattering and inverse β decay,

$$\bar{\nu}_e+p\rightarrow n+e^+-1.8\ \mathrm{MeV}, \qquad (2)$$

in the detection of neutrinos from a collapsing star by using low-background underground scintillation detectors of large volume with hydrocarbon scintillators. Reactions (2) contribute most of the effect (80–90%) in such detectors. Some of these interactions can be identified on the basis of the accompanying radiative capture of neutrons by hydrogen:

$$n+p\rightarrow d+\gamma+2.2\ \mathrm{MeV}, \quad \tau\simeq 185\ \mu\mathrm{s}. \qquad (3)$$

It thus becomes possible to break up the file of events into "ν_e" and "$\nu_{\mu,\tau}$" groups. By comparing these groups of events we can distinguish reactions (1), 90–95% of which are caused by $\nu_{\mu,\tau}\bar{\nu}_{\mu,\tau}$.

In order to actually implement the separation method described in Ref. 1, it is necessary to arrange a low frequency of simulations of events. It is also necessary to achieve a high efficiency in the detection of γ rays with an energy of 15 MeV, emitted during the decay of excited carbon, and 2.2 MeV, from the radiative capture of neutrons, (3). In addition, the mass of the detector must be sufficient to build up a good statistical base of interactions. Such characteristics are offered by some installations using "white spirit": the Artemovsk Scintillation Detector[2] (ASD), in a salt mine in the Don River Basin; the Liquid Scintillation Detector[3] (LSD), in a tunnel under Mt. Blanc; and the Large Volume Detector[4] (LVD), in the Gran Sasso underground laboratory (in Italy).

TABLE I. Number of neutrino interactions detected in scintillation devices as the result of the collapse of a star at a distance $D=10$ kpc. Here χ is a parameter associated with the selection of interactions of the type in (1) (see the text proper).

Detector	Mass, metric tons	Number of interactions			χ for the range 11–18 MeV
		$\bar{\nu}_e p$	νe^-	$\nu^{12}C$	
ASD	105	57	2.1	9.5	2.4
LSD	90	45	1.8	5.2	0.6
Projected	1840	924	36.3	102	0.6
LVD, oper.	368	185	7.3	20	0.6

Table I shows estimates of the expected effects at the ASD, the LSD, and the LVD. In calculating the number of interactions of the type in (1) here we used the cross section of Ref. 5, which has received experimental support.[6] We assume that the neutrino spectra are[7]

$$\varphi(E_\nu)=\frac{C\epsilon^2}{1+\exp(\epsilon)}\exp(-\alpha\epsilon^2), \tag{4}$$

where the constant C is determined by the energy of the neutrino flux, which we took to be 10^{53} for $\bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$ and 1.1×10^{53} erg for ν_e; $\epsilon=E_\nu/(kT)[kT(\nu_e)=3.5$ MeV, $kT(\bar{\nu}_e)=4.5$ MeV, and $kT(\nu_{\mu,\tau}, \nu_{\mu,\tau})=8$ MeV]; and $\alpha(\nu_e)=0.01$, $\alpha(\bar{\nu}_e)=0.02$, and $\alpha(\nu_{\mu,\tau}, \bar{\nu}_{\mu,\tau})=0$. The spectra of μ and τ neutrinos thus have a Fermi–Dirac shape with a zero chemical potential.

Bruen and Haxton[8] have calculated the shape of the $\nu_{\mu,\tau}\bar{\nu}_{\mu,\tau}$ spectrum in the initial stage of the collapse, taking account of the inelastic scattering of neutrinos by nuclei of the stellar matter, through neutral currents. The result can be approximated by

$$\varphi(E_\nu)=\frac{C\epsilon^2}{1+\exp(\epsilon-\mu)};\quad kT=6\ \text{MeV};\quad \mu=2.85. \tag{5}$$

In other words, incorporating inelastic interactions softens the neutrino spectrum, at least in the stage in which a shock wave exists. If we use spectrum (5), the data in the last two columns of Table I should be reduced by about a third.

To select events involving the excitation of carbon through neutral currents, the events detected in the amplitude range 11–18 MeV are thus classified into two groups on the basis of whether there are indications of accompanying reactions (3). As a result, the $\bar{\nu}_e$ group contains only counts from reactions (2), while the $\nu_{\mu,\tau}$ group is left with a mixture of events of the type in (1) and (2). The ratio (χ) of the counts from the different reactions in the $\nu_{\mu,\tau}$ group will depend on the efficiency with which neutrons and 15.1-MeV γ rays are detected.

If the neutrinos do have a rest mass, and if there exists a hierarchy of masses, the mean delays in the arrival of counts for the two groups of events will be different. The difference between the arrival times of two neutrinos with different masses and energies which are emitted simultaneously at a distance D from the detector is

$$\Delta t=\frac{D}{2c}\left[\left(\frac{m_1}{E_1}\right)^2-\left(\frac{m_2}{E_2}\right)^2\right], \tag{6}$$

where m is in electron volts. We assume for simplicity that there exist two types of neutrinos, with different masses, and we replace the index 1 by τ, and 2 by e. Taking an average over the energy spectra, we find

$$\overline{\Delta t}=\frac{D}{2c}\left[\left(\frac{m_\tau}{kT_\tau}\right)^2\frac{I_{0\tau}}{I_{2\tau}}-\left(\frac{m_e}{kT_e}\right)^2\frac{I_{0e}}{I_{2e}}\right], \tag{7}$$

where $I_{li}=\int_{E_{\min}/(kT_i)}^{E_{\max}/(kT_i)}\epsilon^{1-2}\phi_i(\epsilon)d\epsilon$, and $E_{\min}$ and $E_{\max}$ are the minimum and maximum energies, respectively, of the neutrinos involved in the reaction. These energies are, respectively, 15, 11 MeV, and ∞ for $\nu_{\mu,\tau}, \bar{\nu}_{\mu,\tau}$; and $(11+1.8)$ and $(18+1.8)$ MeV for $\bar{\nu}_e$. The index i specifies the type of neutrino, and l the power of ϵ inside the integral.

If the temporal variation of the luminosity is nearly identical for $\bar{\nu}_e$ and $\nu_{\mu,\tau}, \bar{\nu}_{\mu,\tau}$ (this suggestion is supported by the results of a simulation of the gravitational collapse of a star), expression (7) remains valid for the delay between the centers of gravity of the packets of events, with energies of about 15 MeV, caused by different types of neutrinos. It can be shown that the delay of a mixed packet consisting of N_τ interactions of the type in (1) and N_e interactions of the type in (2) with respect to the $\bar{\nu}_e$ group of events is

$$\overline{\Delta t_m}=\frac{N_\tau}{N_e+N_\tau}\overline{\Delta t}=\frac{\chi}{1+\chi}\overline{\Delta t};\quad \chi=\frac{N_\tau}{N_e}. \tag{8}$$

From (7) and (8) we find an expression for determining m_τ:

$$\frac{m_\tau}{kT_\tau}=\left[1.94\frac{1+\chi}{\chi}\left(\frac{10\text{kpc}}{D}\right)\overline{\Delta t_m}+\left(\frac{m_e}{kT_e}\right)^2\frac{I_{0e}}{I_{2e}}\right]^{1/2}\left[\frac{I_{2\tau}}{I_{0\tau}}\right]^{1/2}, \tag{9}$$

where the masses are in electron volts, the kT's are in MeV, $\overline{\Delta t_m}$ is in seconds, and D in kiloparsecs.

The minimum neutrino mass measurable by this method depends on the error in the determination of the delay $\overline{\Delta t_m}$. Assuming that the temporal distribution of the counts is uniform within the group of neutrino events, we find the following expression for $(\overline{\Delta t_m})_{\min}$:

$$(\overline{\Delta t_m})_{\min}\approx\delta\left[\frac{N_1^2+N_2^2}{N_1^2N_2^2}\right]^{1/2}, \tag{10}$$

where δ is the length of the packet, and N_1 and N_2 are the number of counts in the $\bar{\nu}_e$ and $\nu_{\mu,\tau}$ groups of events.

If m_τ is sufficiently large, the packet of events "spreads out" and is lost in the background. The broadening for the $\nu_{\mu,\tau}$ group is due entirely to the delay in the arrival of $\nu_{\mu,\tau}\bar{\nu}_{\mu,\tau}$ with an energy of 15.1 MeV. If we assume that the condition for neutrino detection is that the number of neutrino interactions exceed the number of background counts over the duration of the packet, then $(m_\tau)_{\max}$ can be found from

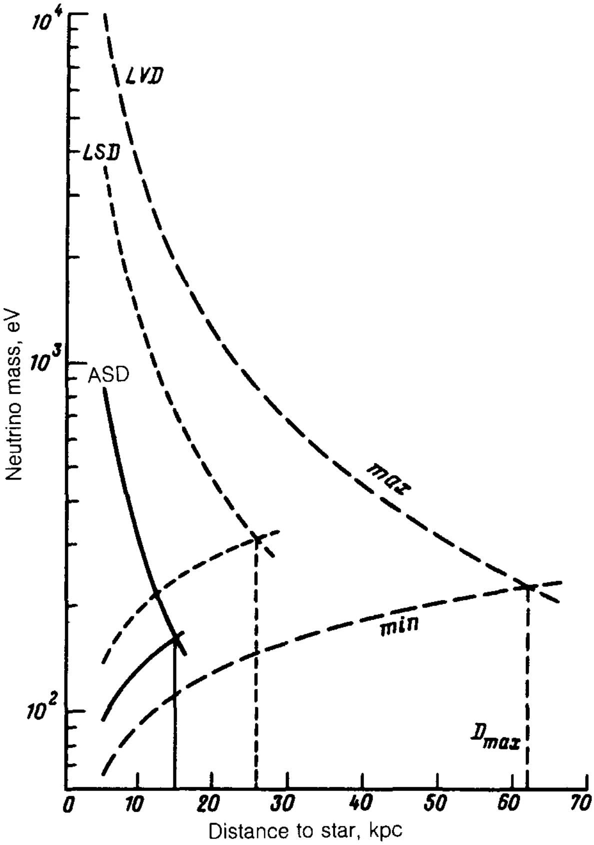

FIG. 1. Maximum and minimum detectable neutrino masses versus the distance to the collapsing star. The vertical lines show the maximum distances at which the method discussed in this letter can be used for various installations.

$$(m_\tau)_{\max}=21.1\left(\frac{N_2}{n_b}\cdot\frac{10kpc}{D}\right)^{1/2}\ \text{eV}, \tag{11}$$

where n_b is the background count rate (in counts per second).

Figure 1 shows plots of $(m_\tau)_{\min}$ and $(m_\tau)_{\max}$ versus D for the case $kT_\tau=8$ MeV, $\mu=0$. In these calculations we used the data in Table I along with the values $\delta=20$ s and $m_e=10$ eV. If we have $m_e\leqslant 10$ eV, in accordance with the present limit[9,10] on the mass of ν_e, the value of $(m_\tau)_{\min}$ depends weakly on m_e.

The estimates of $(m_\tau)_{\min}$ and $(\mu_\tau)_{\max}$ for the LVD should apparently be regarded as conservative, since a comparison of the pulse-height and time distributions in the two groups of events in the case of a sufficiently large statistical base of the interactions of the types in (1) and (2) will lead to a more accurate determination of the masses of ν_μ and/or ν_τ. Interestingly, for large neutrino masses, for which the broadening of the packet of counts is greater than the duration of the neutrino burst, one can determine the energy of $\nu_{\mu(\tau)}$ from the count arrival time.

The value of D at which we have $(m_\tau)_{\min}=(m_\tau)_{\max}$ can be thought of as the limiting range $D_{\max}$ for which this method is useable. For ASD, the LSD, the LVD, and the first tower of the LVD (368 metric tons of scintillator) the values of D_{max} are 16, 26, 62, and 51 kpc, respectively (Fig. 1). We thus see that even the first LVD tower is capable of measuring m_τ for the collapse of a star anywhere in the local galaxy. For the projected mass of the LVD, this capability extends to gravitational collapse in the Magellanic Clouds. The values of D_{max} for ASD and the LSD correspond to the observation of 87% and 98% of the stars in the local galaxy.[11]

It can thus be expected that the detection of neutrino emission from the gravitational collapse of a star by low-background underground scintillation detectors will make it possible to measure (by the time-of-flight method) the mass of ν_μ and/or ν_τ or to set limits on the values of these masses at the level of 50–100 eV.

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