The coherent contribution of all neutrons in neutrino nucleus scattering due to the neutral current offers a realistic prospect of detecting supernova neutrinos. For a typical supernova at 10 kpc, about 1000 events are expected using a spherical gaseous detector of radius 4 m and employing Xe gas at a pressure of 10 Atm. We propose a world wide network of several such simple, stable and low cost supernova detectors with a running time of a few centuries.

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INTRODUCTION.

In a typical supernova an energy of about $10^{53}$ ergs is released in the form of neutrinos \([1, 2]\). These neutrinos are emitted within an interval of about 10 s after the explosion and they travel to Earth undistorted, except that, on their way to Earth, they may oscillate into other flavors. The phenomenon of neutrino oscillations is by now established by the observation of atmospheric neutrino oscillations \([3]\) interpreted as $\nu_\mu \rightarrow \nu_\tau$ oscillations, as well as $\nu_e$ disappearance in solar neutrinos \([4]\). These results have been recently confirmed by the KamLAND experiment \([5]\), which exhibits evidence for reactor antineutrino disappearance. Thus for traditional detectors relying on the charged current interactions the precise event rate may depend critically on the specific properties of the neutrinos. The time integrated spectra in the case of charged current detectors, like the SNO experiment, depend on the neutrino oscillations \([6]\). An additional problem is the fact that the charged current cross sections depend on the details of the structure of the nuclei involved. With neutral current detectors one exploits the fact that the vector component of the current can lead to coherence, i.e. an additive contribution of all neutrons in the nucleus (the proton component is tiny). Furthermore the deduced neutrino fluxes do not depend on the neutrino oscillation parameters (e.g. the mixing angles). Even in our case, however, the obtained rates depend on the assumed characteristic temperature for each flavor, see sec. \([7]\).

Recently it has become feasible to detect neutrinos by measuring the recoiling nucleus and employing gaseous detectors with much lower threshold energies. Thus one is able to explore the advantages offered by the neutral current interaction, exploring ideas put forward more than a decade ago \([7]\). A description of the NOSTOS project and details of the spherical TPC detector are given in \([8]\). We have built a spherical prototype 1.3 m in diameter which is described in \([9]\). The outer vessel is made of pure Cu (6 mm thick) allowing to sustain pressures up to 5 bar. The inner detector is just a small sphere, 10 mm in diameter \([10]\) and developments are currently under way to build a spherical TPC detector using new technologies. First tests were performed by filling the volume with argon mixtures and are quite promising. High gains are easily obtained and the signal to noise is large enough for sub-keV threshold. The whole system looks stable and robustaaaaaa made of stainless steel as a proportional counter located at the center of curvature of the TPC. Furthermore this interaction, through its vector component, can lead to coherence, i.e. an additive contribution of all neutrons in the nucleus. Since the vector contribution of the protons is tiny, the coherence is mainly due to the neutrons of the nucleus.

In this paper we will derive the amplitude for the differential neutrino nucleus coherent cross section. Then we will estimate the expected number of events for all the noble gas targets. We will show that these results can be exploited by a network of small and relatively cheap spherical TPC detectors placed in various parts of the world (for a description of the apparatus see our earlier work \([8]\)). The operation of such devices as a network will minimize the background problems. There is no need to go underground, but one may have to go sufficiently deep underwater to balance the high
At the nucleon level we get:

\( (\text{diagonal in flavor space}) \).

Thus beyond the standard level one has further interactions which need not be diagonal in flavor space.

In the above expressions \( \lambda \) acquires additional R-parity violating terms:

\[
\text{framework of the MSSM with R-parity non-conservation MSSM. In this case the superpotential } W \text{ acquires additional R-paity violating terms:}
\]

\[
W_{R_p} = \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} U_i^c D_j D_k^c + \mu_j L_j H_u
\]
Of interest to us here is the \( \lambda'_{\alpha_11}L_iQ_jD_k \) involving first generation quarks and s-quarks, i.e the term \( \lambda'_{\alpha_11} \alpha \beta \gamma \delta \). From this term in four component notation we get the contribution

\[
\frac{\lambda'_{\alpha_11} \lambda'_{\beta_11}}{m^2_{d_L}} \bar{\nu}_\alpha L \gamma^\mu \nu_\beta L \bar{d}^\mu \gamma^\nu \nu_\alpha d, \quad \alpha, \beta = e, \mu, \tau
\]

where \( \nu_\alpha = \frac{1}{2}(1 - \gamma_5)\nu_\alpha \) etc. Thus

- The first term at tree level yields the interaction

\[
- \frac{\lambda'_{\alpha_11} \lambda'_{\beta_11}}{m^2_{d_L}} \bar{\nu}_\alpha L \bar{d} \gamma^\mu \nu_\beta L \gamma^\nu \nu_\alpha d
\]

By performing a Fierz transformation we can rewrite it in the form:

\[
\frac{1}{2} \lambda'_{\alpha_11} \lambda'_{\beta_11} \frac{m^2_{d_L}}{m^2_{d_L}} \bar{\nu}_\alpha L \bar{d} \gamma^\mu \nu_\beta L \gamma^\nu \nu_\alpha d
\]

The previous equation can be cast in the form:

\[
\mathcal{L}_d = -\frac{G_F}{\sqrt{2}} \epsilon_{\alpha \beta} \left[ \bar{\nu}_\alpha \gamma^\mu (1 - \gamma^5) \nu_\beta \right] \left[ \bar{d} \gamma^\nu (1 - \gamma^5) d \right];
\]

\[
\epsilon_{\alpha \beta} = \frac{\lambda'_{\alpha_11} \lambda'_{\beta_11}}{m^2_{d_L}} \frac{m^2_{W}}{m^2_{d_L}}
\]

There is no such term associated with the \( u \) quark, \( \epsilon_{\alpha \beta} = 0 \).

- Proceeding in an analogous fashion the collaborative effect of the first and second term, for \( \alpha, \beta = e, \mu, \tau \), yields the charged current contribution:

\[
\mathcal{L}_d = \frac{G_F}{\sqrt{2}} \epsilon_{\alpha \beta} \left[ \bar{\nu}_\alpha \gamma^\mu (1 - \gamma^5) \nu_\beta \right] \left[ \bar{d} \gamma^\nu (1 - \gamma^5) d \right]
\]

- Finally the second term, for \( \alpha, \beta = e, \mu, \tau \), leads to a neutral current contribution of the charged leptons:

\[
\mathcal{L}_u = \frac{G_F}{\sqrt{2}} \epsilon_{\alpha \beta} \left[ \bar{\nu}_\alpha \gamma^\mu (1 - \gamma^5) \right] \right[ \bar{u} \gamma^\nu (1 - \gamma^5) u \right]
\]

The above non standard flavor changing neutral current interaction have been found to play an important role in the infall stage of a stellar collapse [22]. Furthermore precise measurements involving the neutral current neutrino-nucleus interactions may yield valuable information about the non standard interactions [23]. They are not, however, going to be further considered in this work.

**COHERENT NEUTRINO NUCLEUS SCATTERING**

The cross section for elastic neutrino nucleon scattering has extensively been studied [1], [24]. The energy of the recoiling particle can be written in dimensionless form as follows:

\[
y = \frac{2 \cos^2 \theta}{(1 + 1/x_\nu)^2 - \cos^2 \theta}, \quad y = \frac{T_{\text{recoil}}}{m_{\gamma}}, \quad x_\nu = \frac{E_\nu}{m_{\gamma}}
\]

The maximum energy occurs when \( \theta = 0 \), \( y_{\text{max}} = \frac{2}{(1 + 1/x_\nu)^2 - 1} \), in agreement with Eq. (2.5) of ref. [1]. One can invert Eq. (13) and get the neutrino energy associated with a given recoil energy and scattering angle. From the above expressions we see that the vector current contribution, which may lead to coherence, is negligible in the case of the protons. Thus the coherent contribution [25] may
come from the neutrons and is expected to be proportional to the square of the neutron number. The neutrino-nucleus coherent cross section takes the form:

$$\left( \frac{d\sigma}{dT_A} \right)_{\text{weak}} = \frac{G_F^2 Am_N}{2\pi} \left( \frac{N^2}{4} \right) F_{\text{coh}}(A, T_{A\nu}, E_{\nu}),$$

$$F_{\text{coh}}(A, T_{A\nu}, E_{\nu}) = \left( 1 + \frac{A - 1}{A} \frac{T_{A\nu}}{E_{\nu}} \right) + \left( 1 - \frac{T_{A\nu}}{E_{\nu}} \right)^2 \left( 1 - \frac{A - 1}{A} \frac{1}{m_N E_{\nu}/T_{A\nu} - 1} \right) - \frac{Am_N T_{A\nu}}{E_{\nu}^2} \frac{m_N}{T_{A\nu}} E_{\nu}$$

(14)

SUPERNOVA NEUTRINOS

The number of neutrino events for a given detector depends on the neutrino spectrum and the distance of the source. We will consider a typical case of a source which is about 10 kpc, i.e. $D = 3.1 \times 10^{22}$ cm (of the order of the radius of the galaxy) with an energy output of $3 \times 10^{53}$ ergs with a duration of about 10 s. Furthermore we will assume for simplicity that each neutrino flavor is characterized by a Fermi-Dirac like distribution times its characteristic cross section and we will not consider here the more realistic distributions, which have recently become available [26]. This is adequate for our purposes. Thus:

$$\frac{dN}{dE_{\nu}} = \sigma(E_{\nu}) \frac{E_{\nu}^2}{1 + \exp(E_{\nu}/T)} = \Lambda \frac{x^4}{JT} \frac{1}{1 + e^x}, \quad x = E_{\nu}/T$$

(15)

with $J = \frac{31\pi}{252}$. $\Lambda$ a constant and $T$ the temperature of the emitted neutrino flavor. Each flavor is characterized by its own temperature as follows:

$T = 8$ MeV for $\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau$, and $T = 5 (3.5)$ MeV for $\bar{\nu}_e (\nu_e)$.

The constant $\Lambda$ is determined by the requirement that the distribution yields the total energy of each neutrino species.

$$U_{\nu} = \frac{\Lambda T}{J} \int_0^\infty dx \frac{x^5}{1 + e^x} \Rightarrow \Lambda = \frac{U_{\nu}}{T}$$

We will further assume that $U_{\nu} = 0.5 \times 10^{53}$ ergs per neutrino flavor. Thus one finds:

$$\Lambda = 0.89 \times 10^{58} (\nu_e), \ 0.63 \times 10^{58} (\bar{\nu}_e), \ 0.39 \times 10^{58} (\text{all other flavors})$$

The emitted neutrino spectrum is shown in Fig. 1.

The differential event rate (with respect to the recoil energy) is proportional to the quantity:

$$\frac{dR}{dT_A} = \frac{\lambda(T)}{J} \int_0^\infty dx \frac{F_{\text{coh}}(A, T_A, xT)}{1 + e^x}$$

(16)

with $\lambda(T) = (0.89, 0.63, 0.39)$ for $\nu_e, \bar{\nu}_e$ and all other flavors respectively. This is shown in Figs. 2 and 3. The total number of expected events for each neutrino species can be cast in the form:

$$\text{No of events} = \tilde{C}_{\nu}(T) h(A, T, (T_A)_{th}),$$

(17)

$$h(A, T, (T_A)_{th}) = \frac{F_{\text{fold}}(A, T, (T_A)_{th})}{F_{\text{fold}}(40, T, (T_A)_{th})}$$

(18)

with

$$F_{\text{fold}}(A, T, (T_A)_{th}) = \frac{A}{J} \int_{(T_A)_{th}}^{(T_A)_{max}} \frac{dT_A}{1 \text{MeV}} \times \int_0^\infty dx \frac{F_{\text{coh}}(A, T_A, xT)}{1 + e^x}$$

(19)
FIG. 1: The supernova neutrino spectrum. The short dash, long dash and continuous curve correspond to $\nu_e$, $\bar{\nu}_e$ and all other flavors respectively.

FIG. 2: The differential event rate as a function of the recoil energy $T_A$, in arbitrary units, for Xe. On the left we show the results without quenching, while on the right the quenching factor is included. We notice that the effect of quenching is more prevalent at low energies. The notation for each neutrino species is the same as in Fig. 1.

and

$$\tilde{C}_\nu(T) = \frac{G_2^2 m_N 1 \text{MeV} N^2}{2\pi} \Lambda(T) \frac{1}{4\pi D^2} \frac{P V}{k T_0}$$  \hspace{1cm} (20)$$

Where $k$ is Boltzmann’s constant, $P$ the pressure, $V$ the volume, and $T_0$ the temperature of the gas. Summing over all the neutrino species we can write:

$$\text{No of events} = C_\nu \frac{K(A, (T_A)_{th})}{K(40, (T_A)_{th})} Qu(A)$$  \hspace{1cm} (21)$$

with

$$C_\nu = 153 \left(\frac{N}{22}\right)^2 \frac{U_\nu}{0.5 \times 10^{58} \text{ergs}} \left(\frac{10 \text{kpc}}{D}\right)^2 \frac{P}{10 \text{Atm}} \left[\frac{R}{4m}\right]^3 \frac{300}{T_0}$$  \hspace{1cm} (22)$$

$K(A, (T_A)_{th})$ is the rate at a given threshold energy divided by that at zero threshold. It depends on the threshold energy, the assumed quenching factor and the nuclear mass number. It is unity at $(T_A)_{th} = 0$. From the above equation we find that, ignoring quenching, the following expected number of events:

$$1.25, 31.6, 153, 614, 1880$$

for He, Ne, Ar, Kr and Xe respectively. For other possible targets the rates can be found by the above formulas or interpolation. The quantity $Qu(A)$ is a factor less than one multiplying the total rate, assuming a threshold energy
\( (T_A)_{th} = 100 \text{eV} \), due to the quenching. The idea of quenching is introduced, since, for low emery recoils, only a fraction of the total deposited energy goes into ionization. The ratio of the amount of ionization induced in the gas due to nuclear recoil to the amount of ionization induced by an electron of the same kinetic energy is referred to as a quenching factor \( Q_{fac} \). This factor depends mainly on the detector material, the recoiling energy as well as the process considered [27]. In our estimate of \( Q_u(T_A) \) we assumed a quenching factor of the following empirical form motivated by the Lidhard theory [27]-[28]:

\[
Q_{fac}(T_A) = r_1 \left[ \frac{T_A}{1 \text{keV}} \right]^{r_2}, \quad r_1 \simeq 0.256, \quad r_2 \simeq 0.153
\]

Then the parameter \( Q_u(A) \) takes the values:

\[
0.49, \ 0.38, \ 0.35, \ 0.31, \ 0.29 \text{ for He, Ne, Ar, Kr and Xe}
\]

respectively. The effect of quenching is larger in the case of heavy targets, since, for a given neutrino energy, the energy of the recoiling nucleus is smaller. Thus the number of expected events for Xe assuming a threshold energy of 100 eV is reduced to about 560.

The effect of quenching is exhibited in Fig. 3 for the two interesting targets Ar and Xe. We should mention that it is of paramount importance to experimentally measure the quenching factor. The above estimates were based on the assumption of a pure gas. Such an effect will lead to an increase in the quenching factor and needs be measured.

**CONCLUSIONS**

In the present study it has been shown that it is quite simple to detect typical supernova neutrinos in our galaxy, provided that such a supernova explosion takes place (one explosion every 30 years is estimated [29]). The idea is to employ a small size spherical TPC detector filled with a high pressure noble gas. An enhancement of the neutral current component is achieved via the coherent effect of all neutrons in the target. Thus employing, e.g., Xe at 10 Atm, with a feasible threshold energy of about 100 eV in the detection the recoiling nuclei, one expects between 600 and 1900 events, depending on the quenching factor. We believe that networks of such dedicated detectors, made out of simple, robust and cheap technology, can be simply managed by an international scientific consortium and operated by students. This network comprises a system, which can be maintained for several decades (or even centuries). This is is a key point towards being able to observe few galactic supernova explosions.

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