Supernova Neutrinos in Liquid Scintillator Detectors by means of neutrino-proton elastic scattering

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A brief review of supernova neutrino detection by massive underground liquid scintillators is presented. Prominence is given to the neutrino-proton elastic scattering detection channel which is unique for such detectors.

1 Introduction

In this paper we deal with massive underground liquid scintillator detectors which might search for supernova neutrinos. An organic liquid scintillator is made of carbon and hydrogen atoms and neutrinos from a core collapse supernova can be detected by a number of interaction channels (see also [1]): inverse-beta decay, neutrino-proton elastic scattering, neutrino-electron elastic scattering, charged current and neutral current on carbon nuclei. Among these interaction processes the *golden* detection channel is the inverse-beta decay for electron anti-neutrinos: $\bar{\nu}_e + p \rightarrow e^+ + n$. This interaction has the largest cross-section and a threshold equal to 1.806 MeV. Moreover, it offers an important tagging through the delayed signal provided by the capture reaction: $n + p \rightarrow d + \gamma(2.22\text{ MeV})$. This reaction can be thought of as background free in liquid scintillators.

For a standard supernova at 10 kpc [2] we predict about 300-400 events for a target mass with 10^{32} protons in the inverse-beta decay channel. Another important interaction channel is the neutral current on carbon nuclei: $\nu_x +^{12} C \rightarrow \nu_x +^{12} C + \gamma(15.11\text{ MeV})$. For this reaction we predict about 70 events for 10^{32} ^{12}C nuclei and for a standard supernova. This is also a background free reaction and will provide an unambiguous signal of supernova neutrinos. Yet, it will not be possible to disentangle the degeneracy between the supernova luminosity and temperature. Charged current interactions on ^{12}C and neutrino-electron elastic scattering will

Detector	N_p	Design
LVD	9.3×10^{31}	segmented
Borexino	1.7×10^{31}	unsegmented
KamLAND	5.9×10^{31}	unsegmented
Baksan	1.2×10^{31}	segmented
MiniBooNE	5.2×10^{31}	unsegmented
SNO+(*)	5.9×10^{31}	unsegmented
LENA(**)	3.3×10^{33}	unsegmented

Table 1: Liquid scintillator detectors which might detect supernova neutrinos. (*) SNO+ is planned to be operational in 2013. (**) LENA is in an advanced proposal stage.

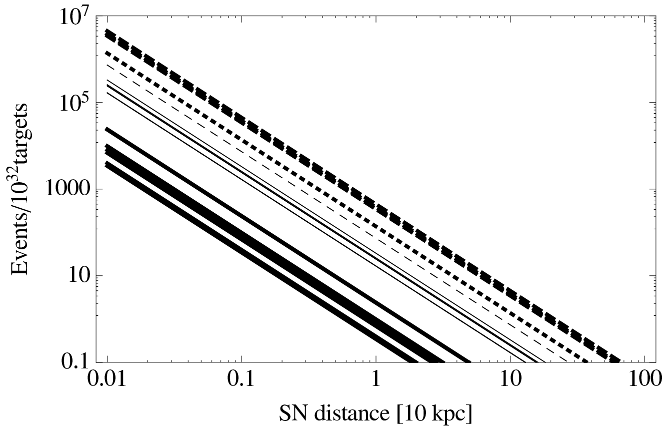

Figure 1: Predicted number of events for a standard supernova against the supernova distance. Black thick dashed lines: inverse-beta decay. Black thick dotted line: neutrino-proton elastic scattering. Black dashed: NC on ^{12}C. Black solid lines: CC on ^{12}C. Black thick solid lines: neutrino-electron elastic scattering.

play a minor role in the detectors in operation. The technology of massive liquid scintillators underground has been developed over the last 20 years. In Tab. 1 we report the list of detectors which make use of an organic liquid scintillator. One main design feature can be outlined: some detectors have a segmented structure, others not. This is an important aspect for supernova neutrinos due to the fact that in a segmented detector the duty cycle is often larger. However, an unsegmented detector can work better for other neutrino sources such as solar neutrinos, geo-neutrinos and electron antineutrinos from reactors, as an example. The possibility to search for just a rare event as that of a supernova cannot justify the construction of a massive underground neutrino detector nowdays. Therefore, the detectors listed in Tab. 1 have other main research goals besides supernova neutrinos.

In Fig. 1 we report a summary of the expected number of events for a standard supernova in a liquid scintillator detector. This figure includes the effect of neutrino oscillations with direct and inverted hierarchy. A galactic supernova can be as far as about 30 kpc with a most likely distance around 10 kpc. The SN1987A was at about 50 kpc.

In liquid scintillators at present electron neutrinos will produce only a minor signal. This could be different with the very massive LENA detector. The signal from electron neutrinos is important to probe the early neutrino production during the collapse. One possibility to disentangle electron neutrinos could come from the CC interaction on ^{12}C: $\nu_e + ^{12}C \rightarrow e^- + ^{12}N$ with a threshold equal to 17.34 MeV. This reaction is followed by the β-decay of ^{12}N which can provide a delayed tagging. However, in spite of the prompt-delayed signals, the rate in a kton scale detector is of the order of 10-20 events for a 10 kpc supernova. Moreover the CC channel on electron antineutrinos will make the measurement difficult with a small statistic data sample due to an overlap of the two visible spectra from ν_e and $\bar{\nu}_e$.

2 Neutrino-proton elastic scattering for supernova neutrinos

The idea to search for neutrino-proton elastic scattering was introduced by J. Beacom, W. Farr and P. Vogel in 2002 [3]. This work has been recently revised [4] to make use of quenching measurements and more realistic detector features. For this detection channel the visible energy is due to the recoiled protons. The yield of an ionizing proton in a liquid scintillator is affected by a non-radiative energy transfer. This effect is accounted for with a quenching factor which depends on the energy [5]. For a 20 MeV incoming neutrino the recoiled proton will have an energy of about 1 MeV and a visible energy of 0.2 MeV. Therefore, in order to exploit such a detection channel, the experimental apparatus needs a sub-MeV threshold. At present Borexino is working with a 0.2 MeV threshold to search for sub-MeV solar neutrinos [6]. The quenching of protons has been measured in KamLAND by means of a dedicated test facility [7] and in Borexino by means of an AmBe source deployed inside the detector. In Fig. 2 we show the expected spectrum for this interaction channel where $\nu_{\mu,\tau}$ in the supernova model have an average energy of 20 MeV. From this figure it is possible to see that the spectrum of ν_e and $\bar{\nu}_e$ are shifted below threshold due to the quenching effect: only $\nu_{\mu,\tau}$ can be detected above 200 keV. In Borexino, which has the smallest target size among the detectors listed in Tab. 1, we expect about 30 events for a 10 kpc supernova. From Borexino data [6] one expects about 3 accidental counts in 10 seconds which is the duration of the supernova burst. Therefore, we could claim that with the present technology developed for massive underground and high radiopurity liquid scintillators it is feasible to detect such supernova neutrinos. The neutrino-proton channel is a feature of liquid scintillators and is particularly important due to the fact that allows to break the degeneracy between temperature and binding energy for $\nu_{\mu,\tau}$ neutrinos. As a matter of fact, the temperature or average energy and the binding energy are related to the number of events detected: $N_{ev} \propto \langle\sigma\rangle E_{binding}/\langle E_{\nu_x}\rangle$. It turns out that the measurement of the spectrum of recoiled protons can break this degeneray and provide fundamental information about the supernova mechanism. In order to perform an accurate measurement it can be shown that the knowledge of the quenching at the level of a few %'s is important to disentangle the average neutrino energy. In a few years SNO+ with about 800 tons of target mass should also be able to detect sub-MeV energies.

3 Conclusions

Present massive liquid scintillators are ready to observe some 100-400/10^{32}targets neutrino events for a standard supernova at 10 kpc. The *golden* detection channel is the inverse-beta decay which probes $\bar{\nu}_e$. The neutrino-proton elastic scattering provide a unique investigation tool for $\nu_{\mu,\tau}$ neutrinos with high purity massive underground liquid scintillators detectors. Neutral current on carbon nuclei will offer an unambiguous signal of supernova neutrinos with about 70 events/10^{32}targets. Liquid scintillators at present cannot offer a good detection channel for electron neutrinos. This could be a goal for future super-massive detectors such as LENA.

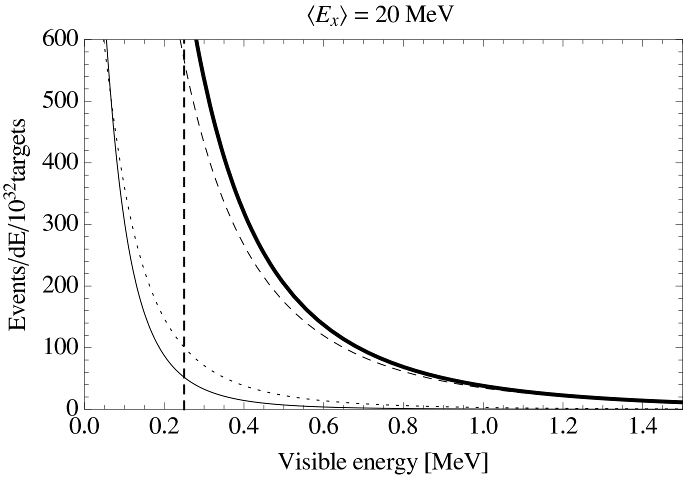

Figure 2: Expected visible spectrum for a 10 kpc supernova in the neutrino-proton elastic scattering detection channel. Back thin line: ν_e. Black dotted thin line: $\bar{\nu}_e$. Black thin dashed line: $\nu_{\mu,\tau}$

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