

Detection of supernova neutrinos via coherent ν -nucleus scattering

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Abstract. We consider the possible detection of Supernova neutrinos via Coherent ν -Nucleus Scattering in a scintillation detector. The envisaged applications include the separate determination of the energy and temperature of the neutrinos and antineutrinos of the second and third family by exploiting the spectral information encoded in the recoiling nuclei and inherited from the impinging neutrinos. Our results suggest that despite a significant quenching factor and a high detector threshold, determination of one of the neutrino observables is achievable for a wide range of the parameter space.

1. Introduction

Supernova events are extremely powerful explosions exhibitivive of the last stages of the evolution of stars with masses above the Chandrasekhar limit, roughly 1.44 solar masses. Of particular interest to neutrino phenomenology are *core collapse* supernovae, in which a large massive star burns out all its fuel and its interior nucleus rapidly shrinks by gravitational pressure until it reaches nuclear densities. Then, the nucleon degeneracy pressure abruptly stops the collapse and the falling outer parts of the dying star literally bounce back after crashing with the wall of dense inner matter, initiating a series of events, in which neutrinos are suspected to play a prominent role, that trigger the explosion [1].

When a large massive star becomes a core collapse supernova, several solar masses of material end up ejected in the explosion into interstellar space with kinetic energies of the order of 10^{51} erg, which amounts to approximately 10^{30} Hiroshima nuclear bombs. The fingerprints of the ejected material are easily identified even long afterwards from the distance as beautiful shapes known as nebulae. From the perspective of human history, the most prominent feature of a supernova is the accompanying luminous explosion when the star increases its luminosity and becomes, for several days, as bright as its hosting galaxy. Despite the copious amounts of energy involved in these processes, it is estimated that only 0.01% and 1% of the total energy released in a supernova is accounted for, respectively, by the luminous explosion and the ejected material kinetic energy.

Surprisingly, the 99% of the energy in a core collapse supernova event, around 3×10^{53} erg, is released through neutrinos of all flavours. Moreover, the neutrino pulse accompanying such an event only lasts a few seconds and precedes the luminous explosion. In the short time interval of the neutrino pulse, an estimate of 10^{58} neutrinos are emitted from the supernova with an average



energy of 10 MeV. This means that the luminosity in neutrinos of a core collapse supernova is comparable to the combined luminosity in photons of all the stars in the visible universe [2].

From a global perspective supernovae occur quite often in the whole universe, approximately 1 event per second. Of course, we are forced due to technological impediments to focus our attention to the immediate local environments. In particular, when we are interested in the detection of supernova neutrinos only galactic supernovae offer viable scenarios for detection of these particles. An exception occurred in 1987 when a neutrino signal was obtained in several neutrino detectors operating at the time, correlated with the discovery of the supernova explosion in the Large Magellanic satellite galaxy orbiting the Milky Way. The estimated core-collapse supernova rate in the Galaxy is about 3 times per century, though external effects such as interstellar dust blocking the light of an event might explain the lack of reported observations in the last four centuries, since the last galactic supernova observation in 1604. Present neutrino detectors can easily observe a supernova anywhere in the Galaxy or its immediate satellite companions but do not have large enough volumes to observe one in even the nearest galaxy, some 700 kpc away.

In a supernova event, because different flavours of neutrinos have different interactions with matter, and because the nascent neutron star's temperature is decreasing with increasing radius, the neutrino decoupling temperatures are different. Theoretical and numerical estimates are model dependent, in the usual model the ν_μ and ν_τ neutrinos and their antiparticles have a temperature of about 8 MeV, the $\bar{\nu}_e$ neutrinos about 5 MeV, and the ν_e neutrinos about 3.5 MeV. In the following we shall assume these values in our calculations.

At present most neutrino detectors operate in the charged current detection channel, so it is to be expected that in the event of an actual supernova neutrino signal the properties of the electron neutrino flavour and its antiparticle will be probed with good statistics. It was pointed out some time ago [3] that the neutral current detection channel also offered the possibility of determining separately the energy and temperature of the supernova neutrinos of the second and third generation, for example through the elastic neutrino-proton dispersion channel. In this complementary channel the information on the recoiling proton energy is crucial, which is non-relativistic and therefore invisible on Cerenkov detectors but detectable in scintillation ones. Soon afterwards [4] the same idea was explored with the detection via neutrino-nucleus elastic scattering taking advantage of the very large coherent cross section and the sensitivity to all flavours of neutrinos and antineutrinos.

Backgrounds for supernova neutrinos can be handled relatively easy, mostly because all of the events are concentrated in a few second interval. On the other hand an important obstacle present in these neutral current detection channels is the phenomenon of quenching, which refers to energy losses by ionization. The low energy recoiling particles are highly ionizing in such a way that their scintillating light is reduced (quenched) relative to a minimum ionizing particle like an electron. Because of these energy losses the recoiled particle spectrum is affected significantly. This feature is accounted for by introducing the quenching factor Q_f . As an illustration of the effect of Q_f on the yield of recoiling nuclei in coherent neutrino-nucleus scattering on a Xenon detector we show in Figure 1 how the number of events per ton above an illustrative detector threshold cut is notoriously reduced by the effects of ionization.

This quenching effect is particularly damaging for the electron (anti)neutrino contribution to the neutrino-nucleus elastic scattering channel signal. While in principle this channel is sensitive to all types of neutrinos, the electron neutrinos and antineutrinos cannot be detected in real situations due to their relative low decoupling temperatures. For the same reason, the corrections due to quenching are notoriously strong for the electron neutrino and its antiparticle. That being said, we shall ignore possible *spectral split* effects [5] where oscillation between neutrino types might produce changes that would be perceived as different decoupling temperatures than the ones assumed here.

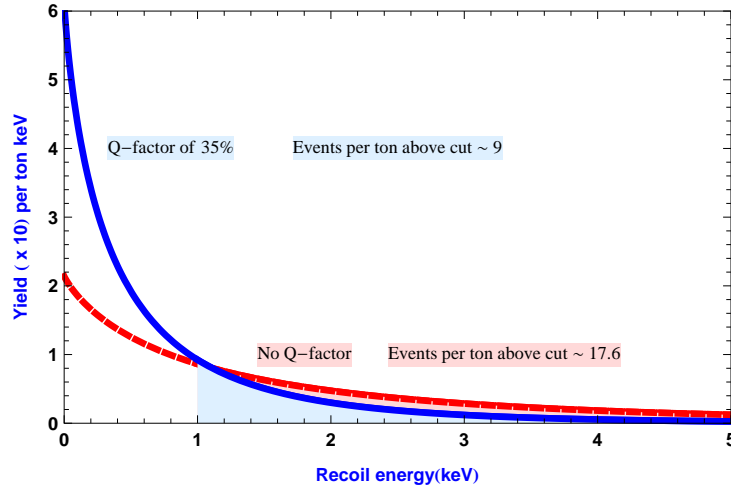


Figure 1. Calculated yield for the elastic neutrino-nucleus scattering channel. Because of energy losses by ionization, the spectrum of recoiling nuclei is affected significantly, this is accounted for by the quenching factor Q_f . The solid (blue) line illustrates the effect of Q_f on the recoiled nuclei spectrum, showing a decrease in the number of events per ton relative to the ideal case illustrated by the dashed (red) line, for a Xe detector with an illustrative detector threshold of 1 keV.

Multi-ton liquid scintillation detectors are attractive proposals in the experimental race to detect the elusive dark matter particles, though their use also include for example measurement of neutrinoless double beta decay of ^{136}Xe , the pp solar neutrino spectrum and in particular, the neutrino flux and temperature from a Galactic supernova [6]. In this letter we perform simulations of detectors sensitivities for the determination of the temperature and energy of galactic core collapse supernova neutrinos of the second and third generation based on neutrino-nucleus elastic scattering in scintillation materials. We take into account realistic quenching factors and detector thresholds and show the viability of this complementary channel for future multi-ton scintillation detectors.

2. Cross section, yield and results

Neutrino-nucleus elastic cross section can be calculated accurately with very little theoretical uncertainty,

$$\frac{d\sigma}{d\Omega} = \frac{G_F^2}{4\pi^2} k^2 (1 + \cos\theta) \frac{Q_w^2}{4} F(Q^2)^2$$

for a neutrino of energy k scattering at angle θ , G_F being the Fermi constant. This coherent cross section depends on the square of the weak charge $Q_w = N - (1 - 4\sin^2\Theta_W)Z$ of a nucleus with N neutrons and Z protons, $\sin^2\Theta_W \approx 0.231$ being the weak mixing angle and F the Helm [7] nuclear form factor at momentum transfer Q , $Q^2 = 2k^2(1 - \cos\theta)$. Assuming a Boltzmann spectra for the neutrinos allows us to obtain an analytic expression for the yield of recoiling nuclei with energy E and mass M :

$$Y(E) = \frac{G_F^2 Q_w^2}{4\pi} M F^2(2ME) \left(\frac{N_t}{4\pi d^2} \right) \sum_{i=\nu_e, \bar{\nu}_e, \nu_x} N_i \left(1 + \left(\frac{ME}{2T_i^2} \right)^{1/2} \right) e^{-\left(\frac{ME}{2T_i^2} \right)^{1/2}}$$

where T_{ν_x} and N_{ν_x} are the temperature and number of (anti)neutrino x , $x = \mu, \tau$ and similarly for the electron (anti)neutrino, the sum being over all neutrino and anti-neutrinos flavours. Here

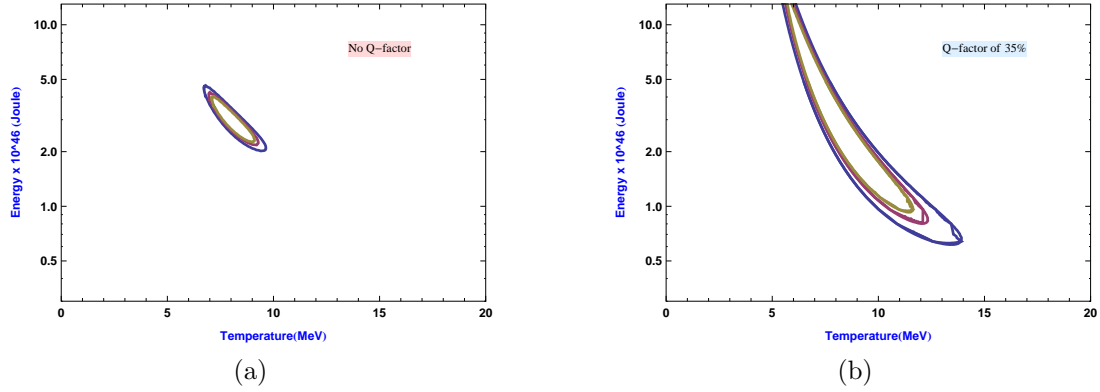


Figure 2. These plots show the effect of Q_f on the detector sensitivity, the confident level (CL) contours in the right panel expand for a much larger area than in the left panel where no energy losses are assumed. Contours shown correspond to 90%, 95% and 99% of C.L. for a Xenon detector with 10 tons and a detector threshold of 8 keVs.

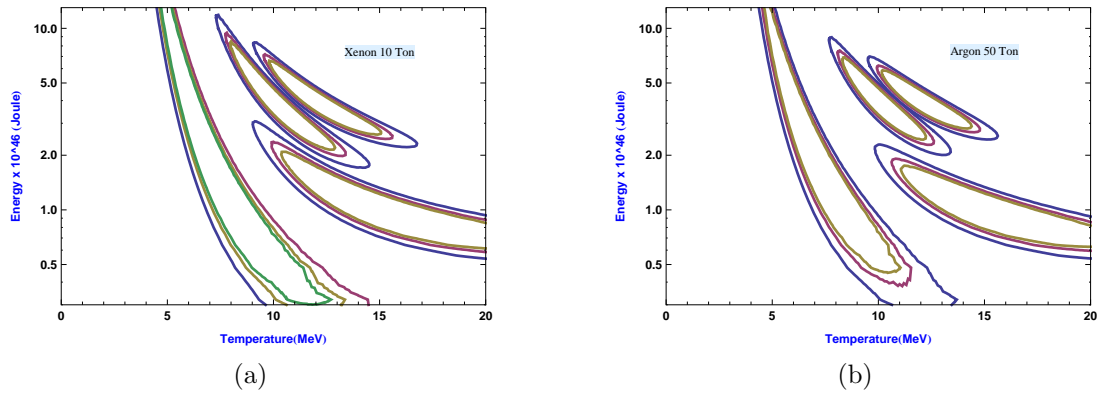


Figure 3. Detector sensitivity plots for various values of $(T_{\nu_x}, E_{\nu_x}) = (7, 2), (10, 4), (12, 4)$ and $(15, 1)$ in the units shown. In the left panel we present results for a detector based on 10 tons of Xenon with a threshold of 8 keVs; the right panel is for 50 tons of Argon with a detector threshold of 20 keVs. In both cases a conservative value of 0.35 is assumed for the quenching factor. Contours shown correspond to 90%, 95% and 99% of C.L.

N_t is the total number of target atoms in the detector, and d is the distance to the supernova which we assume to be 10 kpc. We note that the yield is dominated by the contributions of the neutrinos of the second and third generation due to the relative low values of the temperature of the electron (anti)neutrinos, specially for large recoil energy E . This effect is enhanced by the correction due to quenching effects which practically filters out the contribution of the electron (anti)neutrinos.

As mentioned before, access to the spectrum of the recoiling nuclei is of great importance and to take advantage of this information it is necessary to bin the simulated data in energy. By performing chi-square fits on the simulated data we obtain best fit points for the parameters of interest, determining the regions of sensitivity of the assumed detector configurations, the χ^2 function being defined as

$$\chi^2 = \sum_j 2 \left(n_j^t - n_j^f - n_j^f \ln \frac{n_j^t}{n_j^f} \right)$$

where the sum runs over energy bins. Here, a superscript t is used to denote the predicted number of events n_j^t in the j -th bin, while a superscript f is employed to denote the number of events obtained from the fitting to the simulated data, n_j^f .

In Figure 2 we show sensitivity regions for a 10 ton Xenon detector with (right panel) and without (left panel) energy losses taking into account. The importance of ionizing effects are reflected in the detector sensitivity which is found to worsen significantly for the realistic case of energy losses. Finally in Figure 3 [8] we present our results for two types of scintillating detectors and several assumed (true) values of the temperature and energy of the supernova neutrinos.

3. Conclusions

We have performed simulations of detection of neutrinos from core collapse supernova events in scintillating detectors in the coherent neutrino-nucleus scattering channel with realistic detector thresholds and quenching factor. We have presented sensitivity regions for two types of scintillating materials currently studied for multi-ton detector proposals mainly in the experimental search for weakly interacting dark matter. Our results allow us to conclude that with these set-ups a good determination of the neutrino ν_μ and ν_τ parameters, their temperature and energy, could be achieved for energies above $2 \times 10^{46} J$ and temperatures above 8 MeV.

Acknowledgments

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