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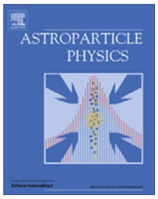

Study of supernova ν-nucleus coherent scattering interactions

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ABSTRACT

Presently, there are several experimental setups dedicated to rare event searches, such as dark matter interactions or double beta decay, in the building or commissioning phases. These experiments often use large mass detectors and have excellent performance in terms of energy resolution, low threshold and extremely low backgrounds. In this paper we show that these setups have the possibility to exploit coherent scattering on nuclei to detect neutrinos from galactic supernova explosions, thus enlarging the number of early detection "observatories" available and helping in the collection of valuable data to perform flavour-independent studies of neutrinos' emission spectra.

1. Introduction

Neutrinos from core-collapse supernovae are messengers of rich information in both particle physics (neutrino properties, oscillations) and astrophysics (supernova mechanism, very dense matter behaviour). They also constitute, as of today, the only prompt detectable signal of a supernova event, as the technology to detect gravitational waves is still under development and no signal has been detected yet.

Charged current (CC) scattering based experiments such as Super-Kamiokande [1,2], Borexino [3] and LVD [4,5] are able to detect incoming electron antineutrinos ($\bar{\nu}_e$) in the supernova energy range with high efficiency by means of the inverse beta decay on free protons (the Cherenkov or scintillation light produced by the positron emitted during the process is the actually detected signal). Electron neutrinos (ν_e) and ν_x (sum of $\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$) can also be detected by these experiments, but the cross sections of the involved processes (CC and neutral current, NC, scattering on electrons) are much smaller. Since the cross sections for neutrino-electron interactions, especially in the MeV energy range, are small, the detector mass has to be overwhelmingly large ($O(1000\,\text{tons})$) to compensate. Furthermore, the detection capability is almost entirely limited to electron neutrinos, while during a supernova explosion neutrinos of all three flavours are supposed to be produced. Hence, the inclusive detection of all neutrino species could provide important and oscillation-independent information about their total emission flux and spectrum.

A very promising but not yet exploited mechanism to detect ν_x is neutrino-nucleus coherent elastic scattering on target nuclei. This process is flavour-blind and, for small enough momentum transfer, the cross section is highly enhanced by the coherent superposition of interaction probabilities for all nucleons within the scattered nucleus. Due to the possibility of detecting all neutrino components and the enhancement of involved cross sections, the expected number of events from a standard supernova turns out to be large enough to make a 1 ton scale detector based on coherent scattering as effective as a 100 ton light water Cherenkov detector. Moreover, the recoil energy of coherently scattered nuclei is correlated to the neutrinos' energy in such a way that some information about the neutrino spectra, the average temperature for example, can be reconstructed. A large mass coherent scattering detector can therefore be used, in principle, as a thermometer for ν_x emitted by collapsing stars.

Demonstrating the capability of an experiment using coherent elastic scattering to detect supernova neutrinos increases the number of experiments potentially involved in early supernovae detection networks like SNEWS [6].

Presently, many experiments for rare events (double beta decay, dark matter search) are in building or commissioning phase. These experiments, which are often based on cryogenic detectors, have in common good energy resolution (hence low threshold capabilities), extremely low background and large masses, and they often use detectors containing high atomic mass elements (Ge, Te, Cd,W). Noble gases (Ar, Xe) and large mass standard scintillating detectors (NaI) are interesting as well. In Table 1 some

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experiments that could potentially use this technique are reported. The purpose of this paper is to show a systematic study of the potential that different materials have as targets for coherent scattering interactions as a function of the target properties and the neutrino spectra. Materials already used (or planned to be used) in large mass rare event detectors are especially considered.

2. Theoretical background

2.1. Type II SN

A core collapse supernova (or type II supernova) is an astronomical phenomenon marking the end of a massive star's life. Models have shown that for stars with masses grater than ~9 solar masses the end of the hydrogen burning phase is followed by a series of predictable cycles of contraction, heating and burning of progressively heavier elements within the star core (which assumes a onion like structure with the heavier element, iron, at the centre). The dynamical stability is granted, in each layer, by the energy produced in the nuclear fusions. However, in the iron core no net energy is produced as no fusion can occur; electron degeneracy pressure is the only force that prevents the core from collapsing. When the Chandrasekhar limit (1.4 M_{sun}) is exceeded, gravity becomes stronger than electron degeneracy and the iron core collapses. During the collapse, the temperature and density increase dramatically and two phenomena occur:

`Photodisintegration`

$$(A,Z)+\gamma\rightarrow(A',Z')+(Z-Z')p+(A-A'-Z+Z')n \tag{1}$$

`Inverse beta decay`

$$\begin{aligned} e^-+p&\rightarrow n+\nu_e \\ e^++n&\rightarrow p+\bar{\nu}_e \end{aligned} \tag{2}$$

The iron core continues to shrink until the density approaches the nuclear density, and strong forces and neutron degeneracy prevent further collapse. The in-falling matter rebounds, creating an outgoing shockwave that dissociates nuclear matter, losing energy and finally stalling. The interaction between the shockwave and the core generates extreme temperature/density conditions where nucleon bremsstrahlung and pair annihilation take place.

`Bremsstrahlung`

$$(A,Z)+\gamma\rightarrow\nu_{e,\mu,\tau}+\bar{\nu}_{e,\mu,\tau}+(A,Z) \tag{3}$$

`Pair annihilation`

$$e^++e^-\rightarrow\nu_{e,\mu,\tau}+\bar{\nu}_{e,\mu,\tau} \tag{4}$$

These last two (Eqs. (3) and (4)) are Z_0 mediated neutral current processes.

Numerical simulations [16] show that the interaction of a small fraction (0.1%) of the neutrinos generated in this phase with the nuclear matter behind the stalled shock should be enough to rise the shock total energy to positive values. Unbounded layers are ejected in the supernova explosion.

Table 1
Experiments that could potentially be able to detect supernova neutrino through coherent scattering.

Experiment	Detector material	Mass [kg]
GERDA (phase II) [7]	Ge	37.5[a]
SuperCDMS (phase B) [8]	Ge	145[a]
CUORE [9,10]	TeO_2	741[b]
COBRA [11]	CdZnTe	0.42
CRESST [12]	$CaWO_4$	10
XENON100 [13]	Xe	62[a]
WARP [14]	Ar	150
DAMA/LIBRA [15]	NaI	250

[a] The experiment feasibility has been demonstrated (project).
[b] The experiment is in commissioning phase.

The processes in Eqs. (2)–(4) are the mechanisms that generate the neutrino fluxes emitted in the supernova explosion. The individual contributions to the total flux are ~10–20% from inverse beta decay and ~80–90% from pair annihilation and bremsstrahlung [17].

A simplified model for the neutrino emission is used in literature [18,19] when the process described in Eqs. (3) and (4) can be considered as the main channels of neutrino production. This approximation is especially valid in the case of detection through coherent scattering. As will be explained in 2.2, coherent scattering is blind to neutrino flavour; processes like the ones in Eq. (4) can thus be considered the main source of the interacting neutrinos.

The same simplified model predicts the equipartition of the total energy ($\sim 3\times10^{53}$ ergs) among the six neutrino and antineutrino flavours at production. The emission spectra will have different shapes due to the different interaction cross sections, free paths and neutrino spheres' radii for the different species, with resulting different temperatures for $\nu_e, \bar{\nu}_e$ and ν_x, where ν_x are all the remaining neutrino and antineutrino $(\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau)$ families (see Fig. 1). Boltzmann spectra with different temperatures are an adequate approximation for our purposes and are used in the literature as well [18,20].

The spectra in Fig. 1 are calculated for a source located at a distance of 8.5 kpc. This is a common assumption in the literature[21–23], as it is the distance of the centre of our galaxy. Sometimes 10 kpc is used, as it can be calculated [24,25] to be the distance with the highest probability of a supernova collapse occurrence.

2.2. Coherent scattering on target nuclei

Coherent nuclear elastic scattering is a neutral current weak interaction. From a theoretical point of view, it is the same process of neutrino-nucleon neutral current scattering. If the momentum of the incoming neutrino is small enough, the single nucleon components (protons and neutrons) will not be distinguished and the nucleus will be scattered as a whole. The scattering amplitudes for the different nucleons then coherently sum to give the total cross section. This turns out to be enhanced by a factor of the order of the square of the neutron number compared to that of a single nucleon. The coherent behaviour of the interaction will depend on the actual momentum transfer between the incoming particles (neutrino and nucleus). The higher the momentum transfer, the higher the capacity of the neutrino to distinguish the single components of the nucleus, and hence the smaller the cross section. The nuclear form factor (see 3.2) is the parameter that accounts

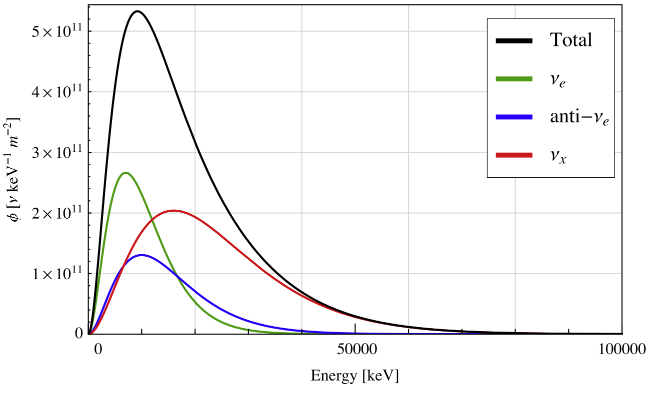

Fig. 1. Boltzmann spectra (at a distance d = 8.5 kpc from the source) for the three neutrino families used in the calculations. Green = ν_e(3.5 MeV), blue = $\bar{\nu}_e$(5 MeV), red = ν_x(8 MeV) and black = total spectrum.