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Low-threshold performance and coherent detection of supernova neutrinos in CUORE-0 and CUORE

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Summary. — Thanks to a trigger algorithm based on the optimum (matched) filter technique CUORE experiment will be able to lower the energy threshold and detect neutrinos from type II supernovae via the observation of the recoil energy (few to tens of keV for a MeV neutrino) of a scattered target nucleus (ν-nucleus NC coherent scattering is a phenomenon relatively well known but never observed experimentally). The studies on the sensitivity to supernova neutrino show that a supernova at 7 kpc should be detected with high efficiency.

PACS `13.15.+g` – Neutrino interactions.
PACS `29.85.Fj` – Data analysis.
PACS `97.60.Bw` – Supernovae.

1. – CUORE performance at low energy

CUORE (Cryogenic Underground Observatory for Rare Events) (ref. [1]) is a 1-ton scale bolometric experiment. Its primary target is the observation of neutrinoless double-beta decay of ^{130}Te. An array of 988 natural TeO_2 crystals is kept at $\sim 10\,\mathrm{mK}$ in a cryostat located in the Hall A of Gran Sasso Underground Laboratories, in Italy. Since neutrinoless double-beta decay is an extremely rare (forbidden in the Standard Model) nuclear decay, CUORE features e large mass, excellent energy resolution, high detector segmentation, and extremely low background, proving to be sensitive also to other rare phenomena involving interactions at low energy. Through neutrino-nucleus neutral current coherent scattering (a phenomenon relatively well known but never observed experimentally) a MeV neutrino (transferring a fraction of its energy to a target nucleus generating a recoil with a typical energy of few to tens of keV) can be detected. A very low threshold of few keV is mandatory to detect these interactions. In CUORE it can be achieved by means of a trigger algorithm based on the optimum (matched) filter technique which is able to reject non-physical events based on the analysis of the shape of the recorded pulses, thus maximizing the signal-to-noise ratio. An online implementation of

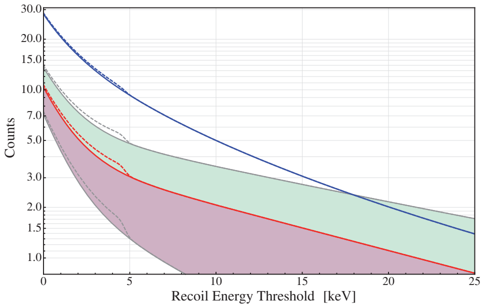

Fig. 1. – Number of signals (for a supernova at a distance of 8.5 kPc and an energy of 10^{53} erg) and background events as a function of the energy threshold (red = background, blue = signal + background).

Table I. – *Number of signals (for a supernova at a distance of* 8.5 kPc *and an energy of* 10^{53} erg*) and background events for some values of the threshold.*

Threshold [keV]	Signal	Background	$S/\sqrt{\mathrm{B}}$
0	17.9	10.7	5.6
3	8.9	4.4	4.4
5	6.2	3.1	3.6
10	2.9	2.1	2.0

this technique, consisting on the real time filtering of the continuous data flow coming from the detectors, lowers the threshold down to its theoretical (resolution-limited) limit (ref. [2]).

2. – Type-II supernova neutrinos and coherent interaction

With an energy threshold in the range of few keV, CUORE becomes sensitive to neutrinos emitted by type-II supernovae in a galactic environment.

Supernova neutrinos are mainly emitted (refs. [3, 4]) in the cooling phase where the equipartition of energy among the different families leads to Boltzmann-shaped spectra with different temperatures(^{1}). Theoretical models predict the fluxes that can be used to calculate the expected number of interactions in a given detector material. The NC coherent interaction is a Standard Model process whose cross section is calculated as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{G_F^2}{4\pi^2} E^2 (1 + \cos\theta) \frac{Q_W^2}{4} F(Q^2)^2, \tag{1}$$

where G_F is the Fermi constant and θ is the angle between the original and the scattering direction. Q_W is the weak charge of the nucleus. Since $Q_W = N - (1 - \sin^2\Theta_W)Z$ the

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(^{1}) The temperature is related to the neutrino sphere radius which is different for ν_e, $\bar{\nu}_e$ and ν_x, all the other families.

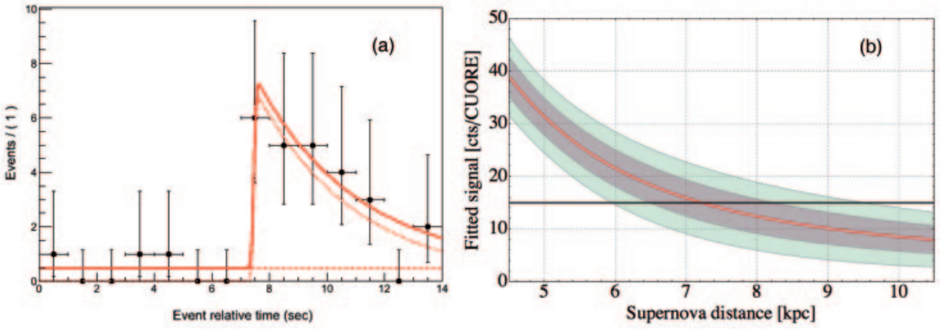

Fig. 2. – Trigger algorithm: (a) toy Montecarlo event time series with signal-plus-background fit, (b) fitted signal with 1σ and 2σ bands as a function of distance.

cross section for a nucleus with N neutrons and Z protons is enhanced by a factor $\sim N^2$ compared to the cross section for the standard ν-nucleon NC elastic scattering. Heavy nuclei (like Te, 592 kg of which are present in CUORE detectors) are favorite targets. As coherent scattering happens only when the wavelength associated to the momentum transferred in the interaction is comparable with the nuclear dimension, a form factor accounts for the probability of having coherent scattering as a function of the nucleus recoil energy (refs. [5-7]).

The expected rate of neutrino interactions and the energy spectrum of recoiling nuclei can be calculated by integrating the form factor, the neutrino spectra and the cross section of eq. (1) (ref. [8]). The integral number of detected nuclear recoils as a function of the energy threshold of the detector is reported in fig. 1 and table I.

3. – Trigger algorithm

A supernova detection dedicated trigger algorithm has been developed based on the online analysis of the time distribution of the low-energy events in the detector. For each particle interaction in CUORE ($\sim$ 1 Hz background expected rate, extrapolated from dedicated background studies, ref. [9]) in the 3–50 keV region the relative arrival time of all the events in a 14 s window is considered. The event time position is fitted with maximum-likelihood method with a flat background plus signal model. The model for the supernova emission time distribution is found in literature (refs. [3, 4]); the dominant contribution to the total number of emitted neutrinos of all species is exponentially shaped with a 3.5 s time constant. The signal amplitude and exponential starting point are free parameters of the fit (fig. 2(a)).

The algorithm discovery power can be studied via toy Montecarlo simulation: background-only event series (no supernova neutrinos interactions) are generated and the distribution of fitted signal is considered. A threshold on the signal amplitude can be determined by requiring a maximum probability of false positive trigger. Once the threshold is fixed, the simulation of non-zero signal event series allows to estimate the success probability of the trigger (trigger efficiency) for a given distance of the supernova (see fig. 2(b)).

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