

# Passive Shielding in CUORE

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**Abstract.** The nature of neutrino mass is one of the frontier problems of fundamental physics. Neutrinoless Double Beta Decay (0νDBD) is a powerful tool to investigate the mass hierarchy and possible extensions of the Standard Model. CUORE is a 1-Ton next generation experiment, made of 1000 Te bolometers, aiming at reaching a background of 0.01 (possibly 0.001) counts  $keV^{-1}kg^{-1}y^{-1}$  and therefore a mass sensitivity of few tens of meV. The background contribution due to environmental neutrons, muon-induced neutrons in the shieldings and external  $\gamma$  is discussed.

**Keywords:** Double Beta Decay, Cryogenic detector, Neutrons background

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## INTRODUCTION

The discovery of neutrino oscillation in solar, atmospheric and reactor experiments [1, 2, 3, 4, 5] has renewed the interest of Neutrinoless Double Beta Decay (0νDBD) as a fundamental, and unique, probe for the neutrino nature, that could also fix the neutrino absolute mass scale through the measurement of the effective Majorana mass of the electron neutrino [6]. The 0νDBD is a rare spontaneous nuclear transition where a nucleus (A, Z) decays into (A, Z+2) nucleus with the emission of two electrons and no neutrino, resulting in a peak in the sum energy spectrum of the electrons. CUORE (Cryogenic Underground Observatory for Rare Events) [7] is an approved experiment, aiming at searching for 0νDBD of  $^{130}\text{Te}$  exploiting the high energy resolution of the bolometric technique. It will be located in Hall A of the Gran Sasso Underground Laboratory (LNGS).

## THE CUORE DETECTOR

The CUORE detector is a system of 988 bolometers, each being a cube of  $5 \times 5 \times 5 \text{ cm}^3$ , the array is composed by 19 vertical towers. Each tower consists of 13 layers of 4 cubes each. The single cube is a crystal of  $\text{TeO}_2$ : this material has reasonable mechanical and thermal properties together with a very large (27% in mass) content of the  $\beta\beta$  candidate  $^{130}\text{Te}$ . The  $^{130}\text{Te}$  has a very high natural abundance (33.8%), and an high transition energy ( $Q_{\beta\beta} = (2530.30 \pm 1.99) \text{ keV}$  [8]), falling in the valley between the peak and the Compton edge of the  $2615 \text{ keV}$   $^{208}\text{Tl}$   $\gamma$  line, at the very end of the *gamma* natural background spectrum. Each crystal is weighing 750 g, so the total mass of the detector is 741 kg of granular calorimeter, corresponding to 203 kg of  $^{130}\text{Te}$ .

The detecting procedure is based on the cryogenic technique proposed for the first time to study nuclear phenomena by Simon [9], and suggested for searching rare events by Fiorini and Niinikoski [10].

Cryogenic thermal detectors are realized by using dielectric crystals cooled down to very low temperature. The signal due to an event releasing the energy  $\Delta E$  is in fact, proportional to the heat capacity of the crystals, following, according to the Debye law, a  $(T/T_D)^3$  dependence at low temperatures. The crystals used in CUORE have a heat capacity  $C \sim 10^{10} \text{ eV/K}$ , evaluated at a temperature of 10 mK. The predicted energy for the 0νDBD gives, therefore, a  $\Delta T = \Delta E/C \sim 0.2 \text{ mK}$ . At this temperature the statistical fluctuation of the crystal internal energy is  $\langle \Delta E \rangle = K_B C T^2 \sim 20 \text{ eV}$ , well below the energy resolution of the readout system. The temperature-to-voltage transducer is realized by a Neutron Transmutation Doped (NTD) Germanium thermistor, due to its strong dependence of the resistance with the temperature.

Each bolometer consists of a crystal, an NTD thermistor, and a heater (Si doped with As) glued with Araldit Rapid Epoxy onto the crystal surface. The connections between the thermistor and the heat sink on the Cu holder are realized by Au wires of  $50 \mu\text{m}$  diameter. Every layer of each CUORE tower is composed by 4 crystals, kept in place by a structure of OFHC Cu and PTFE, being the only materials allowed due to surface and bulk contamination.

In order to shield the materials of the refrigerator from radioactive contaminants, a 6 cm shield of Roman Lead with  $^{210}\text{Pb}$  activity lower than  $4 \text{ mBq/kg}$  [11] is framed around the array to reduce the activity of the thermal shields. The cryostat is externally shielded by a 25 cm of low radioactive Pb layer ( $A_{210\text{Pb}} = (16 \pm 4) \text{ Bq/kg}$ ). The background due to environmental neutrons is reduced by a 20 cm layer of an Borated Polyethylene shield. The refrigerator is enclosed with an anti-Radon box flushed with clean  $\text{N}_2$  and inside a Faraday cage to reduce electromagnetic interferences.

## BACKGROUND SIMULATION

The main goal of the CUORE experiment is to reach, in the energy region of interest, a background level lower than 0.01 (possibly 0.001)  $\text{counts keV}^{-1} \text{kg}^{-1} \text{y}^{-1}$  obtaining hence a sensitivity on the effective Majorana mass of the neutrino lower than 50 meV (15 meV, in the more optimistic case). The actual background in CUORICINO, a small scale CUORE prototype made up of a single CUORE tower, is  $(0.18 \pm 0.01) \text{ counts keV}^{-1} \text{kg}^{-1} \text{y}^{-1}$  [12]. The comprehension of the CUORICINO background origin will therefore drive the choices in the final CUORE design and assembly. With this aim, a MonteCarlo code has been developed in order to simulate decay processes occurring in the bulk and on the surface of the various parts of the experimental setup, in order to disentangle the background sources. The informations thus extracted, are used to evaluate the CUORE background in the 0νDBD region. The analysis of CUORICINO data indicates that roughly 70% of the background events are due to surface contaminations on crystals and Cu detector holders. Most of the experimental effort is now devoted to reduce surface contamination in order to reach the CUORE goal.

Nevertheless it's important to evaluate background coming from underground neutrons and muons. Neutrons, indeed, may constitute a worrisome background for the dark matter and 0νDBD experiment. In the former, simple kinematics implies that in the case of Te, neutrons of 1(5) MeV could elastically scatter off Te nuclei producing recoils of energies up to 31(153) keV and therefore mimic a WIMP interaction. In the latter, the de-excitation of Te nuclei, following an inelastic scattering, could produce a photon cascade with total energy released in the 0νDBD region.

Neutrons with energies less than 8 MeV are produced through ( $\alpha$ ,  $n$ ) reactions and from spontaneous  $^{238}\text{U}$  fission in the rock, concrete and setup materials. They could be efficiently tagged by mean of an external veto. Very fast neutron could be produced through muon-induced interactions in the detectors shields (mainly the heavier ones) and in the rock. Despite of their much lower rate ( $\sim 10^{-3}$ ) with respect to the former ones, they are difficult to shield or tag in coincidence with the primary muon owing to the hard energy spectrum and long propagation range.

This study is performed in two separated steps. In the first one the external neutrons and muon-induced neutrons are propagated through the CUORE shieldings with FLUKA [13] generator. FLUKA is a well established tool in nuclear and particle physics and has been used for neutron calculations in a variety of experiments. The recorded particle flux hitting the detector is, then, used as input in GEANT4 [14] generator, propagated through the detector and the background in the 0νDBD region is evaluated.

It should be stressed that this mixed approach (FLUKA+GEANT4) has been used up to now, only for technical reason but a full end-to-end simulation with FLUKA is under development. Moreover, correlations among generated particles (photons, muons, neutrons, electrons) in a single events are lost in this approach, lessening the power of the anti-coincidence technique in a very granular detector like CUORE and leading to an overestimate of the background. Neutron propagation and muon-induced neutron interaction and propagation in FLUKA have been studied in many works [16, 17, 18, 19]; a reasonable agreement between simulation and experimental data (although with large uncertainties) is found, some old data [20, 21] show a significant higher neutron yield production in heavy materials.

FLUKA simulation takes into account heavy nuclear fragmentation evaporation, muon photonuclear interaction, photon interaction with nuclei, and, for charged hadrons and muons: delta ray production down to  $10^{-4}$  GeV, bremsstrahlung and pair production, production threshold and transport down  $10^{-4}$  GeV. Electron and photon production and transport is set to 50 keV. All particle are propagated and recorded on detector boundaries.

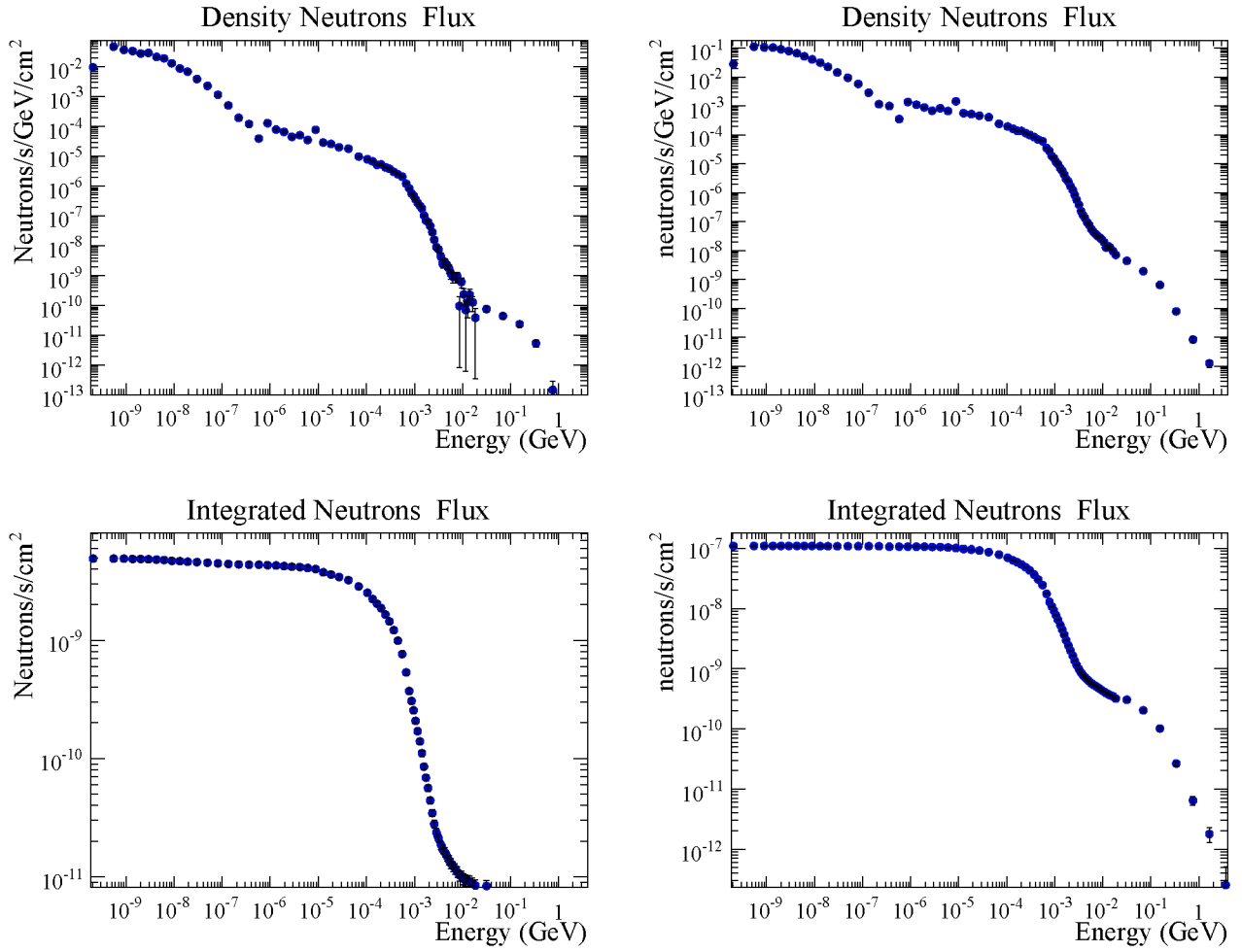
## Neutron Background

The external neutron flux in the Gran Sasso Laboratory has been measured up to  $\sim 10$  MeV [23, 24], the muon-induced neutrons in the rock spectrum have been simulated in [25, 18]. In order to be conservative, for each energy the highest flux among measurements and simulations has been used as input in FLUKA. The total neutron flux is  $3.7 \cdot 10^{-6} \text{ n cm}^{-2}\text{s}^{-1}$ .

External shields of different materials have been simulated: 20 cm Polyethylene shield with different Boron concentration and 17 cm of external pure Polyethylene shield followed by a 3 cm internal layer of Borated-Polyethylene or Boric Acid in powder. All results are consistent, the neutron flux hitting the detector, as a function of the kinetic neutron energy, is shown in the left column of Fig. 1; the total neutron flux fluctuates from  $5 \cdot 10^{-9} \text{ cm}^{-2}\text{s}^{-1}$  to  $7 \cdot 10^{-9} \text{ cm}^{-2}\text{s}^{-1}$  depending on the shielding material. This flux is used as input for GEANT4 and propagated through the detector, the background in the 0νDBD is computed using a detector energy resolution of  $\sigma = 5 \text{ keV}$  and a symmetric region of interested of  $5 \sigma$  around the nominal Q-value. The total background is of the order of  $\sim 10^{-4} \text{ counts keV}^{-1}\text{kg}^{-1}\text{y}^{-1}$  and the total anti-coincidence of the crystal in a 10 ms window and 50 keV threshold gives a contribution an order of magnitude less, resulting therefore well below the CUORE goal. The background due to neutron-induced photons is  $\sim 10^{-6} \text{ counts keV}^{-1}\text{kg}^{-1}\text{y}^{-1}$  and therefore negligible.

## Muon Background

In order to reproduce the muon spectrum, the muon flux measured by the MACRO experiment, as a function of the polar and azimuthal angle, was used. The energy spectrum is parametrized at the ground level and then extrapolated underground taking into account for each given direction, amount and shape of overburden mountain. The total muon flux is fixed to the highest measured flux found in literature  $(3.2 \pm 0.2) \cdot 10^{-4} \mu \text{ cm}^{-2}\text{s}^{-1}$  [15]. The muon-induced neutron flux hitting the detector as a function of the kinetic energy is reported in the right column of Fig. 1 and found



**FIGURE 1.** The left column refers to recorded neutron flux induced by external neutrons, the right column, instead, refers to the recorded neutron flux induced by muon. In both cases: the upper plot is the density flux as a function of the neutron kinetic energy, the bottom is the integrated neutron flux as a function of the neutron kinetic energy.

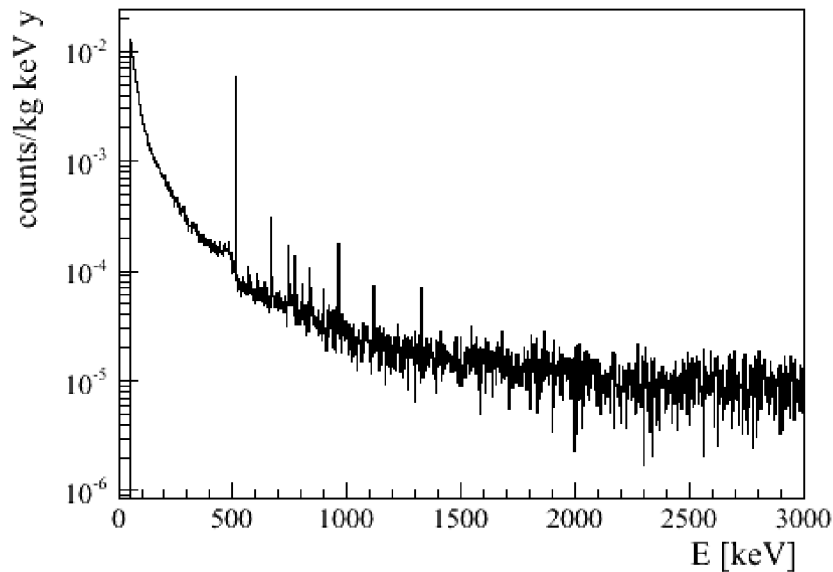
to be:  $(110 \pm 1) \cdot 10^{-9} \text{ n cm}^{-2} \text{ s}^{-1}$ . This gives a background in the 0vDBD region of  $\sim 5 \cdot 10^{-4} \text{ counts keV}^{-1} \text{ kg}^{-1} \text{ y}^{-1}$  as shown in Fig. 2, the photon contribution in the anti-coincidence spectrum is  $\sim 10^{-3} \text{ counts keV}^{-1} \text{ kg}^{-1} \text{ y}^{-1}$ .

### Photon Background

A potential background could be also represented by environmental photons, the  $\gamma$  spectrum in the Gran Sasso Laboratory has been measured, with Germanium detector, to be  $7.7 \cdot 10^6 \text{ } \gamma \text{ cm}^{-2} \text{ s}^{-1}$ . This flux, propagated through the detector with GEANT4, gives a contribution in the 0vDBD region of approximately  $\sim 1.5 \cdot 10^{-5} \text{ counts keV}^{-1} \text{ kg}^{-1} \text{ y}^{-1}$ .

The analysis of CUORICINO shows that roughly 30% of the total background in the region of interest, is due to the 2615 keV Tl  $\gamma$  line via multi-Compton scattering. The Tl origin is ascribed to a Th contamination of the old cryostat shields themselves. Given the  $^{232}\text{Th}$  contamination of the Copper of the new CUORE cryostat shields and thanks to a better and more compact design, the contribution of the Tl  $\gamma$  line to the total background is evaluated from simulation to be less than  $10^{-3} \text{ counts keV}^{-1} \text{ kg}^{-1} \text{ y}^{-1}$ .

The external Lead contamination in  $^{232}\text{Th}$  is measured to be  $\sim 100 \text{ } \mu\text{Bq kg}^{-1}$  and gives a contribution in the region of interest of  $2.4 \cdot 10^{-4} \text{ counts keV}^{-1} \text{ kg}^{-1} \text{ y}^{-1}$ , while the Roman Lead contamination ( $(60 \pm 17) \text{ } \mu\text{Bq kg}^{-1}$ ) leads to



**FIGURE 2.** The total anti-coincidence background spectrum induced by muon-induced neutrons in CUORE.

a contribution of  $5.4 \cdot 10^{-3} \text{ counts keV}^{-1} \text{ kg}^{-1} \text{ y}^{-1}$ . Due to high contribution of the ancient lead, other material, less contaminated in Th, like copper, are under investigation.

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