The CROSS experiment: search for $0\nu 2\beta$ decay with surface sensitive bolometers

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Abstract. CROSS (Cryogenic Rare-event Observatory with Surface Sensitivity) is a project aiming to develop a new bolometric technology enabling an active background rejection in $0\nu 2\beta$ search. The isotopes of interest are $^{100}$Mo and $^{130}$Te, and bolometers are based on Li$_2$MoO$_4$ and TeO$_2$ crystals. The key feature of CROSS detectors is the possibility of pulse-shape discrimination of near surface interactions. An ultrapure superconductive aluminum film, deposited on the crystal surface, is acting as a pulse-shape modifier for phonon sensors, providing separation of surface events from bulk ones. First prototypes were produced and successfully tested aboveground with the rejection of $\alpha$ surface radioactivity higher than 99.9%. A demonstrator with 32 0.28-kg Li$_2$MoO$_4$ crystals will be installed in a dedicated cryostat in the Canfranc underground laboratory (Spain) to confirm the reproducibility of surface sensitive bolometers. CROSS demonstrator can obtain sensitivities to the effective Majorana mass down to 70 meV in the most favorable conditions. The CROSS technology can be applied for future ton-scale experiments, reaching sensitivities to the effective Majorana mass down to 10 meV.

1. Introduction

Neutrinoless double beta decay ($0\nu 2\beta$) is a hypothetical nuclear transition with emission of two electrons and no neutrino: $(A,Z) \rightarrow (A,Z+2) + 2e^-$ [1]. It is a key process in neutrino physics: $0\nu 2\beta$ decay existence would confirm the Majorana nature of neutrinos and lepton number violation. The signature of neutrinoless double beta decay is a narrow peak at the energy of transition ($Q_{\beta\beta}$). The current most stringent limits on $0\nu 2\beta$ decay half-life are at the order of $10^{25}–10^{26}$ yr [2]. The CROSS (Cryogenic Rare-event Observatory with Surface Sensitivity) experiment aims to provide a technology of surface-sensitive bolometers for $0\nu 2\beta$ searches with high sensitivity [3]. CROSS cryogenic detectors will use Li$_2$MoO$_4$ and TeO$_2$ crystals as absorbers (where $^{100}$Mo and $^{130}$Te are the isotopes of interest).

2. Active background rejection capability

The sensitivity of $0\nu 2\beta$ experiments can be strongly limited by different sources of background (e. g., see in [4]). Natural $\gamma$ radioactivity gives a strong contribution for isotopes with $Q_{\beta\beta} < 2615$ keV (position of the highest energy $^{208}$Tl line), such as $^{130}$Te. Degraded $\alpha$'s from $^{238}$U and $^{232}$Th chains contribute to background in a region above the $^{208}$Tl line. As $\alpha$ and $\gamma(\beta)$ particles emit a different amount of light in crystals, $\alpha$ background can be rejected with double readout bolometers, by reading simultaneously heat and light channels. This technology is already implemented in several $0\nu 2\beta$ intermediate experiments [5, 6].
As it was shown in the CUORE experiment [7], the surface contamination of materials surrounding the detectors is an important component of total background, and its rejection would allow to reach higher sensitivities to 0ν2β decay half-life for next-generation experiments [8]. The CROSS technique is foreseen to reject surface background of single read-out bolometers. To do so, a thin (few µm) superconducting Al film is deposited on the crystal surface in order to act as a pulse-shape modifier for near surface particle interactions (up to 1 mm depth from the crystal surface). When a particle releases energy in the absorber close to the surface it generates high energy phonons that break Cooper pairs in the superconducting film. This effect is less important for bulk events, since the generated phonons reach the surface with a lower average energy due to the quasi-diffusive mode of phonon propagation. The subsequent recombination of quasiparticles to lower-energy 1.2-K phonons will accelerate the detector response in case of thermal phonon sensors (mainly used in the present study and based on Neutron Transmutation Doped Ge thermistors) with respect to bulk events due to a faster thermalization.

This technology would allow bolometric experiments to reach background levels of the order of less than 0.5 counts/yr in 1 ton of isotope in the region of interest (ROI). With such background levels future large scale experiments could investigate the direct-ordering region of the neutrino masses, reaching $m_{\beta\beta}$ sensitivity down to 10 meV.

3. The CROSS project development

The CROSS project realization is ongoing in two main branches:

- R&D on different bolometric detectors in order to find the best configuration for pulse shape discrimination. There were performed series of measurements at CSNSM (Orsay, France), achieving promising results: the possibility to fully discriminate the surface α contamination was demonstrated for both Li$_2$MoO$_4$ and TeO$_2$. These series of tests are extensively described in [3].

- Installation and preparation of the underground CROSS facility for the operation of a mid-scale demonstrator with fully coated crystals.

A pulse tube based dilution refrigerator was installed in the Canfranc underground laboratory (Spain) in April 2019 for the CROSS project. This instrument can provide a base temperature of 10 mK and is optimized for the operation of macro-bolometers. A muon veto will be set up by covering with scintillating elements the walls of the hut housing the cryostat.

The first underground run of CROSS was held from April to August 2019 with 98% duty cycle. Three detectors were installed in the cryostat to test performance and background level (see Fig. 1). Several interventions on the external lead shielding were performed to protect better the experimental volume. A natural Li$_2$MoO$_4$ scintillating bolometer (mass of 210 g) was measured during this run (see Fig. 1). With no mechanical decoupling of the detector, we obtained FWHM of 7.1 keV at 2615 keV γ quanta of $^{208}$Tl, which is compatible with other measurements of Li$_2$MoO$_4$ crystals for 0ν2β searches [5]. Background level has not been estimated since the experimental volume is not yet fully shielded from the external radiation, and the configuration is not final. Further improvements of shielding will be performed during year 2020.

We plan to install a first demonstrator of the CROSS technology in this cryogenic set-up. It will consist of 32 Li$_2^{100}$MoO$_4$ crystals grown with molybdenum enriched in $^{100}$Mo at $> 95\%$ level. Each crystal will be a cube with 45-mm side and 280-g mass. The crystals are already available and have been produced according to a protocol developed in the LUMINEU experiment, which ensures excellent bolometric performance and high radio-purity [9]. The projected sensitivity of such a demonstrator is listed in Table 1.
Figure 1. Left: the CROSS cryostat with three detectors mounted on 10 mK plate. Right: energy spectra of 0.21-kg Li$_2$MoO$_4$ scintillating bolometer acquired with different shielding configurations.

Table 1. Projected sensitivity of the CROSS experiment (Phase I): 32 Li$_2^{100}$MoO$_4$ crystals, 4.7 kg of $^{100}$Mo, $2.8 \times 10^{25}$ nuclei. The region of interest is 8 keV wide, and the efficiency is 75%.

| Bkg, cnts/(keV kg yr) | Live time, yr | Bkg in ROI, counts | $\text{lim } T^{100/23}_{1/2}$, yr | $\text{lim } \langle m_{\beta\beta} \rangle$, meV |
|----------------------|--------------|--------------------|-----------------------------|---------------------------------|
| $10^{-2}$            | 2            | 1.4                | $8.5 \times 10^{24}$        | 124–222                         |
| $10^{-3}$            | 2            | 0.14               | $1.2 \times 10^{25}$        | 103–185                         |
| $10^{-2}$            | 5            | 3.6                | $1.7 \times 10^{25}$        | 88–159                          |
| $10^{-3}$            | 5            | 0.36               | $2.8 \times 10^{25}$        | 68–122                          |

4. Conclusions
The CROSS project is now in active R&D phase, already demonstrating promising results on background discrimination capability with surface sensitive bolometers. The CROSS demonstrator, intended to be installed in Canfranc underground laboratory, is supposed to perform test of the technology on a larger scale and to prove the reproducibility of surface sensitive bolometers. The estimation of CROSS demonstrator sensitivity shows that such an intermediate experiment will be also competitive with the most sensitive current $0\nu 2\beta$ decay experiments.

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