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CUPID: The Next-Generation Neutrinoless Double Beta Decay Experiment

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Abstract
CUPID is a next-generation tonne-scale bolometric neutrinoless double beta decay experiment that will probe the Majorana nature of neutrinos and discover lepton number violation in case of observation of this singular process. CUPID will be built on experience, expertise and lessons learned in CUORE and will be installed in the current CUORE infra-structure in the Gran Sasso underground laboratory. The CUPID detector technology, successfully tested in the CUPID-Mo experiment, is based on scintillating bolometers of Li_2MoO_4 enriched in the isotope of interest ^{100}Mo. In order to achieve its ambitious science goals, the CUPID collaboration aims to reduce the backgrounds in the region of interest by a factor 100 with respect to CUORE. This performance will be achieved by introducing the high efficient α/β discrimination demonstrated by the CUPID-0 and CUPID-Mo experiments, and using a high transition energy double beta decay nucleus such as ^{100}Mo to minimize the impact of the gamma background. CUPID will consist of about 1500 hybrid heat-light detectors for a total isotope mass of 250 kg. The CUPID scientific reach is supported by a detailed and safe background model based on CUORE, CUPID-Mo and CUPID-0 results. The required performances have already been demonstrated and will be presented.

Keywords Neutrinoless double beta decay · Bolometers · Low radioactivity · Cryostat · Next-generation bolometric experiment

1 Introduction

Neutrinoless double beta decay ($0\nu2\beta$) is a hypothetical and extremely rare process where two neutrons transform into two protons with only two electrons emitted [1]. This decay would violate lepton number conservation but become possible with only a minimal extension of the standard model. This extension implies that neutrinos are Majorana particles, meaning that neutrinos are the same as antineutrinos. The observation of this decay would then be a major breakthrough in our

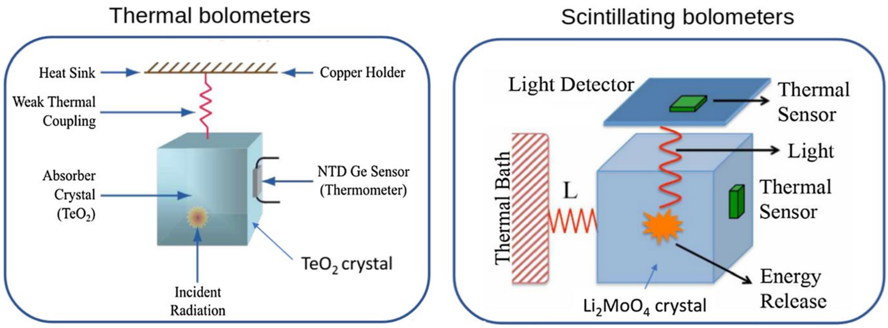

Fig. 1 (Color figure online) Left: Schema of a pure thermal bolometer, used in CUORE. Right: Schema of a scintillating bolometer, used in CUPID-Mo

knowledge of particle physics and could give answers to problems such as the origin of the neutrino mass or the matter/antimatter asymmetry [2]. The expected signal is a peak at the Q-value of the decay in the spectrum of the summed energies of the two emitted electrons, at the end-point of the continuous spectrum of two-neutrinos double beta decay ($2\nu2\beta$). Observing or not this peak allows to constraint a parameter related to neutrino physics in the case where the process is mediated by a light Majorana neutrino exchange: the Majorana effective mass ($m_{\beta\beta}$). The possible values for this parameter depend on the PMNS matrix elements, the mass scale of neutrinos and on the neutrino mass ordering. Running experiments, as CUORE, will be able to probe the value of the effective Majorana mass in the region where both inverted and normal ordering are possible. The goal of next-generation experiments as CUPID is to reach the sensitivity to the mass range where only normal ordering would be allowed. However, this is an experimental challenge since it requires restrictive detection conditions such as, for example, an excellent energy resolution of 5 keV (FWHM) in the region of interest (ROI), a large mass of the nuclide of interest and a long time exposure. Moreover it's required to reduce the number of background events in the ROI by a factor 100 regarding to what is currently reached by CUORE. In fact, minimizing the background index b which represents the number of expected background events in the ROI in counts/keV kg year (ckky) is really one of the key points to increase the sensitivity to the half-life of the process and so to $m_{\beta\beta}$ for an experiment.

2 From CUORE to CUPID

2.1 CUORE Achievements and Limitations

It is hard to talk about CUPID without mentioning its predecessor CUORE, currently taking data in Laboratori Nazionali del Gran Sasso (LNGS). Indeed, CUORE is the first tonne scale experiment using bolometers (Fig. 1). These are crystals embedding a $0\nu2\beta$ candidate that are acting as almost perfect calorimeters when at low temperature (~20 mK). When a decay occurs inside, the energy release results in a rise in temperature which is measured by a sensor glued directly on it, usually a neutron-transmutation-doped germanium sensor (NTD). This method is fulfilling most of the requirements presented in Sect. 1, thanks to, for example, the "detector=source" method assuring a high detection efficiency. CUORE is using ^{130}Te ($Q_{\beta\beta}$=2527 keV) as candidate for the $0\nu2\beta$, embedded inside TeO_2 crystals. It is the largest bolometric experiment ever built with 988 cubic crystals arranged in 19 towers for a total mass of 706 kg (206 kg of ^{130}Te) placed inside a huge cryostat at LNGS. With one tonne-year of exposure, CUORE has obtained a limit on the half-life for $0\nu2\beta$ of the ^{130}Te of $T^{0\nu}_{1/2} > 2.2 \times 10^{25}$ yr [3] which is the best ever for this isotope. CUORE has shown the reliability of the bolometric detection method: it has proven that a tonne scale experiment using bolometers is technically feasible and that the analysis of data from a very large number of crystals is handable. Moreover, the cryostat of CUORE is showing an excellent stability over time and good performances, which make it suitable to be used for CUPID [4]. However, CUORE is not a background-free experiment: ~200 background counts/year in a region of 20 keV around the $0\nu2\beta$ peak are expected, corresponding to $b \sim 1.5 \times 10^{-2}$ ckky. Indeed, the CUORE background model shows that there are two main contributions to the background. First, the dominating one, the α events coming from surface radioactivity of surrounding materials or crystals contamination. The second one is from the rather high amount of γ events coming from the natural γ radioactivity since the $Q_{\beta\beta}$ of ^{130}Te is below the ^{208}Tl γ peak at 2615 keV characterizing its endpoint. Both these contributions are preventing CUORE to reach a much higher sensitivity than currently obtained, this is why an upgrade is needed: CUPID which stands for CUORE Upgrade with Particle IDentification.

2.2 Improvements Brought by CUPID

Two major changes will characterize the CUPID experiment: the use of a $0\nu2\beta$ candidate with Q-value above 2.6 MeV and a scintillating crystal hosting the nuclide of interest. A sketch of a detector module with scintillating crystal is shown in Fig 1b. Therefore, when an event occurs inside the scintillating absorber, some heat is released but some light is also emitted. By placing a light detector consisting of a Germanium bolometer next to the main crystal that will detect the scintillation light reaching it using also a Ge NTD, each event will then have a heat and a light signal. α events are usually emitting a different amount of light when depositing their energy in the crystal than β or γ events. Then, by plotting the light signal as a function of the heat signal, we are able to identify and then to discriminate the α events [5] that are the dominating background events in CUORE. This technique was first used with the demonstrator CUPID-0 which was using ZnSe crystal and operated at LNGS [6]. It has shown that it is possible to reject more than 99% of the α events and so to remove their contribution to the background.

The second important improvement is the change of isotope: CUPID will no longer use ^{130}Te but ^{100}Mo. This latter has a $Q_{\beta\beta}$ of 3034 keV, above the natural γ radioactivity endpoint. The expected $0\nu2\beta$ peak is then in a region where the gamma background would be at least a factor 10 smaller that in CUORE. Therefore, $b \sim 10^{-4}$ ckky is reachable without α background. The use of ^{100}Mo inside cylindrical Li_2MoO_4 (LMO) scintillating crystals was first tested by CUPID-Mo, a demonstrator placed at Laboratoire Souterrain de Modane (LSM) [7]. The results were really good, LMO crystals have shown excellent performances like a very good energy resolution in the ROI (~7 keV really close to the objective of 5 keV for CUPID), a radiopurity compatible with CUPID requirements but also a light yield high enough to reject the α background. Moreover, with only a 2.17 kg×year exposure, it has set the best limit ever on the half-life of ^{100}Mo: $T^{0\nu}_{1/2} > 1.5 \times 10^{24}$ yr [7]. These results were really encouraging, and this is why LMO is the natural choice for CUPID.

3 The CUPID Configuration

3.1 The Experimental Setup

As mentioned before, CUPID will be installed in the current CUORE cryostat in LNGS. This cryostat has shown excellent cryogenic performances and will need only a few modifications to host CUPID. It will be available at the end of 2024, just after the CUORE experiment decommissioning. CUPID will be composed of 1596 cubic LMO crystals ($45 \times 45 \times 45$ mm^3) of around 280 g each arranged in 57 towers of 14 floors. Recent tests have shown the same good performances for cylindrical and cubic crystals [8, 9]: the latter making the assembly more compact, they will be used in the final configuration. In total there will be 240 kg of ^{100}Mo thanks to a more than 95% enrichment of the scintillating crystals. Currently, the baseline design for each module consists of two Ge light detectors next to each other inside a copper holder with one LMO crystals placed above each of them. In this configuration, crystals and light detectors are sharing the same holder. The modules will then be stacked in towers, allowing to have one light detector below and above each crystal. The test of the first tower composed of 28 LMO crystals is now on-going in LNGS.

3.2 The Background Model

One of the strength of CUPID is its background model. Indeed, it comes from the acquired knowledge in CUORE [10], CUPID-0 [11] and CUPID-Mo [12], making it quite precise and robust. For example, the contribution to the background of the cryostat and radioactivity shields are well-known thanks to CUORE as well as the crystals contamination that has been studied by CUPID-Mo: they are not harmful contributions and give a contribution which is below $\sim 10^{-4}$ ckky in ROI. The muon and neutron contributions are kept below 10^{-5} ckky thanks to an active muon veto composed of a set of vertical and horizontal scintillator panels surrounding the cryostat [13, 14]. The total background index obtained with this model is $\sim 10^{-4}$ ckky which is exactly the objective of CUPID to explore the region where both normal and inverted ordering are possible. However, there is still one crucial contribution that has to be confirmed: the intrinsic background due to the $2\nu2\beta$ source. In fact, although all its advantages, the ^{100}Mo has the fastest $2\nu2\beta$ half-life among all the $0\nu2\beta$ candidates ($T^{2\nu}_{1/2} = 7.1 \times 10^{18}$ yr). Bolometers are rather slow detectors: a signal can last hundreds of ms and is composed of two temporal components: the rise time corresponding to the rise of temperature which is the fastest (between 10 and 50 ms) and the decay time corresponding to the time needed for the crystal to thermalize to the heat bath (between 100 and 500 ms). This increases the probability to have a random coincidence between two $2\nu2\beta$ events that could be misinterpreted as a $0\nu2\beta$ event if they occur in a time window of the same order of magnitude than the rise time of the signal. In a first approximation, the contribution of this "pile up" component is equal to $b \sim 3.10^{-4} \times \tau$[ms] with τ the minimal time interval between two events so that they can be discriminated [15]. The work is then ongoing to improve τ thanks to a rejection of these pile up events using a pulse shape analysis. Last results give a 90% rejection efficiency for the pile ups events with a time difference of 2 ms [16]. The objective is not yet achieved, but there are several areas of improvements: it is possible to increase the sampling frequency, reduce the baseline noise or even use the light signal that is faster than the heat signal. Moreover, it exists other thermistors like MMC [17] that can obtain faster rise time than NTDs and so that could be consider at some point. The collaboration is therefore quite confident to say that this contribution will be kept under control (i.e., $< 10^{-4}$ ckky).

4 CUPID Sensitivity and Phased Approach

If we consider a background index of 10^{-4} ckky, an energy resolution of 5 keV in the ROI and a 10 year exposure, the expected half-life 3σ discovery sensitivity is $T^{0\nu}_{1/2} > 1 \times 10^{27}$ yr corresponding to $m_{\beta\beta} < 12 - 20$ meV depending on the nuclear matrix element [13]. This would allow the full exploration of the region where inverted and normal hierarchies are possible, making CUPID one of the most promising experiments of the next generation. Moreover, it is possible to consider a phased approach for CUPID to prepare the far future. The first phase, *CUPID baseline* that is described in this article, is technically ready and will take place just after CUORE. The second phase, *CUPID reach*, would be able to reach an even lower background index of 2×10^{-5} ckky thanks to some modifications on the setup. Even if it is optimistic regarding the current background model, a lot of various projects like CROSS [18] are already working on new methods and techniques to reach a lower amount of background events and are already presenting interesting results however more R &D in this direction is definitely required to hit this objective. The third phase would be the ultimate bolometric experiment, *CUPID-1T*, using 1000 kg of ^{100}Mo inside a brand new cryostat. We can consider that at this time, R &D on materials screening and radiopurity, background rejection and advanced high-speed, high-resolution sensors development would allow to reach a background index of 5×10^{-6} ckky. This would allow CUPID-1T to reach a sensitivity of $T^{0\nu}_{1/2} > 9.1 \times 10^{27}$ yr allowing to start the exploration of the normal hierarchy.

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