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CUPID: CUORE Upgrade with Particle IDentification

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Abstract. CUPID is a next-generation experiment designed to search for neutrinoless double beta decay and other rare events using enriched Li_2MoO_4scintillating bolometers.
The experiment, hosted in the CUORE cryostat at the Laboratori Nazionali del Gran Sasso (Italy), will operate with 240 kg of ^{100}Mo and aims for an energy resolution of 5 keV FWHM at 3 MeV with a background index of 10^{-4} cts/(keV·kg·yr). With ten years of exposure, CUPID aims for a 90% C.L. half-life exclusion sensitivity of $1.8 \cdot 10^{27}$ yr, corresponding to an effective Majorana neutrino mass reach of about 10 meV.

1 Introduction

Among the techniques with a long-standing tradition in neutrinoless double beta decay ($0\nu\beta\beta$) searches, thermal detectors — or bolometers — represent one of the most established approaches, reaching in CUORE [1] their most advanced implementation. Compared to other methods, bolometers stand out for two key features: their excellent energy resolution (second only to Ge diodes) and their intrinsic versatility, which enables multi-isotope investigations.

CUPID (CUORE Upgrade with Particle IDentification) is the next-generation experiment designed to search for $0\nu\beta\beta$ using scintillating bolometers with ^{100}Mo. It represents the natural upgrade of CUORE, exploiting the experience gained with its technology while introducing significant improvements. In particular, the TeO_2 crystals used in CUORE are replaced with enriched Li_2MoO_4 ones containing ^{100}Mo and having scintillation properties. The bolometric setup is complemented by Neganov–Trofimov–Luke (NTL) enhanced light detectors for the readout of the Li_2MoO_4 scintillation light. This evolution turns the experiment from a ^{130}Te $0\nu\beta\beta$ search into a ^{100}Mo $0\nu\beta\beta$ search, upgrading it from a detector without active background rejection to one able to identify the nature of the interacting particle. This strategy provides two major benefits, both leading to an improvement in sensitivity by about one order of magnitude compared to CUORE: the high $Q_{\beta\beta}$ value of ^{100}Mo (3.034 MeV) and the ability to perform particle identification.

2 The CUPID project

CUPID [2] will employ an array of 1596 Li_2MoO_4 scintillating bolometers, arranged in 57 towers, each composed of 14 floors with two crystals per floor. Each crystal is a $45 \times 45 \times 45\,\mathrm{mm}^3$ cube of molybdenum enriched to ≥95% in ^{100}Mo, with a mass of ~280 g,

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resulting in a total active mass of about 240 kg of ^{100}Mo. The detector will be housed in the cryogenic facility that currently hosts CUORE [1, 3] at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy. Before installation, the facility will undergo a major upgrade, including improvements to the cryogenic system with state-of-the-art technologies, the deployment of a muon veto, and the enhancement of the neutron shield.

With this strategy, CUPID will take advantage of an existing infrastructure, already well characterized in terms of operational performance — CUORE has demonstrated the stable operation of a ~1-ton bolometric detector over several years — as well as in terms of the expected radioactive and cosmogenic backgrounds [1, 3, 4]. At the same time, this approach saves both time and financial resources for the experiment.

2.1 The scintillating bolometer

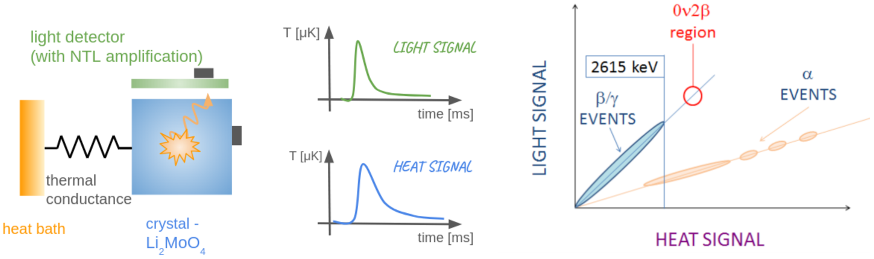

Figure 1. Left: schematic view of the CUPID single module according to the baseline design. Right: cartoon illustrating how heat and light pulses are used for particle identification.

A CUPID scintillating bolometer consists of two individual bolometric detector elements (see Fig. 1). The scintillating Li_2MoO_4 crystal, which contains the $0\nu\beta\beta$ candidate isotope, is equipped with a Ge thermistor specially developed for low temperature operation and provides the heat (phonon) signal. A thin Ge wafer, placed in front of the crystal to collect its scintillation light, acts as a bolometric light detector (LD). This device is capable of operating at mK temperatures, where conventional light sensors — such as SiPMs or photomultipliers — are ineffective or introduce severe assembly and readout challenges. The LD is positioned as close as possible to the scintillating crystal, without direct contact, in order to avoid thermal cross-talk. It is instrumented with electrodes for Neganov-Trofimov-Luke (NTL) amplification to compensate for the poor scintillation yield characteristic of Li_2MoO_4 crystals.

The heat signal provides a precise energy measurement with excellent resolution, but it is almost insensitive to particle type and thus cannot be used for active background rejection. The light signal is particle sensitive. Indeed the amount of scintillation light is proportional to the deposited energy, but the conversion efficiency depends on the type of interacting particle, with heavy particles (such as α particles) producing less light than electrons. The dual readout of heat and scintillation light enables powerful background discrimination, particularly against α particles.

Finally, thanks to its rise time nearly ten times faster than that of the heat signal, the light signal is also used to identify and reject pile-up events. This requirement is crucial for CUPID detectors. The expected counting rate, dominated by the $2\nu\beta\beta$ decay of ^{100}Mo, is high compared to the light signal timing (about 1 ms rise time). As a result, a considerable number of pile-up events can occur, populating the Region of Interest (ROI) and spoiling the sensitivity. To meet this challenge, NTL amplification is employed to improve the signal-to-noise ratio of the light detector, ensuring the required pile-up rejection efficiency.

2.2 The bolometer array

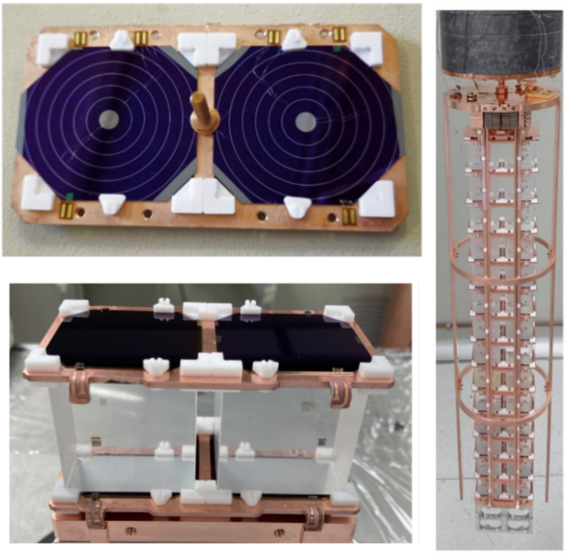

Figure 2. Top left: two light detectors assembled in a copper frame (the electrodes used for signal amplification are clearly visible). Bottom left: the two-crystal module including light detectors and Li_2MoO_4 crystals. Right: the CUPID prototype single tower ready for operation.

CUPID detector is an array of 1596 Li_2MoO_4 scintillating bolometers [2]. The detector assembly is based on a modular, floating mechanical structure in which each floor is stacked by gravity. This design simplifies construction, relaxes tolerance requirements, and minimizes potential background contributions by eliminating the need for reflective foils. Extensive R&D with both small and full-scale prototypes demonstrated bolometric performance close to the CUPID design goals, with energy resolutions approaching the target of 5 keV at the $Q_{\beta\beta}$ of ^{100}Mo [5, 6]. Following the prototyping phase, the project has entered the final testing stage of the new detector design, including the semi-automatic assembly procedures, readout, DAQ, and data analysis. To this end, in 2025 a detector tower (see Figure 2) was constructed and installed in the Hall A cryostat at LNGS, where it is now operating to validate the target performance and to address any weaknesses that may emerge during construction or operation.

Also in 2025 were delivered the first enriched crystals produced by SICCAS (Shanghai, China) — the company selected as the baseline supplier for the growth of the ~1600 CUPID crystals. The crystals are now being tested as bolometers to verify their performances and radiopurity. This crystal pre-production phase, aimed at optimizing a growth process that ensures both crystal quality and radiopurity, is expected to be completed by the end of 2025, after which mass production will start in the following years.

2.3 Background and sensitivity

The target background index for CUPID is a counting rate in the ROI of 10^{-4} cts/(keV·kg·yr). Figure 3 shows the breakdown of this rate into five main sources, classified by type and location:

- neutron- and muon-induced events;
- accidental pile-up events from the superposition of $2\nu\beta\beta$ ^{100}Mo signals that survive pile-up rejection cuts;
- residual radioactivity in the infrastructure (cryostat and shields), extrapolated from CUORE data;
- intrinsic radioactivity of the Li_2MoO_4 crystals, mainly from surface contamination;
- residual radioactivity in the mechanical assembly and other passive elements close to the crystals.

The histogram compares the design contribution (dark blue) with the projected one (light blue), based on current experimental achievements. The average value is indicated by the blue vertical line, while the uncertainty is shown by the orange interval.

Current background projections correspond to an average counting rate of 1.12×10^{-4} cts/(keV·kg·yr) that already meets the CUPID goal of 10^{-4} cts/(keV·kg·yr) leaving open the possibility of a further improvement of background and $0\nu\beta\beta$ sensitivity in the few years remaining before the completion of the construction phase.

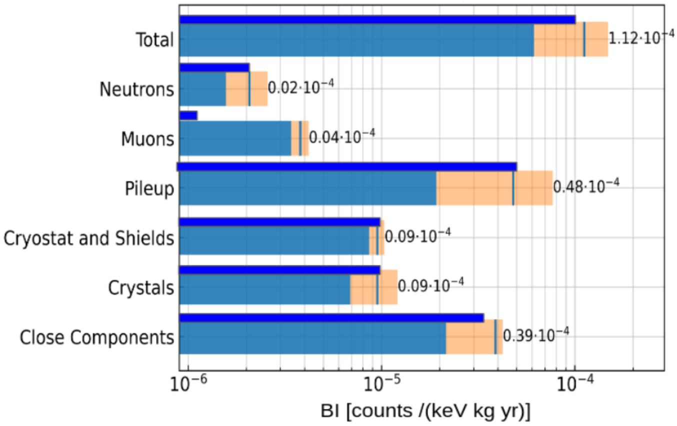

Figure 3. CUPID counting rate in the ROI. Background goals (thin, dark-blue bars) are compared with data-driven projections (light-blue and orange bars) based on experimental results extrapolated to CUPID using a full Monte Carlo simulation of the experimental apparatus. The uncertainty on the projections is obtained propagating experimental uncertainties and it is shown by the orange bar with a blue vertical line corresponding to the average rate.

Based on the target background counting rate and energy resolution and assuming a 10 yr livetime, the CUPID 3σ discovery sensitivity [7] is $\hat{T}^{0\nu}_{1/2} = 1 \cdot 10^{27}$ yr. This value corresponds to a set of different $m_{\beta\beta}$ values. The lower value is obtained with the EDF model [8], and is 12 meV. The QRPA and IBM models [9, 10] yield a $m_{\beta\beta}$ ranging from 13 to 21 meV while the only available calculation with NSM [11] yields 35 meV.

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