Contribution Prospectives 2020

CUPID: a next-generation $0\nu2\beta$ experiment

Principal author: Andrea Giuliani
Institution: CSNSM-IN2P3/CNRS
e-mail: andrea.giuliani@csnsm.in2p3.fr

on behalf of *CUPID France*[1]

Abstract

The search for neutrinoless double-beta decay ($0\nu2\beta$) is one of the most important topics in neutrino physics, with strong implications on particle physics and cosmology. Bolometers are among the most attractive devices for the construction of a large, sensitive and competitive $0\nu2\beta$ experiment. CUORE, running in the Gran Sasso underground laboratory in Italy (LNGS), is the largest $0\nu2\beta$ bolometric detector. With a large cryostat able to cool a one-ton detector to temperatures below 10 mK, CUORE is searching for $0\nu2\beta$ in the isotope ^{130}Te with unprecedented sensitivity and is one of the most competitive $0\nu2\beta$ experiments in operation. However, CUORE is not background free, because of a residual surface α radioactivity in proximity of the detectors and of γ background generated by the inner cryostat shields. The technology developed in France in the framework of the LUMINEU project and succesfully tested in the CUPID-Mo experiment — currently running in the Modane underground laboratory (LSM) — can substantially reduce both contributions, approaching the zero-background level in a CUORE-size detector. This technology consists of $Li_2{}^{100}MoO_4$ scintillating bolometers, enriched in the $0\nu2\beta$ isotope ^{100}Mo. On the basis of the LUMINEU/CUPID-Mo results, the CUORE collaboration decided in May 2018 to adopt the Li_2MoO_4 technology as a baseline for the proposed future experiment CUPID (Cuore Upgrade with Particle IDentification), which will use the existing CUORE cryostat. The CUPID collaboration is now established and a Conceptual Design Report (CDR) has been finalized. CUPID is technologically ready, data driven and cost-effective, and exploits an existing infrastructure. The ten years expected sensitivity is 10–17 meV, which places CUPID as one of the worldwide leading next-generation experiments. France's role in CUPID is expected to be major, given the contribution provided by the French groups in the definition of the basic CUPID technology and the support that can come from the double-beta-decay French community to the construction of the experiment. If funding is secured, CUPID data taking can start in six years from now.

This document is organized in two main Sections. In the first one, we summarise the advantages of the bolometric technique for the study of $0\nu2\beta$ and discuss the premises for the CUPID experiment, with emphasis on the role played by the French groups involved in this search. In the second Section, we present CUPID in terms of infrastructures, physics reach, timeline, cost and collaboration, with a discussion of the possible involvement of the French double-beta and rare-event communities and synergies with other searches. For a deeper insight into $0\nu2\beta$ and for an appreciation of the placement of CUPID in the international context, we refer to the document discussing in general the $0\nu2\beta$ strategy of IN2P3 [1].

1 Bolometric predecessors of CUPID

1.1 Bolometers

Bolometers are powerful low-energy particle detectors for the conduction of sensitive $0\nu2\beta$ searches in the calorimetric approach, i.e. with coincident detector and source. A bolometer consists of a single dielectric crystal — the active part of the detector that contains the isotope of interest — coupled to a temperature sensor. The signal, collected at very low temperatures (< 20 mK for large bolometers, with masses in the 0.1–1 kg range), consists of a thermal pulse registered by a dedicated sensor, with an amplitude of the order of 0.1 mK/MeV.

The bolometric technique can provide high sensitive mass (via large detector arrays), high detection efficiency (70%-90%), high energy resolution (down to 0.15%) and extremely low background thanks to potentially high material

[1] *CUPID France* consists of the French members of the CUPID Group of Interest, which has signed the CUPID CDR https://arxiv.org/abs/1907.09376 — *CUPID France* comprises about 35 members, of which 25 belong to IN2P3 laboratories

radiopurity and powerful methods to reject parasitic events. Most of the favorable high Q-value $0\nu2\beta$ candidates (^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{124}Sn, ^{130}Te) can be studied with this technique.

1.2 Merits and limitations of CUORE

An isotope of great interest for $0\nu2\beta$ decay is ^{130}Te. The signal is expected at 2527 keV, just below the end point of the γ radioactivity at 2615 keV. The natural isotopic abundance of ^{130}Te (34%) is by far the highest among all the $0\nu2\beta$ candidates. The experiment CUORE [2] — located in LNGS (Laboratori Nazionali del Gran Sasso) and currently in data taking — consists of 988 TeO_2 bolometers (containing tellurium with a natural isotopic composition) with a mass of about 750 g each, corresponding to about 200 kg of ^{130}Te. CUORE is one of the most sensitive $0\nu2\beta$ experiments up-to-date. It has set a limit of 2.3×10^{25} y on the half-life of ^{130}Te, which leads to bounds of 90–420 meV on the effective Majorana mass. This limit will be improved by about a factor 2 at the conclusion of the 4 year CUORE physics program.

The background in the region of interest (ROI) of CUORE, corresponding to about 50 events/y, is dominated by energy-degraded α particles generated by surface contamination. They account for a background index b of the order of 10^{-2} counts/(keV kg y). This background level prevents the CUORE technology, as it is, from being used for a next-generation experiment. The CUORE background model, built using directly the CUORE data, demonstrates that, after the elimination of the α component, $b = 2.5 \times 10^{-3}$ counts/(keV kg y) is expected at ~ 2.5 MeV (in the ROI of ^{130}Te), because of a ^{232}Th contamination present in the cryostat inner thermal shields. On the contrary, $b = 10^{-4}$ counts/(keV kg y) is safely estimated at energies higher than 2.6 MeV, where the contribution of ^{232}Th is negligible.

The CUORE cryostat is an unprecedented system in the field of cryogenics, which has represented a huge technological challenge. It took the CUORE collaboration around 2 years to understand and solve several technical issues and fully optimise this infrastructure. Now the cryostat is working smoothly and the data taking is going on efficiently. The CUORE cryostat can be considered a reliable infrastructure to cool down ~ 1000 macro-bolometers to about 10 mK and successfully operate them.

1.3 Scintillating bolometers

Scintillating bolometers bring an additional value to the cryogenic-detector technology. In these devices the crystal containing the isotope of interest is a scintillator, and a second auxiliary bolometer to register the emitted scintillation light is operated close to it. The ensemble of the crystal containing the $0\nu2\beta$-candidate and its light detector is referred to as detector module. The simultaneous detection of heat and scintillation light allows one to distinguish α particles from electrons or γ's thanks to the different light yield and signal shape, eliminating the dominant background source observed in CUORE. Scintillating bolometers containing a candidate with a Q-value higher than 2615 keV have therefore the potential to provide a background-free search even at a ton$\times$year exposure scale. Candidates that fit the high-Q-value requirement and can be embedded in scintillating crystals are ^{82}Se (Q-value = 2998 keV, compound ZnSe), ^{100}Mo (Q-value = 3034 keV, compound Li_2MoO_4) and ^{116}Cd (Q-value = 2813 keV, compound $CdWO_4$).

In spite of the excellent results achieved by the demonstrator CUPID-0 in LNGS (which has established the most stringent current limit on the $0\nu2\beta$-half-life of ^{82}Se by using enriched Zn^{82}Se crystals), some drawbacks also appeared for ZnSe. This compound has a difficult crystallization procedure, features a good but not excellent energy resolution (10–30 keV FWHM) and an internal contamination in ^{228}Th at the level of some tens of μBq/kg at the present state of the technology. Good results were achieved also on ^{116}Cd with enriched $^{116}CdWO_4$ crystals at the prototype level, but the isotope ^{116}Cd is intrinsically more difficult to enrich with respect to the other candidates, with a consequent higher cost by a factor ~ 2, and is more prone to cosmogenic activation.

For all these reasons, an intense R&D activity has focused on ^{100}Mo-containing compounds, and in particular on Li_2MoO_4, mainly in the framework of the LUMINEU project. The achieved results have been confirmed on an intermediate scale by the currently running CUPID-Mo demonstrator [3] (consisting of 20 modules of 210 g each), installed in the Modane underground laboratory (LSM). The single module of CUPID-Mo consists of a crystal of $Li_2{}^{100}MoO_4$ enriched at more than 95% in ^{100}Mo. The crystal is a cylinder with 44 mm diameter and 45 mm height coupled to an NTD (Neutron Transmutation Doped) Ge thermistor. At least one of the flat surfaces is exposed to a light detector, consisting of a NTD-instrumented Ge wafer. CUPID-Mo is a French-lead experiment. The IN2P3 groups have the following responsibilities: spokesman of the collaboration; detector construction; detector assembling; radiopurity; mechanics; DAQ coordinator; on-line data analysis; and MC simulations. The results achieved demonstrate the maturity reached by the proposed technology and the high standard of the detectors: energy resolutions of $\sim$5 keV FWHM at 2615 keV have been routinely obtained; α rejection at the level of 99.9% has been obtained thanks to the

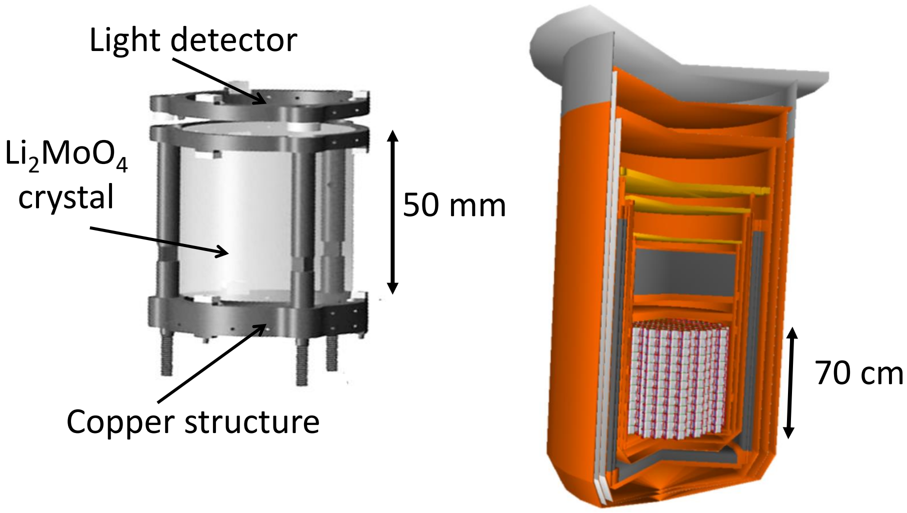

Figure 1: Left: single module of CUPID. Right: CUPID array in the CUORE cryostat.

heat-light readout; minimal internal contamination (inferior to ~ 3 μBq/kg for both ^{232}Th and ^{238}U as well as to 5 mBq/kg for ^{40}K) was guaranteed by detailed crystal production protocols.

These promising achievements, along with the results of the CUORE background model, have lead the CUORE, CUPID-Mo and CUPID-0 collaborations to the decision to select the Li_2MoO_4 technology for the future CUPID experiment.

2 CUPID

CUPID (CUORE Upgrade with Particle IDentification) [4] is a proposed next-generation $0\nu2\beta$ experiment based on scintillating bolometers and to be installed in the cryogenic infrastructure currently hosting CUORE at LNGS.

2.1 The CUPID detector and infrastructures

The CUPID crystals will be grown from $Li_2{}^{100}MoO_4$ enriched to 95% in ^{100}Mo. In its baseline design, the CUPID collaboration envisions cylindrical crystals with 50 mm diameter and 50 mm height, corresponding to a mass of 301 g each (see Fig. 1, left). The flat surfaces of the crystals will be exposed to bolometric light detectors fabricated from Ge wafers with 5 cm diameter, using an NTD Ge thermistor as a thermal sensor. The crystals will be stacked in detector towers conceptually similar to those of CUPID-0 and CUPID-Mo. With this design, about 1500 crystals will be hosted by the CUORE cryostat (see Fig. 1, right), corresponding to about 250 kg of ^{100}Mo. Note that the size of the main crystal and of the light detector, their mechanical and geometrical arrangements, and the readout approach proposed for CUPID closely resemble the configurations successfully adopted in CUPID-Mo and CUPID-0.

The main strengths of CUPID are the following:

- The single-module technology and the related production and purification protocols are fully established.
- The infrastructure for CUPID exists and is operational, even though it needs some upgrades discussed below.
- Most of the detector assembly protocols adopted in CUORE can be extended to CUPID with minor modifications.
- The combination of the results achieved in LUMINEU and CUPID-Mo with the CUORE background model allows to predict a background index of the order of 10^{-4} counts/(keV kg y) in the ROI of ^{100}Mo (see Fig. 2).

The CUORE cryostat will need upgrades. The wiring must be extended in order to read out ~ 3000 channels instead of the current ~ 1000. This operation looks straight-forward and no major problem is envisaged. Light detectors are particularly sensitive to vibrations and must operate in a much lower energy range with respect to the main $0\nu2\beta$ crystals. This may require additional studies and interventions to improve the isolation of detectors from vibrations.

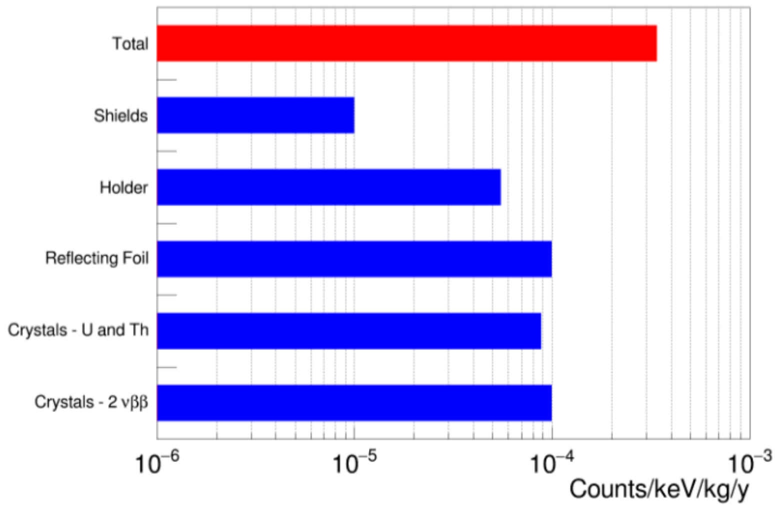

Figure 2: Breakdown of the CUPID β/γ counting rate predicted by the background model in the ^{100}Mo ROI. Here, the baseline configuration is considered. The replacement of the reflective foil with a reflective coating on Li_2MoO_4 crystals would dramatically reduce both the U and Th contributions of crystals (here dominated by surface contaminants) and that of the reflector itself.

2.2 Background estimation and physics reach

Some R&D is still required in order to achieve safely $b = 10^{-4}$ counts/(keV kg y) or even improve this value, the CUPID background goal (see Fig. 2). In particular, pile-up rejection methods need to be refined in order to control the contribution to the background coming from random coincidences of ^{100}Mo ordinary $2\nu\beta\beta$ decay events. An improvement of the signal-to-noise-ratio in light detectors with respect to the state of the art could be required.

Secondly, residual surface radioactivity in the reflective foil surrounding the scintillating crystals can be challenging with respect to the CUPID background target. The most straightforward solution is to avoid completely the foil and minimize the amount of inert material between crystals, but this will reduce the light collection. Dedicated tests will fix the optimal configuration.

The limit that CUPID can set on $m_{\beta\beta}$ in 10 y live time is 10–17 meV and the corresponding 3σ discovery sensitivity is 12–20 meV in 10 y live time. This makes CUPID one of the most sensitive next-generation experiments, providing a unique combination of high discovery potential, readiness of the technology and of the hosting infrastructure, and relatively low cost.

Table 1: Parameters of the CUPID detectors in the baseline scenario (CUPID), in the improved background scenario (CUPID-reach), and for a large bolometric detector with 1 metric ton of ^{100}Mo isotope (CUPID-1T).

Parameter	CUPID	CUPID-reach	CUPID-1T
Crystal	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$
Detector mass (kg)	472	472	1871
^{100}Mo mass (kg)	253	253	1000
Energy resolution FWHM (keV)	5	5	5
Background index (counts/(keV kg y))	10^{-4}	2×10^{-5}	5×10^{-6}
Containment efficiency	79%	79%	79%
Selection efficiency	90%	90%	90%
Livetime (years)	10	10	10
Half-life exclusion sensitivity (90% C.L.)	1.5×10^{27} y	2.3×10^{27} y	9.2×10^{27} y
Half-life discovery sensitivity (3σ)	1.1×10^{27} y	2×10^{27} y	8×10^{27} y
exclusion sensitivity (90% C.L.)	10–17 meV	8.2–14 meV	4.1–6.8 meV
discovery sensitivity (3σ)	12–20 meV	8.8–15 meV	4.4–7.3 meV

Upgrades are possible beyond the currently proposed version of CUPID. The present background model indicates the directions to be taken in order to reduce the background index by a further order of magnitude, bringing it to the level of $b \sim 10^{-5}$ counts/(keV kg y). R&D activities are planned in this prospect. In particular, technologies capable to fully reject the surface radioactivity in bolometers, including the β-particle component, as those studied in the ERC project CROSS, can provide major improvements in the background level. Furthermore, the ^{100}Mo sensitive mass can be increased up to 1 ton by building a larger cryogenic infrastructure and/or by using multiple cryostats.

Proposed follows-ups of CUPID, discussed in the CUPID CDR and named CUPID-reach and CUPID-1T, can be considered as significant steps to extend the reach of the bolometric technologies. CUPID-reach is exactly the CUPID baseline discussed above but with methods that allow to reduce the background by a further factor 5. CUPID-1T is a project at 10-y time scale, as it requires a new infrastructure and important R&D's to further reduce the background. It will have an active mass of 1 ton and need a new cryostat — larger than the one used by CUORE — and a deeper underground site. The new French underground laboratory under discussion in proximity of the Lyon-Turin tunnel would be ideal in terms of depth. We summarize the parameters of the possible CUPID detector phases in Table 1.

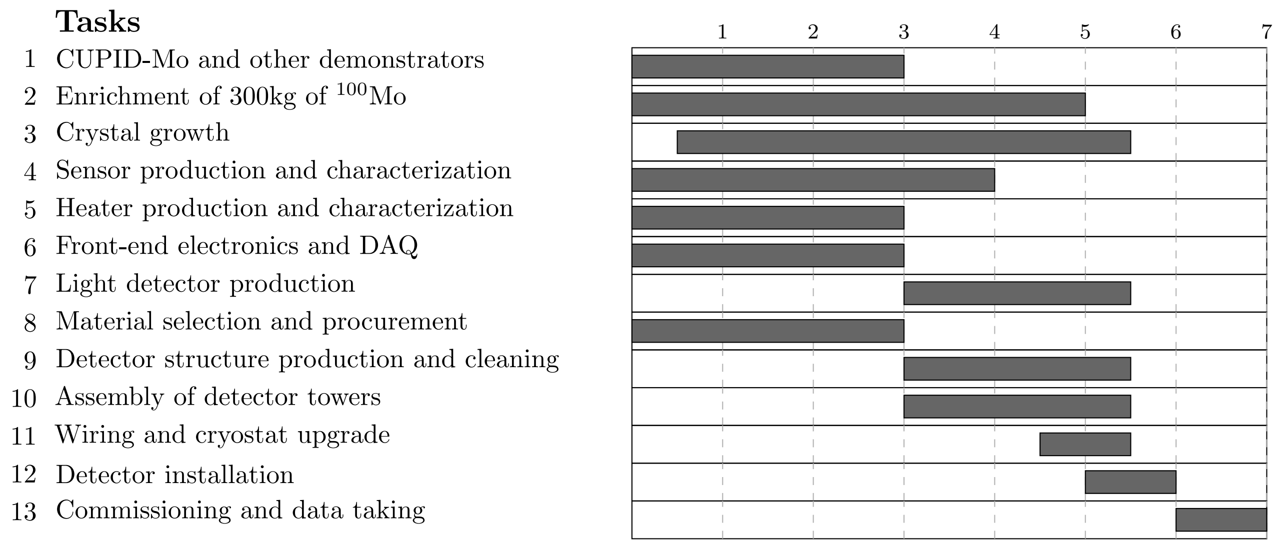

Figure 3: Time schedule of the CUPID experiment. Column numbers indicate years.

2.3 CUPID schedule

The CUPID program is reported in Fig. 3, in the assumption of fully and promptly available funding.

2.4 CUPID collaboration and resources

Since the infrastructure already exists, the cost is dominated by the enrichment (15–20 M€), the crystallization (4 M€), the detector assembly and the cleaning (3 M€) and the upgrade of the electronics and DAQ (4 M€). Possible other costs are related to upgrades and general maintenance of the cryogenic infrastructure. In total, the CUPID cost is expected to be up to a factor 5 less with respect to competing experiments with similar physics reach.

The activities to define the detector structures (2019–2021) are funded in Italy and US. In the latter country, CUPID has been selected by DoE at the CD0 level. Funding for enrichment and crystallization are not secured yet.

The CUPID collaboration builds on the CUORE, CUPID-0 and CUPID-Mo collaborations but is open to new participants. It comprises currently about 130 members from seven countries: France, Italy, US, Ukraine, Russia, China and Spain. A strong effort is ongoing in China to develop locally a scintillating-bolometer technology, with a possible CUPID-China experiment in the CJPL underground laboratory, complementary to CUPID at LNGS.

2.5 French responsibilities in the construction of CUPID

The tasks for the CUPID construction can be grouped in two sets. The first set corresponds to a well-defined program to fix precisely the CUPID structure in the next two years, culminating in the production of the Technical Design Report at the end of 2021. The responsibilities of the IN2P3 groups are the following:

- Data taking and data analysis of CUPID-Mo, currently the most important CUPID demonstrator
- Optimization of the NTD Ge thermistor geometry to increase the bolometer sensitivity and response speed

- Possible replacement of the reflective foil with an Al-film coating, in connection with the CROSS program
- Development of a demonstrator in the Canfranc underground facility to test the aforementioned innovations
- Set up of a purification / crystallization chain for Li_2MoO_4 crystals alternative to the current Russian producer (Nikolaev Insitute of Inorganic Chemistry), in the framework of the ANR project CLYMENE
- Set up of pulse-shape-discrimination algorithms for $2\nu2\beta$ random-coincidence rejection

The French institutions will collaborate also to tests in LNGS, aiming at a possible replacement of the cylindrical crystals foreseen in the baseline configuration with more massive cubic crystals that enable a better packaging and a higher background rejection by anti-coincidences. An important involvement in the improvement of the light detector performance is also foreseen.

The second set of tasks, still under definition in terms of responsibilities, is related to the construction and the data taking of CUPID itself. The IN2P3 groups are considering to be involved in the following tasks:

- Data acquisition software
- GEANT4 simulation of cryostat and detectors for background model
- Anti-radon system
- Design and implementation of the new cryostat wiring
- Semi-automatic system to glue NTD Ge thermistors to Li_2MoO_4 crystals and Ge wafers
- Mechanical production of the detector holders
- Design of anti-vibrational systems to upgrade the CUORE cryostat

The bolometric detection of particles is a very specific technology. However, the construction of a complex detector such as the one envisioned for CUPID requires a wide expertise. This is available in the French double-beta-decay and rare-event communities. The BiPo detector — installed in the Canfranc underground laboratory in Spain and developed by SuperNEMO — features a unique sensitivity in measuring surface radioactive contamination. This device can provide the only method to assess at the required level the surface radioactivity of the reflective foils used to increase the light collection in the scintillating bolometers of CUPID. More in general, the expertise present in IN2P3 laboratories in radon control, low-radioactivity methods, Monte Carlo simulations for background models, interpretation of low-level radioactivity spectra, can complement ideally the bolometric expertise coming from the LUMINEU/CUPID-Mo research line.

References

[1] A. Giuliani and Ch. Marquet, $0\nu2\beta$ strategy for IN2P3 prospectives, 2019

[2] C. Alduino et al. (CUORE Collaboration) Phys. Rev. Lett. 120 (2018) 132501

[3] E. Armengaud et al. (CUPID-Mo collaboration), arXiv:1909.02994 [physics.ins-det] (2019)

[4] The CUPID Interest Group, CUPID pre-CDR, https://arxiv.org/pdf/1907.09376.pdf, 2019