CUPID – CUORE Upgrade with Particle Identification

Document prepared by the CUPID-France team[1]

Summary

CUPID (CUORE Upgrade with Particle IDentification) is the successor of CUORE, the largest bolometric experiment ever, and is designed to search for neutrinoless double beta decay with scintillating bolometers based on Li_2MoO_4 crystals enriched in the isotope ^{100}Mo. The discovery of this process would have profound implications for our understanding of neutrino physics, the fundamental symmetries of nature and the evolution of the Universe. The full experiment, foreseen for the mid-2030s, will deploy nearly 1,600 enriched crystals corresponding to about 240 kg of ^{100}Mo and will be able to reach discovery sensitivity in the range of 10^{27} years, probing fully the inverted hierarchy region of the neutrino mass pattern, and a significant part of the normal one. If the lightest neutrino mass is not inferior to 10 meV, the CUPID discovery potential will be very high. CUPID will be directly competitive with other large-scale projects such as LEGEND-1000, studying ^{76}Ge, and nEXO, studying ^{136}Xe, while being technologically ready and more cost-effective. The staged deployment of CUPID ensures continuity with CUORE, mitigation of risks and early delivery of physics results. CUPID-Stage-I, scheduled to start in 2030 with one third of the final detector mass, will already surpass all experiments of the current generation and will take the lead in the worldwide search for neutrinoless double beta decay at the beginning of the next decade.

France has played a decisive role in establishing the technologies that now form the baseline of CUPID, thanks to the long-term support of ANR and ERC projects such as LUMINEU, CLYMENE, CROSS, BINGO, CUPID-1 and CryoLux. French groups have pioneered the purification and growth of Li_2MoO_4 crystals, developed the high-sensitive Neganov-Trofimov-Luke light detectors adopted by CUPID, and designed the gluing systems and other components that are critical for large-scale detector production and assembly. The institutions involved, mainly IJCLab-Orsay and CEA/IRFU-Saclay, but also IP2I-Lyon, SIMaP-Grenoble and soon LP2i-Bordeaux, hold key scientific and managerial responsibilities within the collaboration, and French researchers occupy leadership roles such as co-Spokesperson and scientific board chairs. Continued engagement will translate into high visibility and prestige for French laboratories and will consolidate their position as international leaders in this strategic field of fundamental physics.

The largest cost item of the project is the production of enriched Li_2MoO_4 crystals, estimated at about nine million euros for Stage-I alone, dominated by the enrichment process. INFN is preparing to launch the procurement in mid-2026 to ensure that the project stays on schedule, and the participation of French institutions in covering ten to twenty percent of this cost would be highly valuable. Other French commitments include the production of light detectors, gluing and electronics systems, as well as a sustained presence at LNGS during the assembly and data taking phases. Reinforcement in human resources is essential, in particular the creation of researcher and engineer positions, and the support of PhD students and postdoctoral researchers.

There is a strong urgency to secure funding for CUPID now. Immediate investment is required to preserve the opportunity for CUPID-Stage-I to start in 2030. Any delay would risk losing the decisive timing advantage that makes CUPID the first of the new generation of neutrinoless double beta decay experiments to produce results in the 2030s. Prompt support will ensure that the leading role of France in developing the core technologies of CUPID is translated into international scientific leadership and visibility at the highest level.

[1] For the authors' list, see Table VIII on page 25

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1. Scientific Challenges

Crucial role of double beta decay in particle physics

Neutrinos, subatomic particles with minuscule mass and weak interactions with matter, challenge the Standard Model (SM) of particle physics. The discovery of neutrino flavour oscillations and, as a consequence, neutrino masses, contradicts SM assumptions, opening new avenues of exploration. In particular, massive neutrinos allow for the existence of neutrinoless double beta decay (0ν2β),[2] a still undetected process that the CUPID experiment [1] aims to observe as its primary scientific goal.

In the realm of nuclear physics, double beta decay is the rarest weak nuclear process. It occurs between two even-even isobars when the decay to the intermediate nucleus is energetically forbidden due to the pairing interaction. This process is possible for 35 nuclides. A form of this transition, known as two-neutrino double beta decay (2ν2β), is allowed by the SM: $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$. It is a second order weak transition that conserves lepton number and has been observed in eleven nuclei, with half-lives ranging from 10^{18} to 10^{24} y. Although this process does not indicate directly new physics, it is highly relevant as it represents one of the most challenging background sources for CUPID.

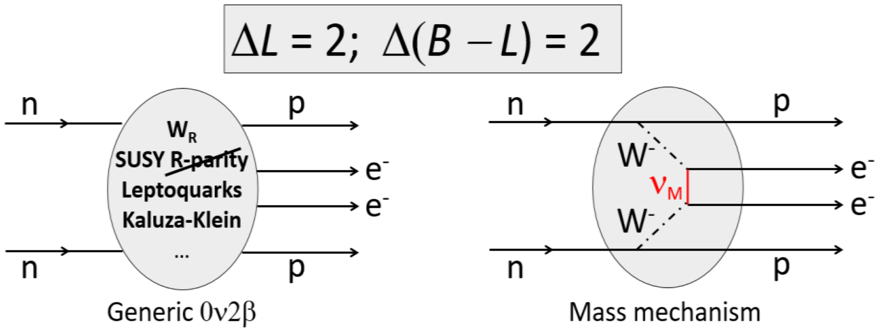

Figure 1 – Mechanisms inducing 0ν2β.

Of course, the primary CUPID's focus is on the neutrinoless process: $(A, Z) \rightarrow (A, Z+2) + 2e^-$, which can be viewed as the transformation of two neutrons into two protons and two electrons, without the accompanying anti-leptons, representing a true creation of matter (**Figure 1**). In the most natural and economical extension of the SM – the one that allows for a Majorana mass term for neutrinos – 0ν2β is mediated by virtual massive light neutrinos, exactly those that are detected in neutrino experiments and oscillate. This process is often referred to as "mass mechanism" (**Figure 1, right panel**). In this context, physical neutrinos would be Majorana particles, indistinguishable from their antiparticles. Thus, they would be Majorana fermions, a new type of matter, representing the most natural theoretical framework for neutral particles, as elaborated by Ettore Majorana nearly a century ago. However, it is important to emphasize that 0ν2β can be induced by a variety of other hypothetical lepton number violation (LNV) mechanisms beyond the SM, such as the exchange of right-handed W-bosons, SUSY super-partners with R-parity violation, leptoquarks, or Kaluza-Klein excitations, and others that have been discussed in the literature (**Figure 1, left panel**). Thus, beyond neutrino physics, 0ν2β serves as a general inclusive test of LNV. Even more significantly, its observation would imply the violation of B-L, where B represents the baryon number. B-L is the only exact (non-anomalous) global symmetry of the SM whose violation has not yet been demonstrated. Therefore, the search for 0ν2β can be considere one of the most critical and urgent endeavours in particle physics, with far-reaching consequences also for cosmology and our understanding of the Universe's evolution, including matter-antimatter asymmetry.

Mass mechanism and neutrino physics

Current interpretations of experiments are mainly framed in terms of the mass mechanism, which effectively relates 0ν2β to key parameters of neutrino physics (partially accessible through other searches). This approach establishes clear experimental targets and provides a metric for comparing the results and objectives of experiments studying different nuclei, even when employing fundamentally different methodological and technological approaches. The two key formulae for the mass mechanism are the following:

$$(1) \qquad \frac{1}{T_{1/2}^{0\nu}} = \log(2)\, G_{0\nu} {g_A}^4 |M_{0\nu}|^2 {m_{\beta\beta}}^2 \; ; \qquad (2) \qquad m_{\beta\beta} = |\textstyle\sum_{i=1}^{3} m_i {U_{ei}}^2|$$

where $T_{1/2}^{0\nu}$ is the 0ν2β half-life, $G_{0\nu}$ the exactly calculable phase space, and $|M_{0\nu}|$ the nuclear matrix elements. The axial charge g_A is a parameter of the order of unity, approximately 1.27 for a free neutron. The calculation of the nuclear matrix elements (NMEs) represents a significant source of uncertainty. Equation (2) defines the effective Majorana mass in terms of the three neutrino masses m_i and of the elements U_{ei} of the neutrino mixing matrix and clarifies the contribution to neutrino physics from 0ν2β. It is clear from Equations (1) and (2) that the

[2] For a complete review (including theory and experiments) see: Matteo Agostini, Giovanni Benato, Jason A. Detwiler, Javier Menéndez, Francesco Vissani. *Reviews of Modern Physics* **95**, 025002 (2023) and references therein

detection of 0ν2β will measure a combination of the three m_i values in the case of the mass mechanism, thereby establishing the absolute neutrino mass scale, which is inaccessible through oscillation experiments. Current experimental limits on $T_{1/2}^{0\nu}$ extend to 10^{26} years, corresponding to upper bounds of $m_{\beta\beta}$ < ~30-150 meV, where the large range is due to the different nuclear models used to compute the NME. We will use the sensitivity to $m_{\beta\beta}$ to present the state of the art and evaluate the role of CUPID. We anticipate that CUPID will assume an international leadership role in the search for 0ν2β at the start of 2030s, achieving an ultimate sensitivity to $m_{\beta\beta}$ in the range ~10-20 meV. It is also important to note that CUPID's technology is inherently scalable, positioning the experiment as a first step toward the development of more sensitive detectors based on the same technology capable of reaching sensitivities below 10 meV within a staged program extending over the next 20 years.

Involvement of French agencies and communities

Like most major funding agencies worldwide, the IN2P3 has a long-standing commitment to the search for 0ν2β, with several laboratories involved in this field. Over the past decades, IN2P3 has directly supported major international experiments, including mainly NEMO-3 and its successor SuperNEMO, as well as, more recently (with funding commitments beginning in 2021), the bolometric program CUPID, which builds on the experience of the CUORE experiment, located in the Gran Sasso underground laboratory (LNGS). In the last years, also new R&D ideas (like RD2 and Liquid0) have been supported.

The IN2P3 double beta decay community has the opportunity to meet and exchange ideas with neighbouring scientific fields in the workshops organised by the Neutrino *Groupement de Recherche* (GdR) (now IRN, International Research Network), which focuses on neutrino fundamental physics and experimental methods, and by the DUPHY (Deep Underground Physics) GdR, which focuses on the physics of rare events and addresses specific questions related to background control and the operation of underground detectors. The CUPID experiment and its related demonstrators, such as LUMINEU [2], CUPID-Mo [3], CUPID-0 [4], CROSS [5] and BINGO [6], have been presented and discussed multiple times during the meetings of these research groups.

The commitment of CEA/IRFU to a major 0ν2β experiment is more recent than that of IN2P3 and has been directed from the outset toward bolometric searches and CUPID, with sustained funding commencing in 2016.

The search for 0ν2β and the technologies advanced by CUPID are highly specialized and therefore do not establish in general direct connections with other research communities associated with Health, INSU, INP or other institutes. However, it is worth noting that the growth of ultrapure lithium molybdate crystals – the key material for CUPID – has fostered a long-standing collaboration with a team at SIMaP Grenoble, which operates within the framework of INP (Institut National de Physique).

2. The CUPID project

Experimental concepts in double beta decay

The distinctive signal of 0ν2β is a monochromatic peak in the sum energy spectrum of the two emitted electrons at the Q-value ($Q_{\beta\beta}$) of the transition (**Figure 2**). Due to the long expected lifetime (the current most stringent limits indicating $T_{1/2}^{0\nu} > 10^{25}$-10^{26} y), the search for 0ν2β requires large sources, containing at least tens or hundreds of kilograms of the isotope of interest.

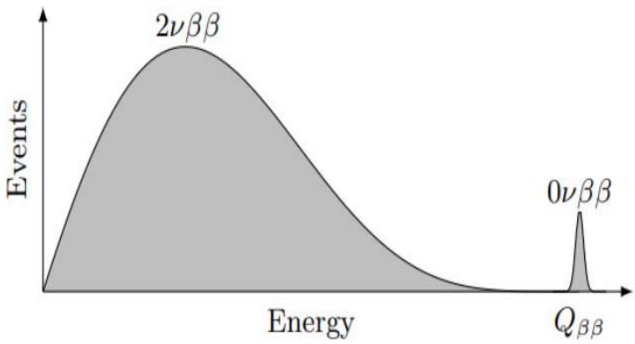

Figure 2 – Spectrum of the sum energy of the two emitted electrons in double beta decay. While 2ν2β is characterized by a continuum, the signature for 0ν2β is a peak at the Q-value of the transition, enlarged only by the detector energy resolution.

The next frontier is achieving a ton-scale source. This requirement makes the so-called "calorimetric" approach particularly appealing, where the source is embedded within the detector. Desirable detector features include high energy resolution and efficiency; however, the key factor is background, which must be minimized (ideally to zero) due to the extraordinarily low rate of the process being investigated. $Q_{\beta\beta}$ is a crucial criterion, as it influences both the phase space $G_{0\nu}$ (which depends on $Q_{\beta\beta}$, with a leading term scaling as ${Q_{\beta\beta}}^5$) and the background. The technical constraints posed by the calorimetric approach, combined with the need for a reasonably high $Q_{\beta\beta}$, render only four isotopes (out of 35) experimentally relevant, at least for the moment: ^{136}Xe, ^{76}Ge, ^{130}Te and ^{100}Mo. CUPID [1] adopts the candidate ^{100}Mo exploiting the bolometric technology. As will be explained in detail below, bolometric technology offers great flexibility in the choice of candidate isotopes to study (with ^{130}Te, ^{116}Cd, and ^{82}Se being other promising options). The main advantage of ^{100}Mo lies in its high Q-value – above the bulk of γ radioactivity – and in the opportunities it provides for background control.

CUORE, the CUPID precursor

To fully appreciate the rationale and the formidable potential of CUPID (that stands indeed for CUORE Upgrade with Particle IDentification), it is essential to outline the journey from CUORE to CUPID in the realm of bolometric technology. A bolometer consists of an energy absorber – typically a single crystal – thermally connected to a temperature sensor. The signal, collected at temperatures as low as 10-20 mK, consists of a thermal pulse registered by the sensor. The bolometric technique is particularly well-suited for a 0ν2β experiment, as it provides wide choice of the candidate, high detection efficiency (70%-90%) and excellent energy resolution (down to approximately 5 keV FWHM at $Q_{\beta\beta}$), which is essential for detecting a peak over an almost flat background. Due to the typical size of single crystals, large arrays containing hundreds or even thousands of elements are necessary for competitive experiments. CUORE is a crucial experiment because, besides being one of the most sensitive current 0ν2β searches, it has demonstrated that modern cryogenic technology can cool down one ton of bolometers to approximately 10 mK, distributed across ~1000 channels, while maintaining the necessary stability and duty cycle.

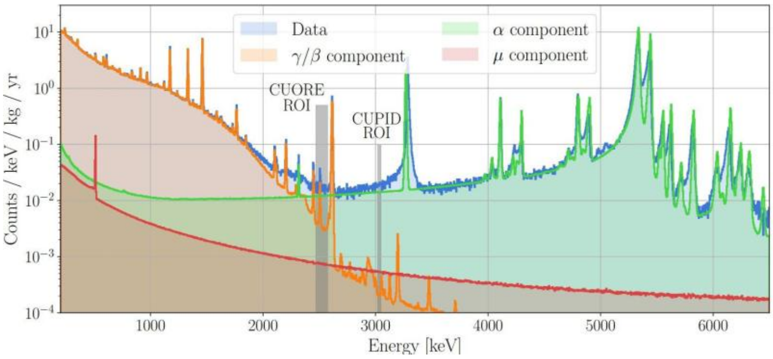

Figure 3 – CUORE background model. The dominant contribution to the background arises from the α component, both at the Q-value of ^{130}Te (2527 keV) and at that of ^{100}Mo (3034 keV). In the latter case, the α component is particularly significant because the contribution of the γ/β background is strongly reduced.

CUORE studies the isotope ^{130}Te, which is characterized by $Q_{\beta\beta} = 2527$ keV and a natural isotopic abundance of 34%, the highest among all viable candidates. CUORE represents the culmination of a series of bolometric experiments based on TeO_2 detectors (MiBeta, Cuoricino, CUORE-0), started in the 90's of last century, which have consistently ranked among the most sensitive searches worldwide. Located in LNGS, CUORE consists of an array of 988 TeO_2 crystals, each with a natural isotopic composition and a mass of 750 g, totalling 206 kg of ^{130}Te. The experiment has collected data corresponding to an exposure of about 2 ton×y and is still ongoing. CUORE's background index (BI), defined as the number of background counts per unit of energy, mass, and time in the region of interest (ROI), is 1.49×10^{-2} counts/(keV·kg·y). Therefore, CUORE is not a background-free experiment, with approximately 70 counts per year in an ROI the size of the FWHM detector resolution (~7 keV). A detailed background model, as shown in **Figure 3**, indicates that the background in this energy region is primarily dominated by energy-degraded α particles emitted from shallow surface radioactive contamination. This contamination is found in a thin layer (on the order of a few microns) on the supporting elements facing the TeO_2 crystals or on the crystals themselves.

CUPID technology and structure

The solution to the α background problem, proposed for future bolometric experiments like CUPID and validated in demonstrators and experiments such as LUCIFER and its continuation CUPID-0 [4], CUPID-Mo [3], AMoRE-I, and other smaller-scale tests, is to develop scintillating bolometers (**Figure 4**). In this approach, each event generates both a thermal signal resulting from the excitation of the crystal's phonon system (heat readout) and a photon signal (light readout). The simultaneous detection of heat and light allows for the discrimination and rejection of α events (the background) due to their typically lower light yield compared to β and γ events (which include the signal of interest), as illustrated in **Figure 5**.

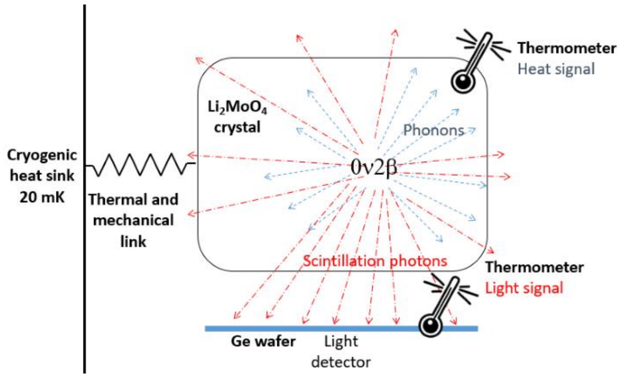

Figure 4 – Diagram illustrating a scintillating bolometer. A 0ν2β event generates phonons and scintillation photons in the energy absorber, which is a Li_2MoO_4 crystal in the case of CUPID. Phonons are registered as heat by a thermometer connected to the crystal. Photons are partly captured and absorbed by a Ge wafer, where they are also detected as heat. The detector provides therefore a dual heat-light signal.

As detailed in **Section 3**, preliminary tests of scintillating bolometers of various types and particularly the CUPID-Mo experiment [3] have ultimately led to the selection of the best isotope and compound for CUPID. In this experiment, each detector module will contain a Li_2MoO_4 crystal enriched to 95% in the isotope of interest for 0ν2β (^{100}Mo) and a light detector. It is important to note that ^{100}Mo has $Q_{\beta\beta} = 3034$ keV, higher than 2.6 MeV, placing therefore the 0ν2β signal outside the bulk of natural γ radioactivity, as shown in **Figure 3**. Enrichment is mandatory due to the relatively low natural isotopic abundance of ^{100}Mo, only 9.7%.

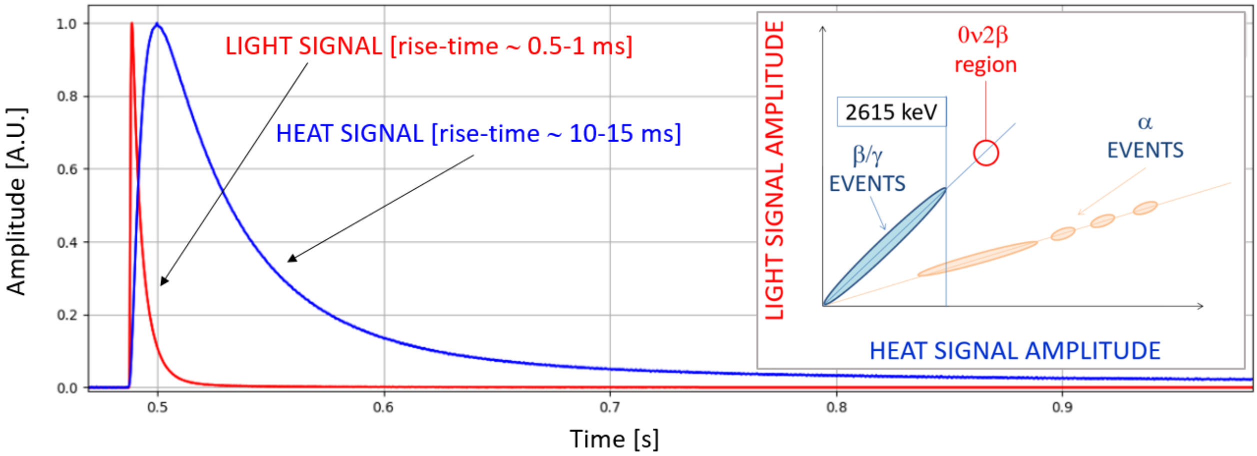

Figure 5 – Shown is the coincidence of light and heat signals from a real Li_2MoO_4 scintillating bolometer. The pulse evolution is slow, as expected for heat-mediated particle detection, and the differing time scales of the light and heat signals are evident, reflecting the much lower heat capacity of the Ge wafer light detector compared to the Li_2MoO_4 crystal. The inset shows how a heat-light amplitude scatter plot can be used to reject background events, ideally isolating the 0ν2β signal in a background-free region for candidate nuclei with a Q-value above 2615 keV, as is the case for ^{100}Mo.

The compound Li_2MoO_4 demonstrates very high radiopurity in its crystalline form [7], coupled with excellent bolometric performance. Energy resolutions of 5-7 keV FWHM are routinely obtained close to the ROI [3-5,8]. Each detector module will contain the enriched Li_2MoO_4 crystal and a light detector [9]. Since the light yield from α particles is only 20% compared to that of β particles for equal thermal energy deposition, α particles can be rejected with 99.9% efficiency while maintaining nearly full acceptance for β events [3], despite a relatively low scintillation efficiency, approximately 0.1%. The Li_2MoO_4 crystals are slightly hygroscopic, but they can be handled without special precautions if the relative humidity is ≤55%.

Details of the CUPID detectors are shown in **Figure 7**. The crystals are cubic in shape, measuring 45 mm on each side and weighing 280 g. The light detector consists of a Ge wafer that closely matches one face of the crystal, also functioning as a bolometer [9]. CUPID will consist of 1596 Li_2MoO_4 crystals and 1710 light detectors, resulting in a total ^{100}Mo mass of 240 kg and corresponding to 1.5×10^{27} ^{100}Mo nuclei. The crystals will be arranged in 57 towers, with two crystals per floor across 14 floors. Both the primary Li_2MoO_4 crystal and the Ge wafer will utilize the same type of temperature readout, specifically a high-impedance neutron transmutation-doped Ge thermistor (NTD). This type of temperature sensor is characterized by a strong dependence of resistance on temperature and operates in the few-MΩ range at 10-20 mK. It is used in the CUORE experiment and in all the CUPID precursors based on Li_2MoO_4, and must be glued to the crystals and the Ge wafers under strict radiopurity conditions, following precise procedures that ensure effective and reproducible thermal and mechanical coupling between the sensor and the detector elements. Another element that must be glued to the crystal is a silicon-based heater.

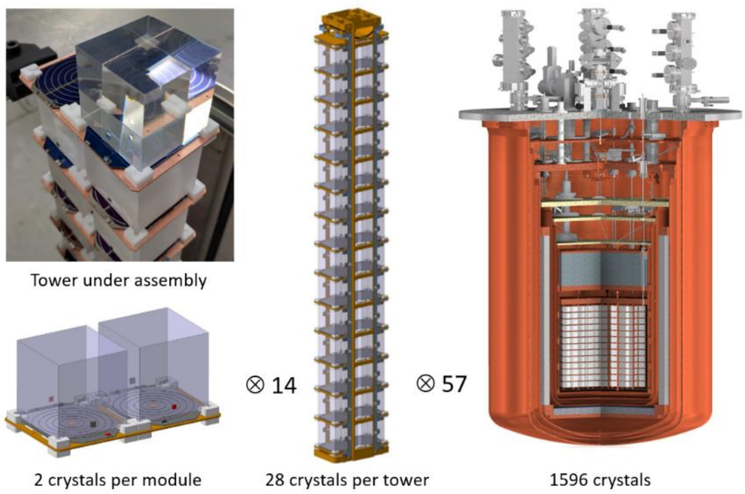

Figure 6 – The top-left photograph shows a CUPID prototype tower being assembled for a test at LNGS. The diagram also illustrates the decomposition of the CUPID array into individual modules (left), a tower (centre), and the complete detector installed in the CUORE cryostat (right).

It consists of a small Si chip with a conductive path providing a stable resistance of about 100 kΩ at 10-20 mK. It enables the periodic injection of fixed amounts of thermal energy that simulate particle pulses and allow stabilization of the detector response.

CUPID crystals and light detectors

We now present a more detailed discussion of the two principal components of the CUPID detector: the Li_2MoO_4 crystal [7] and the light detector [9].

The crystals, which will contain molybdenum enriched to 95% in the isotope ^{100}Mo, must meet strict radiopurity and light-yield requirements. The required radiopurity corresponds to specific activity upper limits of 0.4 μBq/kg for the radionuclides ^{238}U, ^{226}Ra, ^{232}Th, and ^{228}Th, and 1 mBq/kg for ^{40}K. Regarding the light yield, in the current CUPID configuration we require that when 3034 keV ($0\nu2\beta$ signal energy) is deposited in the Li_2MoO_4 crystal, the scintillation photons absorbed by the light detector produce an energy release of at least ~1 keV. This corresponds to approximately 500 photons, based on the emission spectrum of pure Li_2MoO_4 at low temperatures. All these goals were achieved and extensively demonstrated in the CUPID-Mo and CROSS projects, using crystals produced by the Nikolayev Institute of Inorganic Chemistry (NIIC) in Novosibirsk, Russia, [7] which have been grown with the enriched molybdenum supplied by Russian enrichment facilities for the NEMO-3 experiment. However, the geopolitical situation following Russia's invasion of Ukraine in February 2022 has made scientific and commercial collaborations with the involved Russian institutions impossible. The baseline for CUPID crystal production has therefore shifted to the Chinese crystal-growth company SICCAS (the same that produced TeO_2 crystals for CUORE), which uses enriched molybdenum supplied by the Chinese company IPCE (a subsidiary of the China National Nuclear Corporation). Natural crystals of high optical and bolometric quality were successfully produced by SICCAS at the end of 2023, and several enriched samples were fabricated in late 2024 and 2025. These have been measured cryogenically at LNGS (see **Figure 7**) and Orsay, yielding extremely encouraging results in terms of bolometric performance and light yield. High radiopurity can also be achieved through multiple crystallizations, even though no special attention has yet been paid to the contamination of the precursor powders. Final validation of the enrichment-purification-crystallization chain is planned before mid-2026. As a risk mitigation strategy, the French institutions are exploring a fully national route for enriched crystal production, relying on two companies: LUXIUM, which has successfully produced Li_2MoO_4 crystals at its Grenoble site using the technique developed in the CLYMENE project [7], and ORANO, which has the capability to enrich molybdenum in the isotope ^{100}Mo at its stable isotope enrichment laboratory on the Tricastin site. A Non-Disclosure Agreement was signed between CEA and Orano, and natural Mo powder was screened as a first step before evaluating the radiopurity of the enriched material.

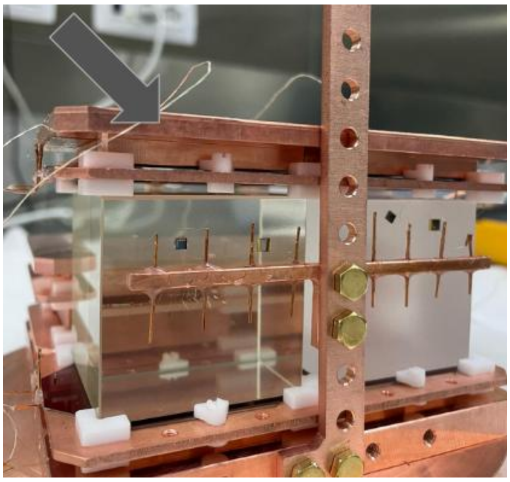

Figure 7 – An enriched $Li_2{}^{100}MoO_4$ crystal (indicated by the grey arrow) developed by the Chinese company SICCAS. The photo shows it assembled for a bolometric test.

CUPID's light detectors feature an ultrapure Ge wafer that is 0.275-0.325 mm thick, coated with a SiO anti-reflective layer, and equipped with an NTD sensor. In addition, they are upgraded through the so-called Neganov-Trofimov-Luke (NTL) effect, which allows to enhance the signal-to-noise ratio (SNR) by about an order of magnitude. For this purpose, the Ge wafer is equipped with Al electrodes on its surface to establish an electric field within the absorber volume (see **Figure 8**) [9]. This field allows for the collection of charges – consisting of electron-hole pairs – generated by absorbed light. As these charge carriers drift towards the electrodes under the electric field's action, they deposit heat in the crystal, which is then measured by the NTD Ge thermistor. In CUPID, with typical voltages applied at the electrodes of $V_{NTL} \sim 100\,V$, the SNR is increased from 10 to about 100. Here, the SNR is defined as

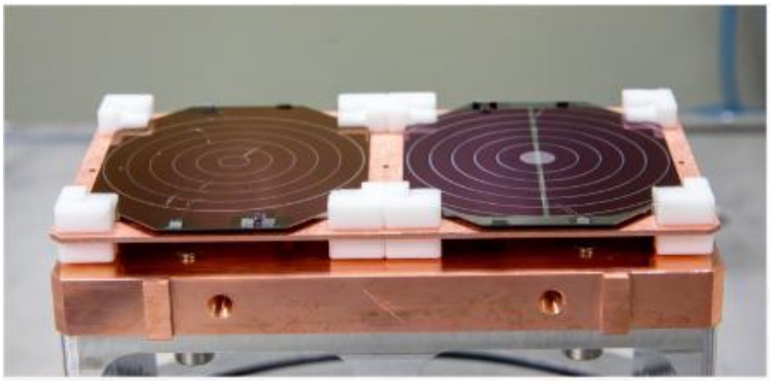

Figure 8 – Two light detectors forming part of a CUPID elementary module. The Al electrodes used to produce the NTL effect are visible.

the ratio between the signal amplitude corresponding to the light collected when an energy equivalent to that of a 0ν2β event is released in the Li_2MoO_4 crystal and the RMS fluctuation of the baseline. This enhancement of the SNR is crucial for achieving the CUPID background goal, as will be discussed later.

CUPID background model

The background index (BI) goal for CUPID is 10^{-4} counts/(keV·kg·y) in the ROI [1]. The CUPID experiment will be installed in the same cryostat currently used by CUORE, which is scheduled to conclude data collection in 2026. This represents a major advantage for CUPID, as the cryogenic infrastructure that will host it already exists and has been thoroughly tested for both technical performance and background contribution.

A detailed study of the CUORE results provides a comprehensive understanding of the background sources associated with the cryostat, shielding, and passive materials that inevitably surround the crystals, such as copper and polytetrafluoroethylene (PTFE). Additionally, the CUPID-Mo and CUPID-0 experiments, which have also developed detailed background models, offer insights into other components, such as the Li_2MoO_4 crystals and light detectors. For this reason, the CUPID background model is primarily data-driven and highly reliable.

Figure 9 illustrates the most up-to-date version of CUPID's background budget. Currently, the expected BI has a central value of 1.15×10^{-4} counts/(keV·kg·y), with a 1σ interval of [0.86,1.44] $\times10^{-4}$ counts/(keV·kg·y), compatible with the CUPID goal. The values for the Muons and Neutrons components take into account an upgrade of the setup, with the construction of an active muon veto and an expansion of the current neutron shielding. It is evident that CUPID's background is dominated by two sources, referred to as Pileup and Close Components that we will discuss in more detail.

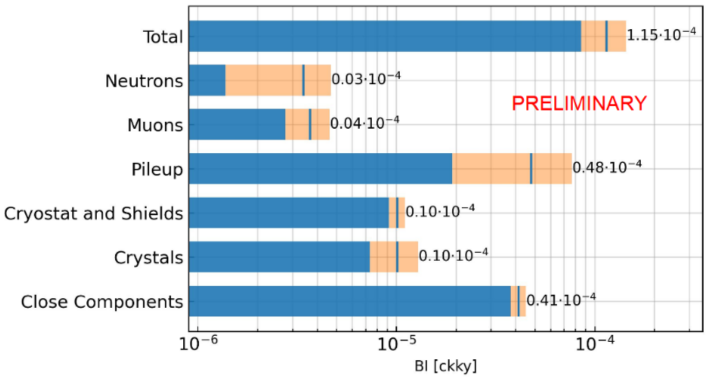

Figure 9 – The current CUPID background estimate, broken down into its main contributions. The blue line represents the expected central value of each component, while the orange band indicates the corresponding 1σ interval.

The Pileup component [10] is associated with the random coincidences of events from 2ν2β. The related energy spectrum in is a continuum from zero to the $Q_{\beta\beta}$ peaked at about $Q_{\beta\beta}/3$, as shown in **Figure 2**. The energy resolution in the heat channel is excellent, meaning that the high energy tail of this distribution does not pose a significant background challenge for the search for 0ν2β. However, in the case of ^{100}Mo, 2ν2β is challenging due to the slow response of NTD-based bolometers. The 2ν2β activity in a CUPID crystal is of ~2.6 mBq, as this transition is relatively rapid in ^{100}Mo, with half-life $T^{2\nu}_{1/2} = 7\times10^{18}$ y. Two events separated by an interval shorter than a typical pulse rise-time may be registered as a single signal corresponding to the sum of the energy of both events. Consequently, the ROI at ~3 MeV becomes populated with unresolved pileup events from 2ν2β. The pileup events can be eliminated through pulse-shape discrimination, which exploits the distortion exhibited in the leading edge by a signal resulting from the superposition of two close distinct events. Pileup discrimination is more effective with fast signals and high SNR. In fact, light detectors are crucial for rejecting this background contribution as their time response is typically on the 1 ms scale, compared to heat channel's 10 ms scale. Preliminary studies [10] have clearly shown that the NTL light detector technology adopted in CUPID achieves a pulse-pair resolving time of ~0.2 ms, defined as the minimum time interval between two equal-amplitude events that sum to the 0ν2β energy, allowing for the rejection of 50% of those events. This value corresponds to the background level shown in **Figure 9** for the Pileup component.

The Close Components contribution arises from the radioactive contamination of the materials used to support the crystals and wafers, typically copper and PTFE. In particular, charged particles emitted from a thin layer at the surface of these materials can reach the detector and pose a risk. Notably, as shown by CUORE's results, there is a dominant α particle component in the raw background. After α strong rejection (> 99.9%) thanks to the scintillating-bolometer technology, other sub-dominant contributions to the background become apparent. In particular, there are two challenging β transitions in the natural radioactivity chain – originating from ^{214}Bi and ^{208}Tl – with Q-values greater than 3 MeV (specifically, 3270 keV and 4999 keV). These isotopes produce γ's and β particles that are energetic enough to generate events around 3 MeV. This source poses a significant challenge because it is difficult to measure and control compared to bulk radioactivity. This background contribution can be mitigated by improving the cleaning processes for the surfaces of the materials surrounding the detectors and/or adjusting the amount and distribution of these materials. With the geometry of the CUPID experiment and the contamination levels inferred from the CUORE background model, we arrive at the value shown in **Figure 9**, which complies with the total background level anticipated for CUPID.

The present estimate should be regarded as conservative. Continued advancements in light-detector performance are expected to further suppress the Pileup contribution already in CUPID. Likewise, refinements to the tower geometry are anticipated to reduce the contribution from Close Components.

It should be noted that the detailed knowledge of the background components, inherited from CUORE data and several smaller-scale experiments, already makes it possible to devise strategies for a total background reduction by an additional order of magnitude. This would enable a successor experiment, CUPID-1T [11], with 1000 kg of ^{100}Mo. There are no technical obstacles in terms of detector or cryogenic technology. While this document is not the appropriate place to discuss CUPID-1T in detail, it is important to emphasize that, unlike most next-generation experiments, CUPID is expandable, ultimately reaching sensitivities capable of deeply probing the normal ordering region of neutrino masses [11].

Theses and publications related to CUPID

The pre-CUPID phase and the current finalization stage of the experiment have been highly productive in terms of PhD theses and scientific publications.

CSNSM/IJCLab		
Student	**Defense year**	**Title**
Margherita Tenconi	2015	Development of luminescent bolometers and light detectors for neutrinoless double beta decay search
Dmytro Cherniak	2015	Development of cryogenic low background detector based on enriched zinc molybdate crystal scintillators to search for neutrinoless double beta decay of ^{100}Mo
Michele Mancuso	2016	Development and optimization of scintillating bolometers and innovative light detectors for a pilot underground experiment on neutrinoless double beta decay
Valentina Novati	2018	Sensitivity enhancement of the CUORE experiment via the development of Cherenkov hybrid TeO_2 bolometers
Hawraa Khalife	2021	CROSS and CUPID-Mo: future strategies and new results in bolometric search for $0\nu\beta\beta$
Léonard Imbert	2023	Étude du bruit de fond des expériences CUPID-Mo, CUPID, et CROSS de double désintégration bêta sans émission de neutrinos
CEA/IRFU		
Anastasiia Zolotarova	2018	Study and selection of scintillating crystals for the bolometric search for neutrinoless double beta decay
Dounia Helis	2021	Searching for neutrinoless double-beta decay with scintillating bolometers
Antoine Armatol	2023	Innovative methods for background rejection in next-generation neutrinoless double beta decay bolometric experiments
Vladyslav Berest	2025	Towards BINGO: Development of Advanced Background Reduction Technologies for Neutrinoless Double-Beta Decay Bolometric Experiments
SIMaP		
Abdelmounaim Ahmine	2021	Croissance Czochralski, comportement et propriétés mécaniques de cristaux massifs de Li_2MoO_4 pour bolomètres scintillants

Table I – PhD theses related to CUPID and associated projects

The theses are listed in Table I, while **the scientific publications are compiled on page 27**. The numbered citations in the present text refer to this list, which also documents the intense scientific output related to CUPID.

We note that at least four of doctors listed in **Table I** now hold permanent positions in research institutions, all in activities connected to the bolometric technique: Michele Mancuso is a research scientist at MPIP Munich, Valentina Novati is a *Chargée de Recherche* at CNRS/IN2P3–LPSC Grenoble, Antoine Armatol is a *Chargé de Recherche* at CNRS/IN2P3–IP2I Lyon, and Anastasiia Zolotarova is a researcher at CEA/IRFU. The latter is also the recipient of an ERC Starting Grant (2022). This clearly demonstrates the excellence of the training provided within the French CUPID research groups.

Several PhD theses are currently in progress, with the expected defense years indicated in parentheses: Mariia Buchynska (2026), Victor Perez (2026), and Roberto Serino (2028) at IJCLab; Mathieu Pageot (2026) and Sara

Vesce (2028) at CEA/IRFU. All these theses have been supported through multiple funding sources, including ANR and ERC projects, IN2P3, CEA/IRFU and Écoles Doctorales. We expect a similar rate of PhD students in the coming years, with typically two students active simultaneously at both IJCLab and CEA/IRFU, each at different stages of their doctoral training.

In terms of publications, we expect a strong flow of papers in the coming years, in line with the groups' tradition. Up to 2030, the articles will mainly focus on technological developments related to the CUPID detectors and associated systems, or will present the results of simulations. During the data-taking of CUPID Stage-I (see the next section), we anticipate physics results of international significance on the $0\nu2\beta$ decay of ^{100}Mo to the ground state of ^{100}Ru (main research topic), along with studies of many other rare processes accessible with CUPID [1,3], such as double beta decay to excited states, searches for violations of fundamental symmetries, investigations of Majoron-emitting modes, and dark matter searches.

3. Genesis, timeline and positioning

Origin of the CUPID project

CUPID [1] essentially originates from the convergence of two research lines. As noted above, on one side is CUORE – the largest bolometric experiment ever conducted – which provides CUPID with its cryogenic infrastructure and extensive expertise in areas such as readout, electronics, DAQ, data taking and analysis for thousands of bolometric channels, large-scale assembly, radiopurity assessment, copper and PTFE cleaning, and other operations associated with the handling and study of large bolometric arrays. CUORE is primarily a U.S.-Italian collaboration, with INFN playing a central role by providing the underground laboratory (LNGS) as well as numerous infrastructures, and technical and scientific expertise. Several U.S. institutions, including Berkeley, Yale, MIT, and others, also play an important role. On the other side, CUORE technology has been upgraded through the use of a new material – enriched $Li_2{}^{100}MoO_4$ crystals – and the adoption of the scintillating bolometer approach. In this domain, the contribution of the French institutions – particularly IJCLab (and its predecessor CSNSM) as well as CEA/IRFU – has been predominant [2-4].

The technology of molybdenum-based scintillating bolometers began with the ANR-funded LUMINEU project (2012–2017) and was also supported by the ISOTTA project (2012-2014) in the framework of ASPERA, an EU funded ERANET agency network [3]. Both LUMINEU and ISOTTA were led by CSNSM (now IJCLab). LUMINEU focused on $ZnMoO_4$ and Li_2MoO_4 crystals, selecting the latter compound for a large-scale experiment. Since 2013, Li_2MoO_4 detectors have been tested at the cryogenic laboratory of CSNSM/IJCLab (Orsay, France), as well as in the underground laboratories of Modane (LSM, France), Canfranc (LSC, Spain) and LNGS (Italy). These studies led to significant achievements, including the development – together with the NIIC (Novosibirsk) – of a purification–crystallization protocol yielding high-quality, radiopure ^{100}Mo-enriched crystals with irrecoverable ^{100}Mo losses below 4% [7]. Detectors based on both natural and enriched crystals demonstrated excellent radiopurity, high energy resolution, and effective α/β discrimination. It is worth noting that, as a risk mitigation strategy, a France-based crystallization technology for Li_2MoO_4 was successfully developed as well through the ANR project CLYMENE [7], launched in 2016, and transferred to a crystal growth company, LUXIUM Solutions (former Saint-Gobain Crystals).

Encouraged by these results, the IJCLab and CEA/IRFU groups and collaborators built small demonstrators containing several kilograms of ^{100}Mo [2-4], designed to verify reproducibility of the detector performance and to investigate background sources, thus laying the groundwork for CUPID. The most advanced of these is CUPID-Mo [3]. This experiment consisted of 20 $Li_2{}^{100}MoO_4$ scintillating bolometers, each weighing 210 g, for a total of 2.34 kg of ^{100}Mo. The detector was assembled in late 2017 and installed in the EDELWEISS cryostat in LSM in January 2018. Since then, it has successfully collected data, demonstrating excellent bolometric and radiopurity performance. CUPID-Mo provided in 2021 the most stringent limit at the time on the $0\nu2\beta$ half-life of ^{100}Mo, fixed at 1.8×10^{24} y, surpassing the historical NEMO-3 limit with ~30 times lower exposure. Moreover, CUPID-Mo has provided the world's most precise measurement of the $2\nu2\beta$ spectral shape and half-life of ^{100}Mo.

Table II details the amounts and sources of the funding during the period 2012–2018, which corresponds to the development of Li_2MoO_4 scintillating-bolometer technology in the pre-CUPID phase, supported by major investments (of the order of 1.4 M€), primarily from ANR projects. Later projects focused on CUPID construction are not reported here.

More recently, thanks to the ERC Advanced Grant project CROSS [5] (launched in 2018) and led by IJCLab, an experimental program to further study Li_2MoO_4 scintillating bolometers has been carried out at LSC, using ~5 kg of ^{100}Mo and 45 mm cubic crystals, which currently represent the CUPID baseline. In parallel, through CROSS and another ERC project led by CEA/IRFU (BINGO [6], started in 2020), it was possible to validate another major contribution from the French institutions: the NTL light detectors [9]. CUPID was initially conceived with standard bolometric light detectors, without NTL amplification. However, during pileup background studies, it became evident that this configuration would not be sufficient to reach the CUPID background goal. The IJCLab team therefore designed upgraded light detectors, fabricated in-house starting from bare Ge wafers, and carried out a long and successful optimization campaign. CROSS played an important role also in the validation of the Chinese enriched crystal production, funding the first batch of enriched crystals produced by SICCAS, and in testing crystals produced by LUXIUM Solutions in the production site of Gières (Grenoble).

In summary, the entire CUPID detector structure, from the preliminary protocol to produce radiopure Li_2MoO_4 crystals to their operation as scintillating bolometers equipped with light detectors using the Neganov-Trofimov-Luke enhancement, represents, in essence, a French achievement.

Funding source	Beneficiary CUPID groups		
	CSNSM (IN2P3) (now IJCLab)	**CEA/IRFU**	Others in France (mainly **ICMCB Bordeaux** and **SIMaP Grenoble** for crystal growth and purchase)
IRFU DPhP (2016-2018)		180 000	
CSNSM “AP Interne”(2016)	20 000		
ISOTTA (2012-2015)	104 000		
ANR LUMINEU (2012-2017)	228 128	199 104	325 624
ANR CLYMENE (2016-2021)	104 640		223 237
TOTAL	456 768	379 104	548 861
GRAND TOTAL		**1 384 733**	

Table II – France’s investment in the pre-CUPID phase (2012-2018) – all amounts are given in €.

CUPID’s history began in 2015 with the creation of the CUPID Group of Interest, aimed at preparing a successor to CUORE with a baseline design based on ^{130}Te in TeO_2 crystals as in CUORE (arXiv:1504.03599v1). In 2017, CUORE began data taking at LNGS, and the CUPID-Mo collaboration was formally established, joining French, U.S., Italian, Russian, Ukrainian and Chinese laboratories. **In May 2018, the Li_2MoO_4 technology was officially adopted as the CUPID baseline, replacing TeO_2.** The CUPID collaboration was subsequently officially formed, including approximately 180 members coming mainly from three countries: Italy, U.S. and France, reflecting the genesis of the project. In 2019, CUPID was approved at the U.S. DoE CD-0 level alongside the experiments LEGEND and nEXO, and was recognized by ApPEC as one of the three most promising European $0\nu2\beta$ experiments, together with LEGEND and NEXT (arXiv:1910.04688v2). The CUPID Conceptual Design Report was released in July 2019 (arXiv:1907.09376v1) and has since been deeply updated to reflect the current structure of the experiment, as described in https://doi.org/10.1140/epjc/s10052-025-14352-1. A corresponding updated Technical Design Report is almost finalized. **In June 2023, the CUPID collaboration chose the NTL technology as the baseline for light detectors**. In 2024–2025, the collaboration began developing a new enrichment–purification–crystallization protocol with Chinese companies (IPCE for enrichment and SICCAS for crystals), which is now in advanced validation. French institutions are playing a major role in this effort, both through crystal procurement and testing. In the three North America–Europe summits on the future of double beta decay held to date (LNGS, Assergi, 2021; SNOLAB, Sudbury, 2023; MPIK, Heidelberg, 2025), which brought together scientists and funding agencies, CUPID has consistently been presented as one of the most promising next-generation experiments, alongside LEGEND and nEXO.

For clarity, **Table III** summarizes the France-led projects which has contributed to develop the CUPID technology. Later projects that are contributing to CUPID construction are shown in **Table IV**.

Project	**Funding**	**Duration**	**Scope**	**Relevance to CUPID**
ISOTTA	EC (ASPERA ERANET)	2012-2014	Detection techniques with radiopure enriched isotopes	First tests on Li_2MoO_4 bolometers
LUMINEU	ANR	2012-2017	Mo-based scintillating bolometers	Li_2MoO_4 bolometric technology
CLYMENE	ANR	2016-2021	Li_2MoO_4 crystallization protocols in French laboratories	Risk mitigation – alternative crystallization methods
CUPID-Mo	Mixed	2017-2021	World-leading ^{100}Mo experiment	Full CUPID demonstrator
CROSS	EC (ERC AdG)	2018-2025	Surface radioactivity rejection in bolometers for $0\nu2\beta$	Final CUPID size and shape enriched Li_2MoO_4 crystals Neganov-Trofimov-Luke light detectors
BINGO	EC (ERC CoG)	2020-2026	Innovative background control in bolometers for $0\nu2\beta$	Neganov-Trofimov-Luke light detectors

Table III – Projects led by France relevant to CUPID for the development of the experiment technology

Timeline of CUPID

CUPID is a mature experiment, ready for construction. It will be deployed in two stages, as shown in **Figure 10**. The first phase of the experiment – CUPID-Stage-I – will consist of 19 towers housing 532 detectors, corresponding to 1/3 of the total. After three years of data collection with CUPID-Stage-I, the experiment will pause for one year and a half to incorporate the additional planned towers. CUPID is anticipated to be the first experiment among those supported by the North America–Europe summits to commence, with the commissioning of CUPID-Stage-I expected to occur in 2030.

The staged deployment was a technical decision adopted by the collaboration in 2024 and endorsed by the LNGS Scientific Committee. This option offers three key advantages: (1) early data taking starting in 2030 while the remaining crystals are still being produced, giving the experiment a potential early leading role in 0ν2β search worldwide; (2) preservation of critical expertise in running detectors and cryogenics during the CUPID-to-CUORE transition (a prolonged shutdown of the CUORE infrastructure, and of related bolometric data taking and analysis, would inevitably lead to a loss of know-how that would take time to recover); and (3) additional room for optimization, improvement, and risk mitigation.

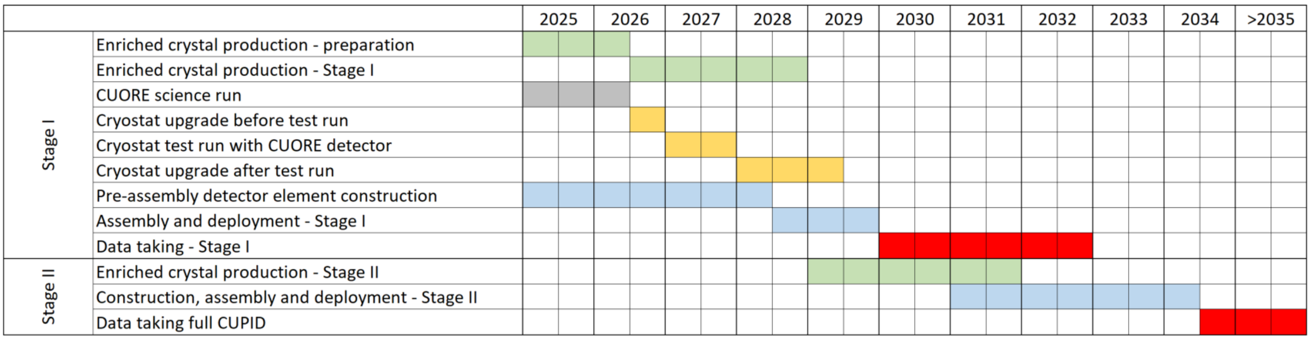

Figure 10 – CUPID timeline with staged deployment.

We will discuss three periods in the CUPID timeline, as presented in **Figure 10**, with a preliminary focus on the French commitments, which will be detailed in **Section 4**, where the distribution among the French institutions will be reported.

On the **three-year scale (2026–2028)**, activities will include the production of enriched crystals, the upgrade of the cryostat with a test run, and the preparation of all detector and readout elements, with the actual detector assembly beginning in mid-2028. The fully French commitments comprise the production of the light detectors, the development of the gluing system for NTDs and heaters, the preparation of the storage and transport system for the detector towers, the development of electronics for the injection of stable pulses into the heaters, and an alternative heater technology as a risk mitigation. The French institutions will also contribute to onsite activities at LNGS, including pre-characterization by sampling of the enriched crystals (CCVRs, CUPID Crystal Validation Runs) and shifts for the CUORE cryostat upgrade and the test run. Additional shared contributions involve NTD characterization and radiopurity measurements. The French institutions will also play relevant roles in developing the tools for data analysis and for the elaboration of the CUPID background model.

In the **following two years (2029–2030)**, the French institutions will share onsite assembly and installation activities with the Italian and U.S. teams and, after the commissioning of the experiment, will contribute to shifts for measurement maintenance and data analysis, leading to the first physics results expected by the end of 2030.

The **third period (after 2030)** involves the construction, commissioning, and data taking for full CUPID. We note that enriched crystal production will continue for Stage-II in parallel with detector operation for Stage-I. The French institutions will be involved in the same activities as in Stage-I. It is worth emphasizing that most infrastructures developed for Stage-I (for example, the gluing system, the light detector production tools, and the NTD characterization systems) will be reused for detector construction in Stage-II without additional equipment costs.

Previous reviews by scientific councils

Regarding IN2P3 and IN2P3-related laboratories, CUPID was reviewed at a very early stage by the Conseil Scientifique commun CSNSM-IPNO-LAL on 23 October 2018 (with a view to the scientific policy of the future merged laboratory IJCLab) and by the Conseil Scientifique of IN2P3 (25-26 October 2018, dedicated to "Physique des évènements rares : Matière noire et décroissance double beta sans neutrino"), and then, more recently (8 March 2023), by the CoDec (Comité de Détection et de suivi des Compétences) of IJCLab.

The CSNSM-IPNO-LAL committee (2018) produced a very positive report, stating: *Le conseil scientifique félicite les groupes français de CUPID-Mo pour la qualité de leurs développements passés qui leur confèrent une expertise de premier plan. Les résultats de physique attendus à court/moyen terme [...] sont très prometteurs et seront les meilleurs pour l'isotope ^{100}Mo.* A specific comment on CUPID follows: *Du point de vue international, le projet global CUPID semble très bien placé par rapport à la concurrence qui sera portée par les évolutions des expériences actuelles les plus sensibles (LEGEND 200 puis 1k, KamLAND-Zen 800 puis KamLAND2-Zen, nExo) et devrait permettre de sonder des masses effectives des neutrinos jusqu'à 7-20 meV.*

The report of the Conseil Scientifique of IN2P3 (2018) was also favorable: *Le détecteur et sa technologie sont très prometteurs sur le long terme dans la recherche d'un signal 2β0v. Il pourra soit le découvrir, soit le confirmer, en mesurant sur un autre isotope (hors Ge ou Xe qui seront à la portée d'autres expériences) dans le cas où le neutrino est une particule de Majorana et si la hiérarchie des masses est inversée.* Some concerns are expressed later about the large cost of the project with respect to the participation: *Le conseil note que c'est un projet à plusieurs millions d'euros avec moins de 7 ETP IN2P3*, but of course the cost is by far dominated by the enrichment of molybdenum.

More recently (8 March 2023) CUPID was reviewed by the CoDec (Comité de Détection et de suivi des Compétences) of IJCLab, with a very positive outcome: *La direction a fortement apprécié la présentation permettant de cerner très clairement la stratégie de l'équipe dans le cadre du projet CUPID. La direction partage cette stratégie et appuiera fortement les demandes RH et financières qui seront remontées auprès de l'IN2P3.* In fact, an IR was recruited at IJLab at the end 2024 (Ion Cojocari) with an important involvement in CUPID (50%) for the development of the light detectors.

At CEA/IRFU, the LUMINEU and CUPID-Mo projects were reviewed by the Conseil Scientifique du Departement (CSTS) in 2014 and 2016, respectively, receiving extremely positive evaluations that led to the early establishment of a CUPID line at CEA/IRFU (from 2016). In the 2016 report, it is stated: *Les résultats actuels obtenus avec les LMO sont excellents. L'ambition scientifique du projet proposé est grande. Les prochaines années seront cruciales pour la sélection des isotopes utilisés dans CUPID. Pour ces raisons, le CSTS recommande d'accompagner l'équipe LUMINEU, avec une priorité et des moyens plus importants que ceux disponibles actuellement, pour permettre la pleine exploitation du potentiel scientifique de cette technologie.*

More recently (18 September 2020), BINGO was positively evaluated by the CSTD (ex CSTS), while CUPID was reviewed within the framework of the Conseil Scientifique d'Institut de l'IRFU (19–20 June 2023), alongside other laboratory activities, with a very positive outcome and a recommendation to continue supporting the experiment. In particular, the report about BINGO (2020) states in the Conclusions: [...] *Given the choice of the bolometer technology as the most promising one for $0\nu\beta\beta$ search, the Conseil looks forward to the definition of a strategy in order to ensure the long-term future of this research line at IRFU. The ERC funding is a wonderful opportunity for infrastructure development, expertise building and should be a leverage to increase the person-power, notably in terms of hiring. In order to keep the privileged position of DPhP as a main player for this research line on the long term, a financing strategy has to be identified, given the huge size of the next experiments on $0\nu\beta\beta$ searches.* In fact, two researchers were recently recruited (Benjamin Schmidt and Anastasiia Zolotarova), and the report clearly recommends significant investments in the research line on 0ν2β.

Positioning of CUPID in the international scenario

The projected BI for CUPID in the ROI is 10^{-4} counts/(keV·kg·y) and the FWHM energy resolution in the ROI is 5 keV. The prototypes fabricated so far show energy resolutions in the 5–7 keV range [3,5,8], with some even below 5 keV. We are confident that an average resolution of 5 keV can be achieved through minor improvements in noise control and an optimal choice of the thermistor operating point. The evolution of the CUPID discovery sensitivity[3] for the 0ν2β half-life of ^{100}Mo as a function of the exposure is presented in **Figure 11** [1]. With an experiment duration of 10 y, we expect an **exclusion sensitivity of 1.4×10^{27} y at 90% c.l. and a 3σ discovery sensitivity of 1.0×10^{27} y**. In terms of the effective Majorana mass, **these values correspond to $m_{\beta\beta}$ < 10.4-17.5 meV and $m_{\beta\beta}$ < 12.2 -20.6 meV**, respectively. To provide a concrete representation of CUPID's sensitivity, a half-life of $T^{0\nu}_{1/2} = 1.0\times10^{27}$ y implies a mean of 11.1 counts over a duration of 10 y, to be compared with 2.2 background counts in a region the size of the FWHM energy resolution.

Considering CUPID-Stage-I, which will have ten times less exposure than full CUPID, the **expected 3σ discovery sensitivity is 0.2×10^{27} y, corresponding to $m_{\beta\beta}$ < 26.3-44.4 meV**.

[3] The 3σ discovery sensitivity is defined as the half-life bound such that there is a 50% probability that the experiment would detect a signal with a significance of at least 3σ.

We have utilized a compilation of NME calculations (pn-QRPA, IBM-2, EDF) to compute $m_{\beta\beta}$, excluding the ones performed in the framework of the Shell Model as we deem this calculation still incomplete, leading to an underestimation of the NMEs. The nucleus ^{100}Mo is asymmetric, and its characteristics push the Shell-Model computational problem beyond its present limits, making it necessary to truncate the model space. If we add the Shell Model results (with effective operator), the upper limit for the $m_{\beta\beta}$ range in the CUPID discovery sensitivity moves from 20.6 meV to 35.9 meV.

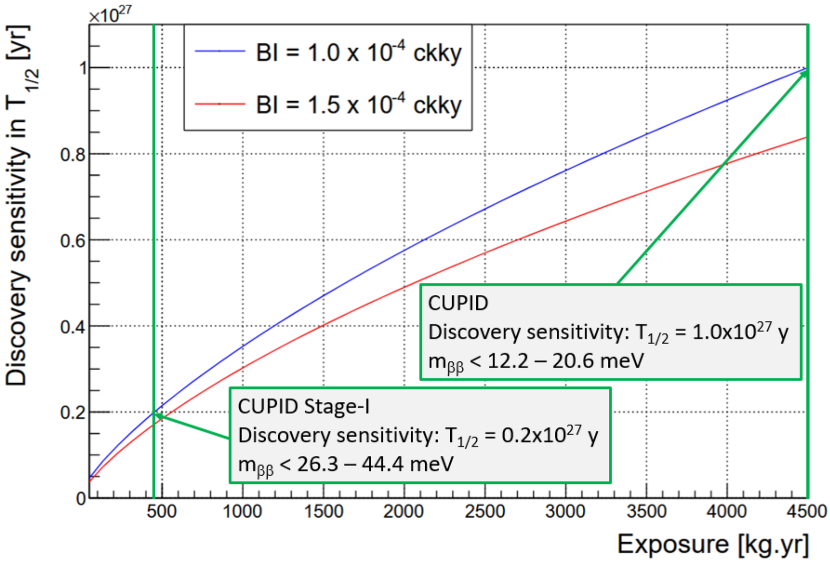

Figure 11 – CUPID discovery sensitivity for ^{100}Mo 0ν2β half-life as a function of the exposure (crystal mass × live time). Two values for the BI are considered. The projected results are quoted for BI = 1.0×10^{-4} ckkv (counts/(keV·kg·y)).

Let us now place CUPID in the international scenario. As already mentioned above, the technical constraints posed by the calorimetric approach, combined with the need for a reasonably high $Q_{\beta\beta}$, render only four isotopes (out of 35) experimentally relevant, at least for the moment: ^{136}Xe, ^{76}Ge, ^{130}Te and ^{100}Mo. Currently, the most stringent published limits are achieved by the experiments KamLAND-Zen 800 ($T^{0\nu}_{1/2} > 2.3\times10^{26}$ for ^{136}Xe), GERDA ($T^{0\nu}_{1/2} > 1.8\times10^{26}$ for ^{76}Ge) and CUORE ($T^{0\nu}_{1/2} > 2.2\times10^{25}$ for ^{130}Te). These experiments utilize different technologies, each with its own advantages and disadvantages, but all enable the construction of large detectors or detector arrays that embed the isotope of interest. Current limits for ^{100}Mo remain in the 10^{24} y range, although this isotope will be central to highly competitive future experiments, such as CUPID and AMoRE. We should mention also the SNO+ experiment, a large liquid scintillator detector re-using the former SNO (Sudbury Neutrino Observatory) cavity. It will investigate the isotope ^{130}Te, by dissolving tellurium into the scintillator. Initially, this experiment was meant to run simultaneously with those mentioned above, but it has faced considerable delays.

Next-generation searches aim to improve sensitivities by at least one order of magnitude, reaching the 10^{27}-10^{28} y range. We note that, thanks to its high $Q_{\beta\beta}$ (which provides a large phase space) and to favourable NMEs in several models, ^{100}Mo offers certain advantages and generally yields more stringent limits on $m_{\beta\beta}$ for equivalent half-lives. In addition to CUPID, two planned experiments are expected to begin data collection in the next decade with significant discovery potential: LEGEND-1000 and nEXO, both already mentioned in connection with the North America–Europe summits. LEGEND-1000 employs the same technology as GERDA, germanium diodes to study the isotope ^{76}Ge, and benefits from a precursor experiment already running in LNGS, called LEGEND-200. The nEXO project builds on the success of EXO-200 from several years ago and will consist of a large liquid xenon TPC designed to study the isotope ^{136}Xe, which is designed to be installed at SNOLAB in Canada. NEXT-HD, a high pressure gaseous xenon TPC containing the isotope ^{136}Xe, will also join the effort in the near future, built on the precursor NEXT-100 operating in LSC. In addition to these North America–Europe projects, there are two Asia-led experiments that will play an important role. The planned expansion of KamLAND-Zen 800, named KamLAND2-Zen and utilizing the same setup in the Kamioka mine in Japan, will enhance current sensitivity but will achieve a sensitivity an order of magnitude lower than that planned for nEXO with respect to the isotope ^{136}Xe. AMoRE-II, to be installed in Yemilab in South Korea, will study the isotope ^{100}Mo using Li_2MoO_4 scintillating bolometers, as in CUPID, but with a different temperature-sensor technology. AMoRE initially planned to use $CaMoO_4$ crystals, but shifted to Li_2MoO_4 after the results of LUMINEU and CUPID-Mo. This wide variety of experimental approaches should not be viewed as redundancy but rather as essential diversity, since the uncertainties in the NMEs and the challenges of the 0ν2β search demand multiple isotopes and technologies for a convincing discovery.

The position of CUPID in this context is illustrated by **Figures 12** and **13**.

Figure 12 clearly shows that **CUPID-Stage-I will already improve upon the results of all current experiments**, marginally surpassing even KamLAND-Zen-800. **Full CUPID, in the absence of a discovery,**

will rule out the inverted ordering region and will have significant discovery potential also in the normal ordering scenario if the lightest neutrino mass exceeds 10 meV.

The comparison of CUPID with future experiments is illustrated in **Figure 13**. The role of CUPID is clear: it has a sensitivity similar to those of LEGEND-1000 and nEXO, with the advantage to have a cost several time inferior (see discussion Section 5) and to be the only one that can actually start the deployment of the detectors before the end of this decade.

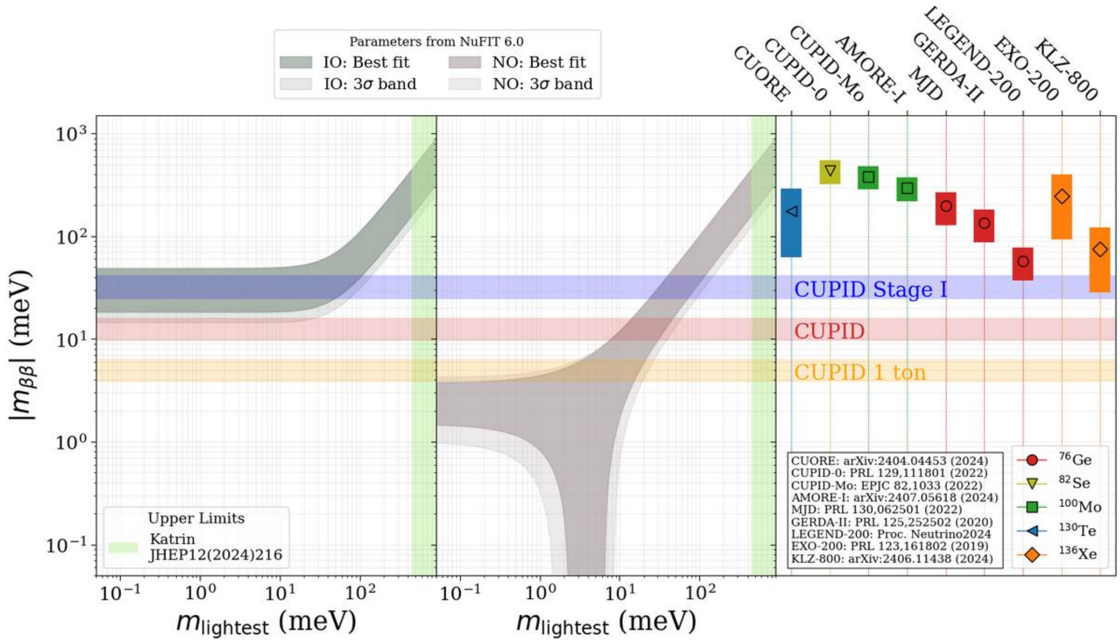

Figure 12 – Right: Sensitivities of CUPID-Stage-I, full CUPID, and a proposed next-to-next-generation experiment (CUPID-1T, based on CUPID technology) compared with those of the most sensitive current experiments. All have completed data taking except CUORE and LEGEND-200, for which the quoted sensitivities correspond to projected final values. Left (centre): regions corresponding to the inverted (normal) neutrino mass ordering.

It is also important to emphasize that CUPID-Stage-I will be highly competitive already in the early 2030s. Experiments plausibly running simultaneously with CUPID-Stage-I include AMoRE, SNO+, and KamLAND2-Zen. In this international context, **CUPID-Stage-I will take a leading role in the search for 0ν2β alongside these projects.**

A dedicated discussion is required when comparing CUPID with AMoRE, given the common isotope and similar technology. The AMoRE collaboration has approximately 100 kg of ^{100}Mo, which, like CUPID, will be deployed in two stages: 27 kg in Stage 1 (significantly less than CUPID-Stage-I) and 157 kg in Stage 2. The experiment's timeline is not clearly stated in articles or at international conferences. **Figure 13** shows the sensitivity of full AMoRE only, as the collaboration does not state that of the first stage. We believe that CUPID technology is currently more reliable for several reasons: (1) Cryostat: CUPID will use an existing cryostat with a well-characterized background, whereas the AMoRE cryostat is new and still under commissioning. (2) Detector experience: CUPID-Mo and the first tested CUPID tower have

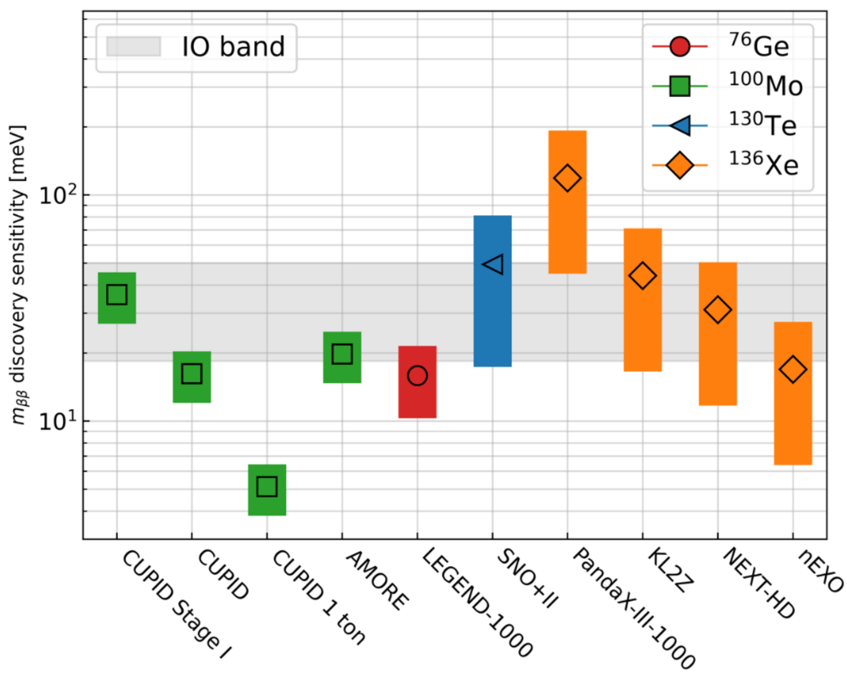

Figure 13 – Sensitivities of CUPID-Stage-I, full CUPID and CUPID-1T compared with those of other future experiments.

successfully operated a total of 48 Li_2MoO_4 detectors (20 + 28), in addition to many others in various tests. To our knowledge, the number of Li_2MoO_4 detectors operated by AMoRE is much smaller (e.g., only 5 in AMoRE-I). (3) Temperature sensors: CUPID employs NTD thermistors with room-temperature electronics, a technology proven in nearly 1000 channels in CUORE and in tens of channels with Li_2MoO_4 detectors, as well as in the dark matter EDELWEISS experiment with Ge detectors. In contrast, AMoRE uses metallic magnetic calorimeters with SQUID readout, developed via microfabrication, requiring a much larger number of readout wires per sensor. While micro-fabricated sensors could potentially be reproducible at the scale of hundreds of channels in macro-bolometers, this has yet to be demonstrated. (4) Background index: looking at the precursors, the background index in AMoRE-I is an order of magnitude higher than in CUPID-Mo. (5) Background model: CUPID's background model is extremely robust, being grounded in results from first-class demonstrators and CUORE. (6) Energy resolution: CUPID generally achieves better energy resolution than AMoRE (5-7 keV vs. 10-15 keV) (7) Readout speed: The only clear advantage of AMoRE technology is a faster readout. However, recent results with NTL technology in CUPID indicate that $2\nu2\beta$ pileup can be effectively controlled, resulting in a background index comparable to that claimed by AMoRE. For all these reasons, we consider CUPID to be better positioned, relying on a more mature, manageable, and extensively tested technology. In any case, we have constructive contacts with the AMoRE collaborations, and we have plan for a possible convergence of efforts toward a ton-scale experiment, dubbed CUPID-1T in the CUPID context.

We conclude by noting that the AMoRE collaboration has already secured the enriched materials and will rely on South Korean and Russian laboratories for purification and crystallization, so it will not compete with CUPID in these respects.

Role and visibility of the French institutions

We consider that robust support for CUPID, both Stage-I and the full experiment, from IN2P3 and CEA/IRFU represents a unique and timely opportunity for both agencies.

The search for $0\nu2\beta$ is a central topic in particle physics and cosmology, actively pursued by leading funding agencies worldwide. CUPID offers a concrete opportunity for French agencies to play a visible and influential role in this strategically important area of research for the next decade and longer.

As outlined above, the core detector technology for CUPID has been developed in France [2,3,5-7,9]. Continued support would therefore allow the agencies to fully leverage a substantial long-term investment – both financial and human – and capitalize on the accumulated expertise in this sophisticated technology. Conversely, limited engagement could result in a missed opportunity to consolidate and translate this experience into leading scientific contributions.

French physicists currently hold key positions within the CUPID collaboration. Andrea Giuliani (IN2P3) serves as co-Spokesman, while Claudia Nones and Benjamin Schmidt (CEA/IRFU) are members of the Executive Board, with Benjamin Schmidt also chairing the Physics Board. Several French researchers lead critical working packages, including those related to light detectors, at the L2 and L3 levels.[4] This reflects the technical and scientific excellence of French institutions and underscores the value of their continued active involvement. A reduction in support could naturally limit the visibility and influence that France currently maintains in the collaboration.

For these reasons, strong support from IN2P3 and CEA/IRFU is both a natural and mutually beneficial decision, for the success of CUPID and for advancing French scientific leadership.

Finally, the CUPID technology is highly promising and competitive. Even if French support were reduced, the experiment is likely to proceed, though potentially with delays and greater challenges. This scenario highlights the importance of maintaining active engagement to fully realize the scientific and technological potential already cultivated in France.

4. IN2P3 and CEA/IRFU responsibilities

The contributions of French institutions to the construction of CUPID will draw on a number of existing facilities, as well as new facilities that are already funded or in production. These include:

- Two fully equipped above-ground dilution refrigerators (one at IJCLab and the other at CEA/IRFU).
- Two underground dilution refrigerators (one at LSC, managed by IJCLab within CROSS, and the other at LSM, managed by CEA/IRFU within BINGO), both fully operational for the study of macro-bolometers.
- A set of film-coating machines – based on electron-beam evaporation, thermal evaporation, and sputtering –

[4] In DOE Work Breakdown Structure terminology: L2 = major subsystems; L3 = detailed components or tasks (**Figure 18**).

installed under clean-room conditions at IJCLab for the production of light detectors. This includes CRYOVAP, a shared IJCLab/IRFU large evaporator for light-detector production.

- Two clean rooms (one at IJCLab and one at CEA/IRFU), fully equipped for the assembly of bolometers.

Details of the specific responsibilities of the French groups are provided below.

Production and characterization of the light detectors

Light detectors represent the most technologically advanced elements of CUPID modules [9]. They play a crucial role in background suppression, enabling the rejection of both α events and pile-up events at the required level. The development of light detector technology, including the implementation of the NTL mode, was led by IJCLab with significant contributions from CEA/IRFU in terms of manpower. The responsibility for light detector production for CUPID-Stage-I, and potentially for the full CUPID experiment, rests with IJCLab. A share of the production with U.S. institutions is possible, and joint work on this topic is ongoing with Berkeley and Argonne. However, given the current circumstances, we consider it safer to assign full production to France.

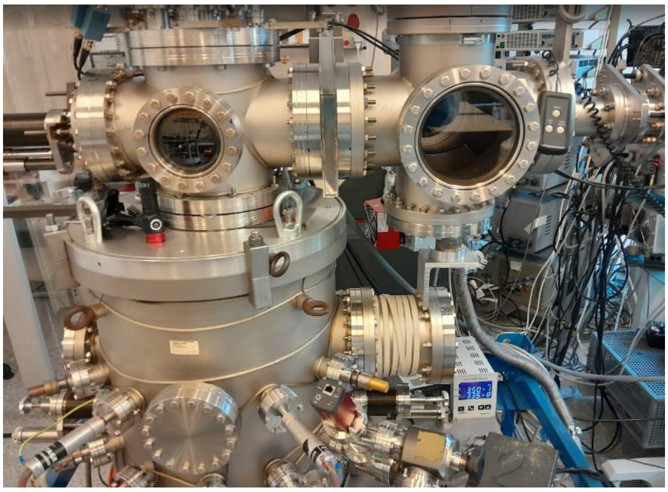

Figure 14 – Electron-beam evaporator used at IJCLab for the optimization and the pre-production of the CUPID light detectors.

Before the introduction of NTL operation, a light detector consisted of an ultrapure Ge wafer coated with a SiO anti-reflective layer and instrumented with an NTD sensor.

To enable the electric field required for NTL signal amplification, a set of Al electrodes must be deposited on the wafer. This step is non-trivial and must follow a highly controlled procedure to prevent destructive leakage currents during detector operation at low temperatures. The procedure was established at IJCLab after years of dedicated studies and optimization.

The electrode fabrication is performed with a dedicated electron-beam evaporator located in a clean room in IJCLab (see **Figure 14**). The main steps are summarized below.

- Definition of electrode patterned structures in concentric rings through shadow masks, with a typical electrode pitch of 4 mm.
- Ar-ion bombardment (to clean the surface) – Ar is ionized by electron-beam and ions are accelerated onto the wafer under 95 V.
- Formation of an amorphous 40-nm-thick layer of Ge and H (to saturate Ge dandling bonds) – Similar procedure as Ar bombardment – H-ions are accelerated again under 95 V.
- Deposition by evaporation of 100-nm thick 0.2 mm-wide Al electrodes by electron gun, according to the pattern defined by the shadow masks.
- Enhancement of electrode thickness up to 160 nm in some parts for ultrasonic bonding, necessary for the electrical contact with the rings.
- Coating of the full wafer (but the bonding zone) by a 70-nm-thick SiO antireflective layer by thermal evaporation, heating the source up to 1100 °C and upwards.

The NTL electrodes in their simplest form consist of a pattern of concentric Al rings, which are electrically connected by ultrasonic bonding with an alternate scheme, so that the same NTL voltage is applied across each couple of adjacent rings. This is the baseline structure for CUPID (see **Figure 8**).

Upgrades to the electrode structure are planned before the start of large-scale production for CUPID. The objectives are to achieve full coverage of the light-detector surface – currently, the Al rings provide an electric field over only ~75% of the wafer – and to reduce the number of bonding contacts.

For large-scale production, a new dedicated evaporator (ordered in September 2025, with commissioning foreseen by the end of 2026) will be installed in a dedicated clean room. With the existing evaporators, the production capacity is limited to ~8 detectors per week. The new system, dubbed CRYOVAP, will enable the processing and completion of tens of detectors per week.

French institutions will also be responsible for the individual characterization and validation of the light detectors.

This step is essential, as typically only about 80% of fabricated detectors achieve the required NTL amplification. While improvements in the electrode deposition procedure are expected to raise this yield, individual characterization remains mandatory. A detector may fail if the voltage applied to the electrodes cannot be increased beyond a certain threshold without generating destructive leakage currents, which heat the entire device and, in some cases, the full cryostat. To ensure correct amplification, this threshold must exceed 100 V at 4 K.

To carry out this characterization, a dedicated 4 K cryostat is being developed at IJCLab. Based on a pulse tube, it will allow semi-automatic characterization of 50 light detectors per cryogenic run. Both the cryostat and the characterization system are under development and are expected to be operational by mid-2026. We have demonstrated that a detector showing no significant leakage currents at 4 K at voltages high enough to establish the requested gain will maintain this property at 15–20 mK, the operating temperature in CUPID.

The light detectors are housed in a dedicated Cu frame (**Figure 8**). The French institutions are responsible for gluing the sensors onto the wafer (see next subsection) and mounting it on the frame, including cleaning the frame's surface in collaboration with INFN.

Detector assembly: sensor gluing station

The gluing station developed by CEA/IRFU enables the attachment of sensors (NTDs and heaters) to Li_2MoO_4 crystals and to Ge light-detector wafers. The specific requirements are: less than 10% variation in glue quantity, >99.9% success rate, no exposure to air, and batch processing capability of O(100 sensors/week). The station design not only meets but surpasses these requirements through robotic operation, a custom glove box, and in-situ quality assurance with a metrological camera.

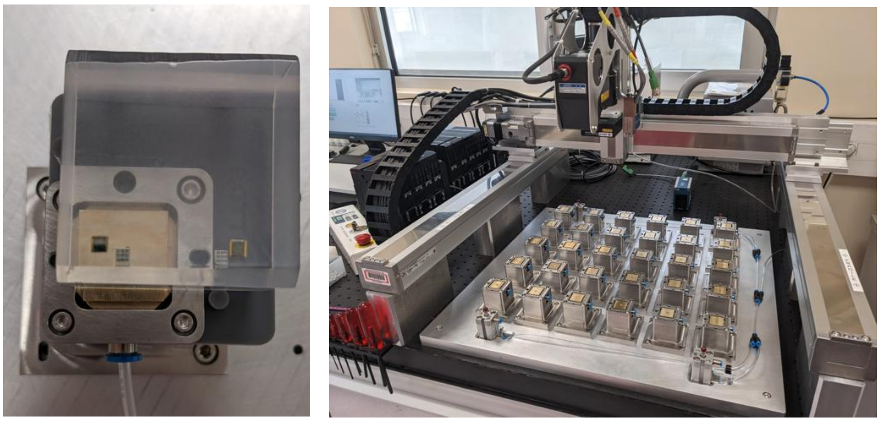

Figure 15 – Commissioning of the gluing station of the CUPID detector assembly line at CEA/IRFU. Left: Single vacuum suction module with sensor attached to a Li_2MoO_4 crystal. Right: Complete picture of the working area of the dispensing robot for batch processing during CUPID assembly.

The design of the gluing station and the definition of the procedures are at an advanced stage, allowing the simultaneous processing of batches of up to 30 detectors. **Figure 15** shows the station layout. It consists of a working area with 30 vacuum suction modules for sensor placement, a robotic XYZ motion dispensing and metrology system, and an electrically actuated aluminum absorber holder that lowers the detectors onto the sensors for final attachment. A zoomed view of a single vacuum suction module after sensor attachment to a Li_2MoO_4 crystal is shown on the left.

A preliminary procedure for sensor gluing onto Li_2MoO_4 has been established through a series of iterative tests, including cryogenic calorimetric operation of detectors:

- Placement of the sensor in the brass recess at the center of a vacuum suction module, with adjustment of the inner brass piece to control the sensor–absorber distance to within 10 μm.
- Robotic dispensing of an array of glue dots (120 μg of Permabond UV 620 for a 3×3 mm NTD) on each sensor, followed by high-quality metrological imaging with a custom on-line image recognition program to verify glue placement and quantity.
- Placement of absorbers on a positioning plate and lowering onto the sensors with electric actuators.
- Curing of the UV-activated glue with an automated UV-LED lamp system (4 minutes).

Dispensing speeds, XYZ motion parameters, and delays have been tuned and validated at room temperature. The system surpasses repeatability requirements, typically achieving dispensing repeatability at the 1 μg level. After successful cryogenic tests, the procedure was adopted for the gluing of the prototype CUPID tower test and most of the CROSS demonstrator (a large array of 36 Li_2MoO_4 crystals developed within CROSS), enabling large-scale validation and further refinement. Current efforts focus on defining a similar procedure for sensor gluing on the light detectors (1/3 size, Ge-NTD on Ge, requiring dielectric break). Following successful room-temperature tests, the first cryogenic tests are expected in the coming months of 2025.

In parallel, work is nearing completion on the fluid handling system for the full CUPID assembly chain.

Preliminary tests on a dummy glove box indicate that the design can meet specifications of <8% humidity and <0.5% oxygen. CEA is finalizing the CAD design of the glove box for the gluing station. Based on current lead times, delivery and integration of the glove box at CEA is expected in 2026, enabling final optimization of procedures that same year.

Development of electronics for the injection of stable pulses into the heaters

In collaboration with the University of Milano–Bicocca, CEA-IRFU has developed an electronic board for the calibration of detectors across all towers. The board injects highly precise pulses with customizable shapes (square, sinusoidal, pseudo-Gaussian), amplitudes, and durations. When connected to a heater, it controls the power dissipated through the Joule effect and emulates a "fake" pulse in the detector.

The system supports up to four channels, each capable of driving approximately 1 kΩ (corresponding to 100 heaters in parallel), with 16-bit resolution for 40 mV of excursion (precision mode) or 10 V (default mode). It offers two operating modes: a precision mode with a 40 mV range and a default mode with a 10 V range.

A prototype board (**Figure 16**) and its backplane have been manufactured, and firmware, software, and testing are currently in progress. The prototype will eventually be produced in 65 units, with one pulser per tower, enabling calibration control at the quarter-tower level.

Figure 16 – Prototype of the pulser board.

Preparation of the storage and transport system for the detector towers

ICJLab is developing dedicated systems for the storage and transport of the CUPID detector towers.

The storage modules (**Figure 17, Left**) are intended for the preservation of individual detector towers prior to installation. To prevent contamination, each module will operate under reduced-radon conditions through continuous nitrogen flushing. The storage system has been designed at IJCLab, and an initial order for 20 modules is schedule to be placed before the end of 2025 for CUPID-Stage-I.

The transport module will ensure the safe transfer of fully assembled towers, contained in their storage module, from the LNGS surface facilities to the underground experimental hall (**Figure 17, Centre and Right**). The design incorporates a dedicated damping system to minimize mechanical stress during handling and transportation. The module is being constructed at IJCLab and will subsequently be delivered to LNGS.

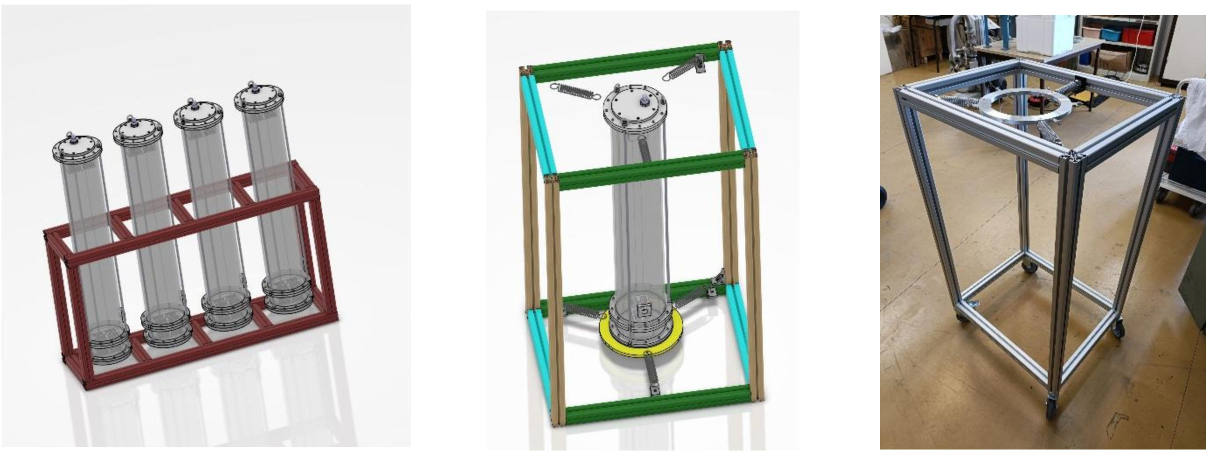

Figure 17 – Left: design off the storage modules. Centre: design of the transport module. Right: prototype of the transport module fabricated at IJCLab.

NTD characterization

The production of NTD sensors falls under the responsibility of the American institutions. After fabrication, the NTDs must be characterized in terms of their resistance–temperature behavior down to 20 mK. This is a delicate process that requires careful cross-checks, and is therefore shared among the three main countries involved in CUPID. The French groups will also contribute, with characterization runs planned at IJCLab, CEA/IRFU, and IP2I-Lyon.

Radiopurity measurements

The radiopurity requirements for CUPID, though demanding, are well within the capabilities developed by the low-background community over the last two decades. To reach the near-zero background goal, strict material screening, handling, and storage protocols are indispensable. France and Italy lead the "Background Control" working group, building on the successful strategy demonstrated in CUORE.

CUPID will introduce several new detector materials: 450 kg of Li_2MoO_4 scintillating bolometers, 102 kg of copper for frames and towers, 10 kg of Ge light detectors, 9 kg of PTFE components, and small parts (<1 kg) including CuPEN cables, thermal sensors, heaters, epoxy, and gold wire. Background studies set requirements of about 10 µBq/kg for copper bulk and ~10 nBq/cm² for copper surfaces. These are addressed with complementary screening techniques: HPGe γ-ray spectroscopy, Neutron Activation Analysis, ICP-MS, α spectroscopy for surfaces, and bolometric screening through CUPID Crystal Validation Runs.

In France we conduct screening campaigns with ultra-low-radioactivity HPGe detectors installed in LSM and we are planning to carry out surface contamination measurements with a XIA-UltraLo-800 commercial alpha spectrometer.

CUPID Crystal Validation Runs (CCVRs)

During the enriched crystal production for CUPID, the Li_2MoO_4 crystals will be systematically tested through a series of CUPID Crystal Validation Runs (CCVRs). In each run, a representative sample of crystals from a new production batch will be cooled to millikelvin temperatures in dedicated cryostats to verify their bolometric performance, radiopurity, and scintillation properties.

The tests will focus on measuring the energy resolution, the levels of bulk and surface radioactive contamination, and the light yield, since all of these parameters are crucial for the background rejection capabilities of the experiment. Crystals will be equipped with NTD thermistors and coupled to light detectors, with performance monitored using reference peaks from both α and γ emissions. The CCVRs are expected to demonstrate resolutions of a few keV and to validate the scintillation response needed for particle identification.

The primary site for these tests will be LNGS, although the possible use of the LSC facility of CROSS is under discussion. The French groups will contribute on-site manpower for detector preparation, cryostat installation, and the start of measurements, and they will also participate in data taking and analysis.

Shifts for the CUORE cryostat upgrade, the test run and CUPID data-taking

An intense activity is planned at LNGS before the start of CUPID-Stage-I. This will include support for the CUORE cryostat upgrade in preparation for CUPID, contributions to the assembly of prototype CUPID towers to be operated prior to the full experiment, and shifts related both to these tower measurements and to tests of the CUORE crystals after the first cryostat upgrade. These operations will require on-site manpower, to be provided jointly by the three main CUPID countries, and will therefore also involve the French groups.

Alternative heater production

For long-term operation of bolometric detectors, it is crucial to stabilize the sensor response against unavoidable temperature fluctuations in the cryogenic setup. This is achieved with stable resistors thermally coupled to the absorber, which receive a fixed energy input from a signal generator. The resulting signals serve as references to correct response variations. Robust and reproducible resistors ("heaters") are therefore required, with additional constraints such as radiopurity, stability, low heat capacity, and small size. Typical resistance values at low temperature range from 10 kΩ to 10 MΩ. The baseline solution for heaters consists of Si chips with meanders doped by ion implantation (as used in CUORE). As a risk-mitigation option, an alternative technique is being developed for CUPID in France at CEA/IRFU. One advantage of this approach is that it does not require pre-characterization at low temperatures.

In this alternative solution, heaters are produced from normal metal films shaped into long, thin meanders on insulating substrates with low heat capacity. The chosen technology is optical (UV) lithography on silicon wafers, followed by evaporation of Ti–Pd films at the CEA SPEC Nanofabrication Facility. A thin Ti layer ensures adhesion, while Pd provides the desired resistance; typical thicknesses are 5 nm Ti and 20 nm Pd. Aluminium is subsequently deposited on bonding pads, and the wafer is diced into 100–150 heater elements. Continuity and resistance are checked at room temperature, which reliably predicts performance at cryogenic temperatures, apart from a factor of two reduction in resistance at ~15 mK due to the Ti content. The final resistance can be tuned by adjusting the meander geometry.

The French groups will be involved in heater characterization, regardless of the technique ultimately chosen by the collaboration.

Structure of the collaboration and formal roles of the French members

The CUPID collaboration consists of approximately 180 members spread across seven countries: Italy, the United States, France, China, Ukraine, Russia, and Spain. The majority of participants come from three countries: Italy, the United States, and France.

The organization of the collaboration contemplates several boards:

- The CUPID Executive Board (EB) provides the overall scientific leadership and oversees the strategic directions of the experiment. It consists of the two Spokespersons (see below) and representative members for each country. Andrea Giuliani (ICJLab), Claudia Nones (CEA/IRFU) and Benjamin Schmidt (CEA/IRFU) are members of the EB.
- The two co-Spokespersons are the Host Country Spokesperson from Italy and an International Spokesperson from a non-Italian institution. The two co-Spokespersons chair the EB. Currently, the International Spokesperson is Andrea Giuliani (IJCLab).
- The Technical Coordinator (TC) is appointed by the EB to be responsible for the overall management of the project during the construction phase.
- The Technical Coordination Board (TCB) co-operates with the TC in the coordination of all the activities of the CUPID construction.
- The Institutional Board consists of one representative from each Collaborating or Associate Institution, and includes Andrea Giuliani (IJCLab), Claudia Nones (CEA/IRFU), Jules Gascon (IP2I) and Matias Velazquez (SIMaP) for France.
- We have in addition the Physics Board – chaired by Benjamin Schmidt (CEA/IRFU), the Publication Board, chaired by Denys Poda (IJCLab), the Vetting Board, with the participation of Hawraa Khalife (CEA/IRFU), and the Speaker Board, with the participation of Pia Loaiza, who is also the Background Model Coordinator.

The CUPID construction activities are organized in 6 major systems, coordinated by L2 managers. These systems are in turn divided into subsystems coordinated by L3 managers. Each subsystem covers various activities/deliverables that in most cases are intended to become the responsibility of a single country that will provide the resources necessary for its implementation/production/construction in terms of materials, supplies, equipment, and labour.

Systems and subsystems constitute the Work Breakdown Structure (WBS) for project construction. At present, we are providing in **Figure 18** a WBS diagram. An updated version is under discussion to include recent changes. French managers are indicated in red, Italian in green and U.S. in blue.

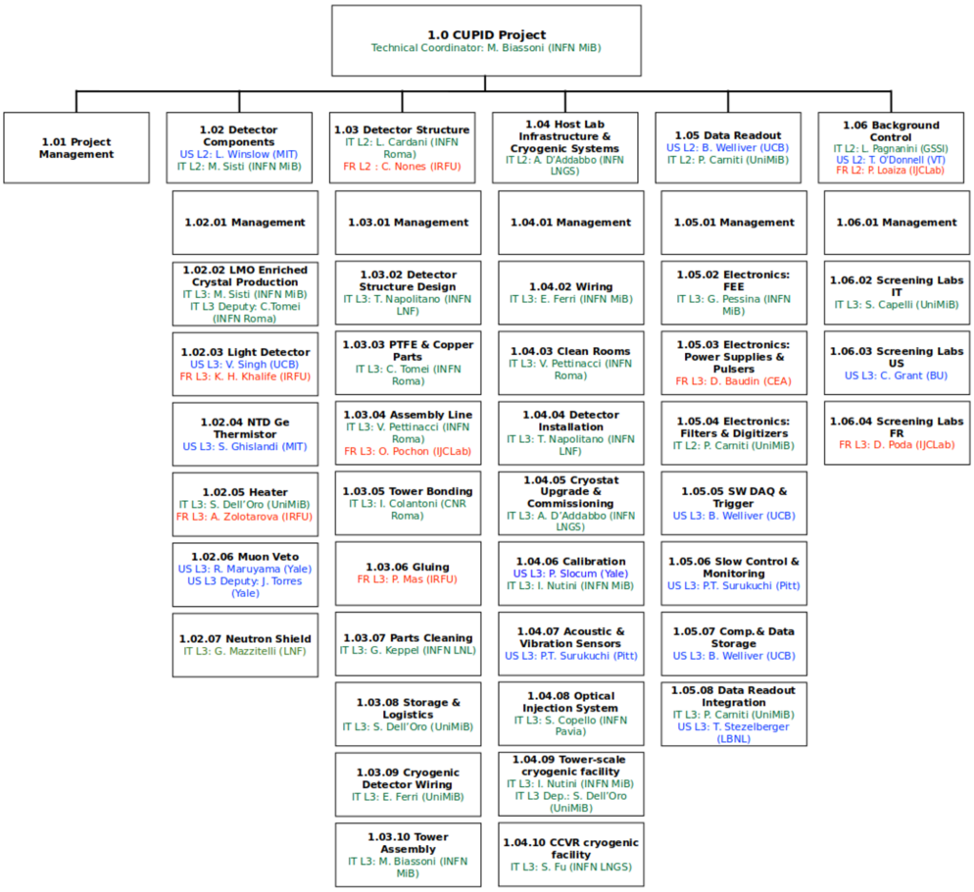

Figure 18 – CUPID Work Breakdown Structure

5. Resources and means

Cost of the experiment (Stage-I and full CUPID)

The cost of CUPID, according the most recent estimations and broken down by stage and by country, is shown in **Figure 19**.

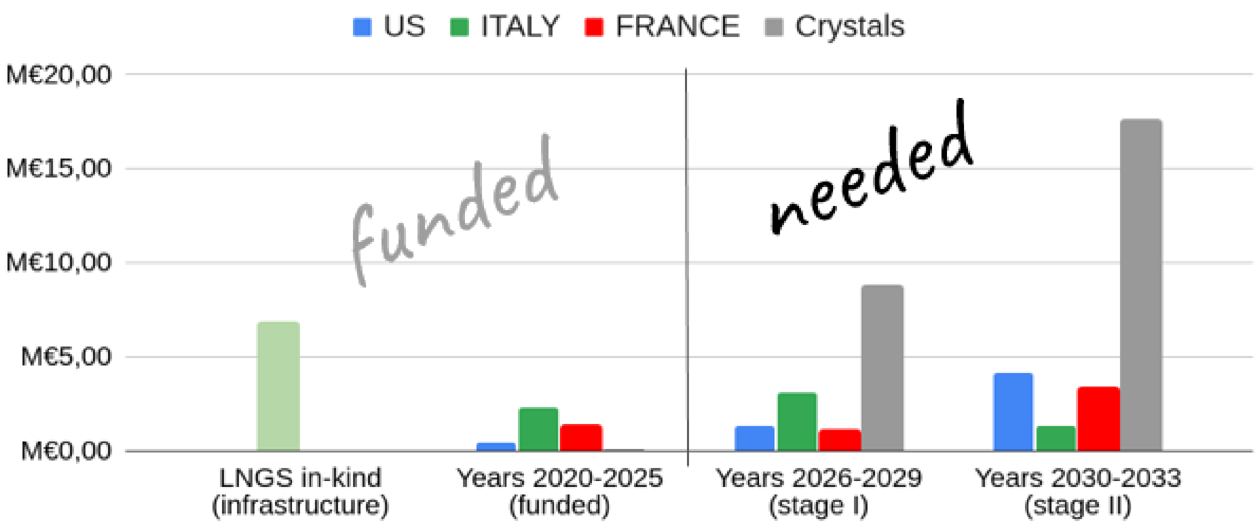

Figure 19 – CUPID costs

We note that the largest share of the cost (grey bands) arises from the enriched Li_2MoO_4 crystals, with enrichment being the dominant expense. In the scheme shown in **Figure 19**, this cost is not attributed to any particular country. The French responsibilities have been detailed in **Section 4**. The related costs are in red, and will be discussed in details in the next subsection. The Italian responsibilities (costs in green) include the assembly line (excluding gluing), clean rooms, copper and PTFE procurement and cleaning, cryostat and facility upgrades, baseline heater production, neutron shielding, and the front-end electronics, filters, and digitizers. The U.S. responsibilities (costs in blue) involve NTD production, the muon veto system, slow control, computing and data storage, and – still to be defined – the possible production of half of the light detectors.

We will now address the costs associated with the implementation of CUPID-Stage-I, which are also the subject of a Memorandum of Understanding (MoU) presently under negotiation among INFN, IN2P3, and CEA/IRFU.

The cost of the enriched crystals is estimated at approximately 9 M€. **INFN is prepared to undertake the procurement of enriched crystals for Stage-I**, with the objective of concluding a contract with SICCAS by mid-2026, thereby ensuring adherence to the schedule presented in **Figure 10**. **This initiative would be substantially reinforced if the French institutions could commit to covering between 10–20% of this cost**, either through immediate support or retrospectively over the coming years.

Financial resources in France (already provided or available)

The French activities in CUPID have been supported since the official formation of the collaboration in 2019, through direct funding from IN2P3 (from 2021) and CEA/IRFU (DPhP), which has continuously supported CUPID and its preparatory phase since 2016.

In addition, CUPID has benefited, and will continue to benefit, from several related projects. These include the ANR projects CUPID-1 (2021–2026) and CryoLux (2025–2028), a P2IO Labex flagship project on neutrino physics dubbed BSM-nu (2020-2024) which contributed to CUPID-Mo and CUPID, the ERC Advanced Grant CROSS (2018–2025, led by IJCLab), the ERC Consolidator Grant BINGO (2020–2026, led by CEA/IRFU), and the ERC Starting Grant TINY (2023–2028, led by CEA/IRFU). This funding is detailed in **Table IV**. For the ERC projects, the table reports not the full grant amounts but a reasonable estimate of the portions that have supported, or are supporting, specific CUPID elements. While the ANR projects CUPID-1 and CryoLux are entirely dedicated to CUPID – the former focused on assembly, electronics and low-radioactivity techniques, the latter on light detectors – the ERC projects have their own objectives but still contribute significantly. CROSS plays a major role in light detector development, in the procurement and validation of enriched crystals and in developing electronics prototypes. BINGO contributes to light detectors as well as to the gluing station. TINY provides access to an above-ground dilution refrigerator for NTD characterization and the other tests related to CUPID.

<table>
<tr><th colspan="3" rowspan="2">Funding Source</th><th colspan="3">Beneficiary laboratory</th><th rowspan="2">Supported items</th></tr>
<tr><th>IJCLab</th><th>CEA/IRFU</th><th>Others</th></tr>
<tr><td colspan="3">AP IN2P3 (2021-2025)</td><td>232 000</td><td></td><td>26 000</td><td>Development and operation costs</td></tr>
<tr><td colspan="3">CEA/IRFU DPhP (2019-2025)</td><td></td><td>420 000</td><td></td><td>Development and operation costs</td></tr>
<tr><td colspan="3">ANR CUPID-1 (2021-2026)</td><td>258 000</td><td>219 654</td><td>50 960</td><td>Storage and transportation of towers
Electronics
Radioactivity measurements
Development and operation costs
Temporary staff</td></tr>
<tr><td colspan="3">ANR CyoLux (2025-2028)</td><td>363 805</td><td></td><td></td><td>Light detectors
4K facility for leakage-current tests
Development and operation costs
Temporary staff</td></tr>
<tr><td colspan="3">ANR – P2IO Labex flagship project BSM-nu (2020-2024)</td><td>90 000</td><td>180 000</td><td></td><td>Support to CUPID-Mo in final phase of data taking (2020)
Temporary staff</td></tr>
<tr><td rowspan="4">CRYOVAP (2025)</td><td>Île-de-France</td><td>380 000</td><td rowspan="4">600 000</td><td rowspan="4"></td><td rowspan="4"></td><td rowspan="4">Evaporation chamber for large-scale light-detector production</td></tr>
<tr><td>IJCLab direction</td><td>90 000</td></tr>
<tr><td>CEA/IRFU DPhP</td><td>80 000</td></tr>
<tr><td>ANR CUPID-1</td><td>50 000</td></tr>
<tr><td colspan="3">ERC AdG CROSS (2018-2025)</td><td>550 000</td><td></td><td></td><td>Enriched crystals
Electronics prototypes
Light detectors</td></tr>
<tr><td colspan="3">ERC CoG BINGO (2020-2026)</td><td></td><td>150 000</td><td></td><td>Gluing station
Light detectors
Enriched material</td></tr>
<tr><td colspan="3">ERC StG TINY (2023-2028)</td><td></td><td>50 000</td><td></td><td>Cryostat access and related costs</td></tr>
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<tr><td colspan="3">Funding from ANR</td><td colspan="4">1 212 419</td></tr>
<tr><td colspan="3">Funding from EC (ERC)</td><td colspan="4">750 000</td></tr>
<tr><td colspan="3">Funding from Île-de-France region</td><td colspan="4">380 000</td></tr>
<tr><td colspan="3">GRAND TOTAL</td><td colspan="4">3 190 419</td></tr>
</table>

Table IV – Financial support for CUPID from France and France-led European projects (2019-present) – all amounts are given in €.

Another important contribution came from the Île-de-France region (CRYOVAP project within SESAME, a funding program that supports research laboratories in the region), completed by IJCLab and CEA/IRFU funds, which enabled the purchase of a large evaporation chamber for large-scale production of CUPID light detectors.

Requested resources in France for CUPID-Stage-I

Funding needed to complete the French scope is detailed in **Table V**, broken down by institution and year.

The cost of the light detectors is shared between IN2P3 and CEA/IRFU and consists of the Ge wafers, their handling – particularly cutting – miscellaneous expenses related to electrode deposition, as the facilities for evaporation and 4 K characterization have already been secured. A significant additional cost is the cleaning of the Cu frames prior to light-detector assembly. This task will be carried out at the INFN Legnaro Laboratory (LNL) using chemical products supplied by the French institutions. We note that LNL will also clean all the other components of the CUPID towers, as this falls within the Italian scope, while the French contribution is limited to the light-detector frames. The breakdown of the light-detector cost (by institution and by year) is given in **Table VI**. This cost could be reduced by half if U.S. groups obtained funding to share light-detector production. A technology transfer for light-detector production from IJCLab to the U.S. groups at Berkeley and Argonne has already been successfully completed.

The gluing station can be completed and, in particular, upgraded for NTD light-detector gluing with an additional funding of 50 000 €. The electronics costs cover the production of pulser boards and the associated power supplies, while storage and transportation costs are linked to the construction of 20 storage modules. NTD characterization, heater production, and radioactivity measurements imply essentially consumables and service costs. The cost for shifts accounts for the continuous presence of at least one representative from French institutions at LNGS, corresponding to approximately 60 person-weeks per year in 2027 and 2028, 80 person-weeks in 2029 (the year dedicated to assembly), and 40 person-weeks in 2030 (CUPID-Stage-I data taking). Common funds are foreseen starting in 2027 and are calculated at 1 500 € per CUPID author, in accordance with a preliminary agreement within the collaboration.

	2027		2028		2029		2030	
	IN2P3	CEA/IRFU	IN2P3	CEA/IRFU	IN2P3	CEA/IRFU	IN2P3	CEA/IRFU
Light detectors	135 000	110 000	135 000	110 000				
Gluing station		25 000		25 000				
Pulser electronics		36 000		36 000				
Tower storage and transport	11 000		11 000					
NTD characterization	5 000	5 000						
Radiopurity measurements	10 000		10 000					
Alternative heater production		7 000		7 000				
Shifts for crystal validation run	15 000	15 000	15 000	15 000	10 000	10 000		
Shifts for test runs, assembly and CUPID Stage-I	15 000	15 000	15 000	15 000	30 000	30 000	20 000	20 000
Common funds	22 500	15 000	22 500	15 000	22 500	15 000	22 500	15 000
TOTAL	**213 500**	**228 000**	**208 500**	**223 000**	**62 500**	**55 000**	**42 500**	**35 000**
TOTAL IN2P3 (2027-2030)	**527 000**							
TOTAL CEA/IRFU (2027-2030)	**541 000**							

Table V – Requested financial resources for CUPID-Stage-I – all amounts are given in €.

	2027		2028	
	IN2P3	CEA/IRFU	IN2P3	CEA/IRFU
Raw Ge wafers	60 000	60 000	60 000	60 000
Ge wafer cutting	20 000		20 000	
Miscellaneous evaporations	5 000		5 000	
Cu frame cleaning (chemical products)	50 000	50000	50 000	50000
TOTAL	**135 000**	**110 000**	**135 000**	**110 000**

Table VI – Cost of light detector production – all amounts are given in €.

The resources required to realize the full CUPID experiment will not be discussed in detail here but are illustrated in **Figure 19**. They represent a **scaling up of the commitments made for Stage-I**. France is expected to complete the light-detector production, upgrade the transport and storage system, and extend the production of the pulser cards. The gluing station should remain reusable as is. Regarding the enriched material, a cost-sharing arrangement among the three main countries is envisaged, and a **second MoU will of course be required**.

We conclude this subsection with a simplified table (**Table VII**) summarizing French investments and requests for CUPID-Stage-I. The key message is that an effort considerably smaller than past investments would position France as a leader in the international search for $0\nu2\beta$.

Investment for the development of the technology	2012-2018	~1.4 M€
Investment for R&D finalization and development of facilities for the construction	2019-2025	~3.2 M€
Requested funding to fulfil France's construction commitments	2026-2030	~1.1 M€
Possible French contribution to enrichment and crystallization (10% – 20%)	2026-2029	~1 – 2 M€

Table VII – Simplified summary of French investments and requests for CUPID-Stage-I

We note that the cost reported in the last line of **Table VII** is not intended to cover construction expenses within the French scope. It depends primarily on agreements between the agencies, rather than on the needs of the French institutions to fulfil their commitments.

Human resources in France: status and requests

Table VIII summarises the current situation in terms of human resources. In addition to the CEA/IRFU group, two IN2P3 laboratories (IJCLab-Orsay and IP2I-Lyon) are currently participating in CUPID, while a third (LP2i-Bordeaux) will join in 2026 with two researchers. Bordeaux's initial commitment will be limited, as the group is still heavily involved in the SuperNEMO demonstrator, but a major scaling-up is expected from 2027-2028, contributing to simulations and tests of light-collection efficiency, low-radioactivity measurements, and radon control.[5] A group in SIMaP-Grenoble led by Matias Velazquez (mentioned above with reference to the CLYMENE project and historically active since LUMINEU) participates with a specific expertise on crystal growth; it is not reported in **Table VII**.

The contributions of PhD students and postdocs are essential. Students and their theses have already been discussed at the end of **Section 3**. Regarding postdocs, we hosted four fellows at IJCLab between 2016 and 2024, for a total of 11 years (funded by IN2P3, ANR CUPID-1, ERC CROSS, and the P2IO project BSM-nu), and three fellows at CEA/IRFU between 2012 and 2025, for a total of 9 years (funded by ERC BINGO, the P2IO project BSM-nu, and ERC TINY). Although these fellows were not exclusively dedicated to CUPID, as they were also involved in projects with specific objectives, their contributions to the experiment have been essential.

To fully meet our French commitments, **additional team support would be highly beneficial**, especially considering upcoming departures, retirements, and the end of fixed-term contracts.

Specifically, it would be valuable to have:

- **One CR position (*chargé de recherche*) at IJCLab** to support data analysis, simulations, and provide onsite manpower. We note that the researchers' group at IJCLab has a critical age profile: of its four members, the youngest is 54 years old and the others are all over 60, with no new recruitment since 2011.
- **One IR position (*ingénieur de recherche*) at LP2i** to assist the Bordeaux group during its transition to CUPID activities.[5]
- **One engineer position at CEA/IRFU** to handle the group's numerous technical responsibilities.
- **One temporary AI position (*assistant ingénieur*) (2027-2028) at IJCLab** to support large-scale light-detector production.

Ensuring the simultaneous presence of PhD students and/or postdocs at both IJCLab and CEA/IRFU is also crucial. Furthermore, providing the Bordeaux group with either a PhD student or a postdoc will be essential to help the laboratory strengthen its involvement in CUPID activities.

IJCLab-Orsay	**IP2I-Lyon**	**LP2i-Bordeaux**	**CEA/IRFU-Saclay**
Researchers	**Researchers**	**Researchers**	**Researchers and Engineers**
Andrea Giuliani (0.8)	Jules Gascon (0.1)	Christine Marquet	Claudia Nones (0.5)
Pierre de Marcillac (0.3)	Antoine Armatol (0.1)	Emmanuel Chauveau	Benjamin Schmidt (0.5)
Stefanos Marnieros (0.2)	Corinne Augier (0.1)		Anastasiia Zolotarova (0.2)
Jean-Antoine Scarpaci (0.7)	Antoine Cazes (0.1)		Federico Ferri (0.1)
→ FTE Researchers: 2.0	→ FTE Researchers: 0.4		David Baudin (0.2)
IR (Ingénieurs Recherche)	**IR (Ingénieurs Recherche)**		Philippe Mas (0.2)
Ion Cojocari (0.5)	Alexandre Juillard (0.1)		Philippe Gras (0.1)
Pia Loaiza (0.9)	→ FTE Ingénieurs: 0.1		→ FTE: 1,8
Emiliano Olivieri (0.8)			
Denys Poda (0.8)			
Philippe Rosier (0.05)			
IE (Ingénieur d'Etudes)			
Laurent Bergé (0.2)			
AI (Assistant Ingénieur)			
Olivier Pochon (0.3)			
→ FTE Ingénieurs: 3.05			
Total permanent researchers and engineers: 24			
Total FTE: 7.35			

Table VIII – Permanent staff involved in CUPID (the fraction of time each member devotes to the project is indicated in parentheses, except for LP2i, whose participation is still to be precisely defined and is expected to increase substantially over time).

6. Technical achievements

The two main technical realizations entrusted to France within CUPID are (1) the **production of light detectors** and (2) the **gluing station**. In both cases, the work will be carried out internally by the CUPID groups, without subcontracting and without relying on shared facilities. The only – but crucial – request, already formulated in **Section 5**, is the **recruitment of an *Assistant Ingénieur* (AI) for two years** to support light-detector production and characterization.

[5] Conditional to approval of LP2i commitment into the project

7. SWOT analysis

Strengths

Solid foundations: CUPID builds directly on the success of CUORE, with established infrastructure at LNGS and expertise in large bolometric arrays

French technological contributions: France pioneered purification and growth of Li_2MoO_4 crystals, developed Neganov-Trofimov-Luke (NTL) light detectors, and designed key assembly/gluing systems

Proven track record: Demonstrator experiments (LUMINEU, CUPID-Mo, CROSS, etc.) validated background rejection, energy resolution, and material purity

International recognition: CUPID is consistently listed alongside LEGEND and nEXO as a top next-generation neutrinoless double beta decay experiment

Leadership positions: French researchers hold prominent collaboration roles in CUPID (co-Spokesperson, Physics Board chair, Executive Board membership, WP leads)

Weaknesses

Human resources: Aging permanent staff at IJCLab (no hires since 2011, all >54 years old in the CUPID researchers' group in this laboratory) create a sustainability risk

Staffing gaps: Need for reinforcements (CR at IJCLab, IR at LP2i, engineer at CEA/IRFU, temporary AI for detector production at IJCLab), as the current FTE count is insufficient for the construction of CUPID Stage-I.

High dependence on enrichment: The largest cost (~9 M€ for Stage-I) is dominated by isotope enrichment, with limited alternatives

Complex coordination: Large, international collaboration requires strong project management and synchronized commitments from INFN, IN2P3, CEA/IRFU, DOE, etc.

Opportunities

Scientific breakthrough: CUPID could be the first experiment in the 2030s to explore the inverted hierarchy region fully, with high discovery potential for $0\nu2\beta$, and even CUPID Stage-I, starting in 2030 with one third of the final mass, will already surpass all current experiments and achieve world-leading sensitivity

French visibility: Continued investment secures France's role as a global leader in bolometric technology and neutrino physics

Synergies: Links to other communities (detector R&D, material science at SIMaP Grenoble, quantum sensors, cryogenics) may foster cross-disciplinary advances

Technology transfer: Light detector know-how already transferred to U.S. groups, opening opportunities for shared responsibilities and cost reduction

Ton-scale expansion: CUPID can be regarded as a crucial step toward a future ton-scale experiment (CUPID-1T), developed in convergence with other collaborations (e.g. AMoRE) and designed to deeply probe the normal hierarchy region of neutrino masses

Valorisation of Modane (LSM): Since LNGS is not deep enough for CUPID-1T or a similar experiment, hosting it at LSM within 10 - 15 years would represent a major opportunity for the laboratory

Threats

Funding uncertainty: Without immediate funding (notably for enrichment and personnel), CUPID-Stage-I risks delays, losing its timing advantage over LEGEND and nEXO

International competition: LEGEND-1000 (^{76}Ge) and nEXO (^{136}Xe) are strong competitors with alternative technologies

Supply chain risks: Initial reliance on a Russian partner for enrichment and crystallization slowed progress on the experiment, and shifting to a Chinese partner could likewise introduce geopolitical and logistical vulnerabilities

Staff turnover: Retirement of key experts without timely recruitment may erode technical capacity

Coordination risks: A delay by one partner (e.g. France in light detector construction, U.S. in NTD production) could impact the whole project schedule

This SWOT shows that CUPID is **scientifically mature and highly competitive**, but **urgently needs reinforcement in funding and staffing** to secure its leadership and avoid strategic delays.

Publications related to CUPID and its preparation

[1] CUPID general

- CUPID Interest Group, CUPID: CUORE (Cryogenic Underground Observatory for Rare Events) Upgrade with Particle IDentification. arXiv:1504.03599
- W.R. Armstrong et al. (The CUPID Interest Group), CUPID pre-CDR. arXiv:1907.09376
- CUPID Interest Group, R&D towards CUPID (CUORE Upgrade with Particle IDentification). arXiv:1504.03612
- K. Alfonso et al., CUPID, the Cuore upgrade with particle identification. Eur. Phys. J. C 85, 737 (2025).
- K. Alfonso et al., Sensitivity of the CUPID experiment to 0νββ decay of ^{100}Mo. arXiv:2504.14369

[2] Technology development

- J.W. Beeman et al., A next-generation neutrinoless double beta decay experiment based on $ZnMoO_4$ scintillating bolometers. Phys. Lett. B 710 (2012) 318
- J.W. Beeman et al., An Improved $ZnMoO_4$ Scintillating Bolometer for the Search for Neutrinoless Double Beta Decay of 100Mo. J. Low Temp. Phys. 167 (2012) 1021
- D.M. Chernyak et al., Optical, luminescence and thermal properties of radiopure $ZnMoO_4$ crystals used in scintillating bolometers for double beta decay search. Nucl. Instr. Meth. A 729 (2013) 856
- M. Mancuso et al., An Aboveground Pulse-Tube-Based Bolometric Test Facility for the Validation of the LUMINEU ZnMoO4 Crystals. J Low Temp. Phys. 176 (2014) 571
- A.S. Barabash et al., Enriched $Zn^{100}MoO_4$ scintillating bolometers to search for 0ν2β decay of ^{100}Mo with the LUMINEU experiment. Eur. Phys. J. C 74 (2014) 3133
- D.M. Chernyak et al., Effect of tungsten doping on $ZnMoO_4$ scintillating bolometer performance. Optical Materials 49 (2015) 67-74
- E. Armengaud et al., Development and underground test of radiopure $ZnMoO_4$ scintillating bolometers for the LUMINEU 0v2b project. JINST 10 (2015) P05007
- T.B. Bekker et al., Aboveground test of an advanced Li_2MoO_4 scintillating bolometer to search for neutrinoless double beta decay of ^{100}Mo. Astropart. Phys. 72 (2016) 38-45
- X.-F. Navick et al., Development of NTD-Ge Cryogenic Sensors in LUMINEU. J. Low Temp. Phys. 184 (2016) 292-298
- A.S. Barabash et al., First test of an enriched $^{116}CdWO_4$ scintillating bolometer for neutrinoless double-beta-decay searches. Eur. Phys. J. C 76 (2016) 487
- E. Armengaud et al., Development of ^{100}Mo-containing scintillating bolometers for a high-sensitivity neutrinoless double-beta decay search. Eur. Phys. J. C 77 (2017) 785
- D.V. Poda et al., ^{100}Mo-enriched Li_2MoO_4 scintillating bolometers for 0ν2β decay search: From LUMINEU to CUPID-0/Mo projects. AIP Conf. Proc. 1894 (2017) 020017
- F.A. Danevich et al., Growth and characterization of a $Li_2Mg_2(MoO4)_3$ scintillating bolometer. Nucl. Instr. Meth. A 889 (2018) 89-96

[3] CUPID-Mo

- E. Armengaud et al., Precise measurement of 2νββ decay of ^{100}Mo with the CUPID-Mo detection technology. Eur. Phys. J. C 80 (2020) 674
- E. Armengaud et al., The CUPID-Mo experiment for neutrinoless double-beta decay: performance and prospects. Eur. Phys. J. C 80 (2020) 44
- R. Huang et al., Pulse shape discrimination in CUPID-Mo using principal component analysis. JINST 16 (2021) P03032
- E. Armengaud et al., New Limit for Neutrinoless Double-Beta Decay of ^{100}Mo from the CUPID-Mo Experiment. Phys. Rev. Lett. 126 (2021) 181802
- C. Augier et al., Final results on the 0νββ decay half-life limit of ^{100}Mo from the CUPID-Mo experiment. Eur. Phys. J. C 82 (2022) 1033
- C. Augier et al., Measurement of the 2νββ Decay Rate and Spectral Shape of ^{100}Mo from the CUPID-Mo Experiment. Phys. Rev. Lett. 131 (2023) 162501
- C. Augier et al., The background model of the CUPID-Mo 0νββ experiment. Eur. Phys. J. C 83 (2023) 675
- C. Augier et al., New measurement of double-b decays of ^{100}Mo to excited states of ^{100}Ru with the CUPID-Mo experiment. Phys. Rev. C 107 (2023) 025503
- C. Augier et al., Searching for beyond the Standard Model physics using the improved description of ^{100}Mo decay spectral shape with CUPID-Mo. Eur. Phys. J. C 84, 925 (2024).

[4] CUPID-0

- J.W. Beeman et al., Performances of a large mass ZnSe bolometer to search for rare events. JINST 8 (2013) P05021

- D.R. Artusa et al., First array of enriched Zn82Se bolometers to search for double beta decay. Eur. Phys. J. C 76 (2016) 364
- O. Azzolini et al., CUPID-0: the first array of enriched scintillating bolometers for 0vbb decay investigations. Eur. Phys. J. C 78 (2018) 428
- O. Azzolini et al., Final Result on the Neutrinoless Double Beta Decay of 82Se with CUPID-0. Phys. Rev. Lett. 129 (2022) 111801

[5] CROSS

- I.C. Bandac et al., The $0\nu2\beta$-decay CROSS experiment: preliminary results and prospects. J. High Energ. Phys. 01 (2020) 018
- I.C. Bandac et al., Phonon-mediated crystal detectors with metallic film coating capable of rejecting alpha and beta events induced by surface radioactivity. Appl. Phys. Lett. 118 (2021) 184105
- A. Ahmine et al., Test of $^{116}CdWO_4$ and Li_2MoO_4 scintillating bolometers in the CROSS underground facility with upgraded detector suspension. JINST 18 (2023) P12004
- D.L. Helis et al., Neutrinoless Double-Beta Decay Searches with Enriched Scintillating Bolometers. J. Low Temp. Phys. 199, 467 474 (2020)
- I.C. Bandac et al., $Li_2{}^{100depl}MoO_4$ Scintillating Bolometers for Rare-Event Search Experiments. Sensors 23 (2023) 5465
- F.T. Avignone et al., Development of large-volume $^{130}TeO_2$ bolometers for the CROSS 2β decay search experiment. JINST 19 (2024) P09013
- D. Auguste et al., A novel mechanical design of a bolometric array for the CROSS double-beta decay experiment. JINST 19 (2024) P09014

[6] BINGO

- A. Armatol et al. BINGO innovative assembly for background reduction in bolometric $0\nu\beta\beta$ experiments. Nucl. Instr. Meth. A 1069 (2024) 169936.

[7] Purification and crystallization

- L. Berge et al., Purification of molybdenum, growth and characterization of medium volume $ZnMoO_4$ crystals for the LUMINEU program. JINST 9 (2014) P06004
- V. Grigorieva et al., Li_2MoO_4 Crystals Grown by Low-Thermal-Gradient Czochralski Technique. J. Mat. Sci. Eng. B 7 (2017) 63-70
- M. Velazquez et al., Exploratory growth in the Li_2MoO_4-MoO_3 system for the next crystal generation of heat-scintillation cryogenic bolometers. Solid State Sciences 65 (2017) 41-51
- G. Buse et al., First scintillating bolometer tests of a CLYMENE R&D on Li_2MoO_4 scintillators towards a large-scale double-beta decay experiment. Nucl. Instr. Meth. A 891 (2018) 87-91
- C. Stelian et al., Experimental and numerical investigations of the Czochralski growth of Li_2MoO_4 crystals for heat-scintillation cryogenic bolometers. J. Cryst. Growth 531, 125385 (2020)
- C. Stelian et al., Numerical modeling of Czochralski growth of Li_2MoO_4 crystals for heat-scintillation cryogenic bolometers, J. Cryst. Growth 545 (2018) 6.
- A. Ahmine et al., Conventional Czochralski growth of large Li_2MoO_4 single crystals, J. Cryst. Growth 578 (2022) 126420.

[8] CUPID experimental tests

- A. Armatol et al., Characterization of cubic $Li_2{}^{100}MoO_4$ crystals for the CUPID experiment. Eur. Phys. J. C 81 (2021) 104
- A. Armatol et al., A CUPID $Li_2{}^{100}MoO_4$ scintillating bolometer tested in the CROSS underground facility. JINST 16 (2021) P02037
- K. Alfonso et al., Optimization of the first CUPID detector module. Eur. Phys. J. C 82 (2022) 810
- K. Alfonso et al., Twelve-crystal prototype of Li_2MoO_4 scintillating bolometers for CUPID and CROSS experiments. JINST 18 (2023) P06018
- K. Alfonso et al., A gravity-based mounting approach for large-scale cryogenic calorimeter arrays. Eur. Phys. J. C 85, 935 (2025)

[9] Light detectors

- M. Tenconi et al., Bolometric light detectors for Neutrinoless Double Beta Decay search. Proc. of Science: PoS (idm2012) 072
- J.W. Beeman et al., Effect of SiO_2 coating in bolometric Ge light detectors for rare event searches. Nucl. Instr. Meth. 709 (2013) 22-28
- M. Mancuso et al., An experimental study of antireflective coatings in Ge light detectors for scintillating bolometers. EPJ Web Conf. 65 (2014) 04003

- V. Novati et al., Charge-to-heat transducers exploiting the Neganov-Trofimov-Luke effect for light detection in rare-event searches. Nucl. Instr. Meth. A 940 (2019) 320-327
- D.R. Artusa et al., Enriched TeO_2 bolometers with active particle discrimination: Towards the CUPID experiment. Phys. Lett. B 767 (2017) 321-329
- L. Berge et al., Complete event-by-event α/γ (β) separation in a full-size TeO_2 CUORE bolometer by Neganov-Luke-magnified light detection. Phys. Rev. C 97 (2018) 032501
- K. Alfonso et al., A first test of CUPID prototypal light detectors with NTD-Ge sensors in a pulse-tube cryostat. JINST 18 (2023) P06033

[10] Pileup study and rejection

- D.M. Chernyak et al., Random coincidence of 2v2b decay events as a background source in bolometric $0\nu2\beta$ decay experiments. Eur. Phys. J. C 72 (2012) 1989
- D.M. Chernyak et al., Rejection of randomly coinciding events in ZnMoO4 scintillating bolometers. Eur. Phys. J. C 74 (2014) 2913.
- D.M. Chernyak et al., Rejection of randomly coinciding events in $Li_2{}^{100}MoO_4$ scintillating bolometers using light detectors based on the Neganov-Luke effect. Eur. Phys. J C 77 (2017) 3
- Armatol et al., Novel technique for the study of pileup events in cryogenic bolometers. Physical Review C 104 (2021) 015501
- A. Ahmine et al., Enhanced light signal for the suppression of pile-up events in Mo-based bolometers for the $0\nu\beta\beta$ decay search. Eur. Phys. J. C 83 (2023) 373
- A. Armatol et al., Cryogenic light detectors with thermal signal amplification for $0\nu2\beta$ search experiments. arXiv:2507.15732

[11] CUPID-1T and next-to-next generation

- A. Giuliani, F. A. Danevich, V. I. Tretyak, A multi-isotope $0\nu\beta\beta$ bolometric experiment. Eur. Phys. J. C 78 (2018) 272
- A. Armatol et al., Toward CUPID-1T. arXiv:2203.08386