



IN2P3
Institut national de physique nucléaire
et de physique des particules



Irfu
Institut de recherche
sur les lois fondamentales
de l'Univers

REPORT

on the search for
neutrinoless double beta decay
with the CUPID project

Joint Scientific Council
of CNRS/IN2P3 and CEA/Irfu

Session of October 6-7, 2025

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Invited members

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IN2P3 management

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Irfu management

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Speakers

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1 Framework

The meeting of the Joint Scientific Council of IN2P3 and Irfu was held on 6 and 7 October 2025 at the CNRS headquarters in Paris. The purpose was to review the French contribution to the CUPID experiment searching for neutrinoless double beta decay ($0\nu\beta\beta$), and to assess their current status in terms of involvement, maturity, competitiveness, collaboration, and expected scientific return. The French teams involved in this research are both from Irfu in Saclay, and from IN2P3 laboratories in Lyon and Orsay. IN2P3 activities were already reviewed by the Scientific Council in 2018, see the [report](#).

The first day was dedicated to the presentation of the current activities and outlooks in an open session. The second day consisted of a closed session of the Scientific Council, which included discussions with the project PIs, the invited external experts, and the managements of IN2P3 and Irfu.

The study of neutrinoless double beta decay is of central importance to particle physics, as it connects to two of the most important open questions: the nature of the neutrino mass, and the origin of the matter–antimatter asymmetry. This decay has never been observed, and its detection would provide clear evidence of physics beyond the Standard Model (SM). It is intimately related to the fundamental nature of the neutrino itself, whether it is a Majorana particle, identical to its antiparticle, a question connected to the origin of neutrino mass. The observation of neutrinoless double beta decay would imply a violation of the lepton number, showing that matter can be produced without an equivalent amount of antimatter. This would provide crucial insight into the mechanism that generated the matter–antimatter asymmetry in the early universe and, more broadly, into the physics beyond the SM. The search for neutrinoless double beta decay is therefore fully in line with the recommendations of the 2020 update of the European Strategy for Particle Physics, as well as with the [IN2P3 Strategic Plan](#) for French Nuclear, Particle and Astroparticle Physics in the 2030 Horizon, and the core of the scientific research missions of Irfu for the study of the elementary constituents and fundamental symmetries in the Universe. This research fully aligns with the following Science Drivers:

- Study matter-antimatter asymmetry and flavor transitions
- Pursue searches for unknown particles and interactions
- Explore further the physics associated with the properties of neutrinos

If the neutrino is equivalent to its own anti-neutrino, it would naturally allow the neutrinoless double beta decay process. Claiming evidence of this decay requires that it can be distinguished from the SM double beta decay with two neutrinos in the final state ($2\nu\beta\beta$), which has already been observed. Experimentally, this is quite challenging. Firstly, given that the SM $2\nu\beta\beta$ process is very rare, and the hypothesised process $0\nu\beta\beta$ is expected to be even rarer, large-scale detectors are essential to achieve meaningful experimental sensitivities. Secondly, the enrichment of the isotope of interest in the crystal is mandatory for most isotopes, Mo used by CUPID is no exception due to its relatively low natural abundance. Thirdly, high $Q_{\beta\beta}$ values above the prominent ^{208}Tl 2.6 MeV line are preferred for mitigating the beta decay background from natural radioactive components of ^{232}Th and ^{238}U . Lastly, the signature relies on the specific kinematics of the two electrons in the final state, and the ability to separate the continuous electron energy spectrum of the standard decays from the signal of the neutrinoless decay, requiring an excellent energy resolution, lowest possible background, and, if possible, topological ways to identify the two electron tracks.

The international community leading the neutrinoless double beta decay search, plans to increase the experimental sensitivity over the next few years. We are now entering an exciting phase where certain experiments are starting to show potential for discovery, depending on the normal or inverted mass hierarchy. There are more than 10 different experiments in the world, focusing on various 2β emitters (such as germanium, xenon or molybdenum), and different detection technologies. New-generation projects are ambitious and expensive, as experimental requirements are becoming increasingly challenging. This research is a long term effort, that requires the optimisation of international expertise and resources.

Agenda of the session and material

Description of the activities under review, agenda, slides and recording of the oral presentations, and the report issued by the Scientific Council including recommendations, are archived publicly on the [web site](#) of the Scientific Council of IN2P3.

The agenda for the open session is available on the Indico page: <https://indico.in2p3.fr/event/36844/>.

2 Questions posed by IN2P3 and Irfu management

In recent years, the international community interested in measuring neutrinoless double beta decay has organised itself around different isotopes and detection techniques. These next-generation projects are very ambitious and expensive, and there has been a perceived need to structure and optimise international efforts, expertise and resources. To this end, the international community has mainly focused on three projects based on different double beta emitters and experimental techniques, which have since reached and demonstrated a certain degree of maturity, as well as bringing together communities from different countries: LEGEND (^{76}Ge), nEXO (^{136}Xe) and CUPID (^{100}Mo).

For more than ten years, teams from IN2P3 and Irfu have been part of the CUPID Collaboration. Irfu and IN2P3 are currently studying the possibility of establishing a more structured and planned involvement of the two institutes, through the signing of a Memorandum of Understanding (MoU) with INFN.

In this context, the managements of IN2P3 and Irfu propose in particular that the Joint Scientific Council analyses and gives its opinion on the following points:

- How competitive is Stage 1 of CUPID in the international context: expected sensitivity and potential scientific impact?
- What are the main specific features of France's involvement in the CUPID Collaboration? What is the scientific and instrumental weight that the French teams currently have within the Collaboration?
- Is the commitment (human and financial resources) of the teams to the project appropriate? Is it sufficient to achieve the objectives set out in the proposed timetable for Stage 1? Does it allow France to expect a strong scientific return?
- In the context of possible French involvement in Stage 2 of the project (to be discussed at a later date in a second MoU, should the financial resources be clearly identified), what contributions would the French teams like to make? What scientific feedback would be expected?

3 Review of the French contributions to the CUPID experiment

This section presents the Joint Scientific Council’s opinion on the questions posed by IN2P3 and Irfu managements. The recommendations are given in the conclusion of the document (see Section 4).

CUPID in the international competition

In recent years, the neutrinoless double-beta decay search community has undergone a selection process to identify the next-generation experiments to probe the inverted mass hierarchy half-life prediction, based on isotope target scalability and technological achievements to reject background. The three remaining experiments are LEGEND (^{76}Ge), CUPID (^{100}Mo) and nEXO (^{136}Xe). These experiments critically rely on isotope enrichment, which accounts for most of the costs. The next-generation experiments require funding in the range of 20–300 M€.

To develop this programme, a significant contribution from the US DOE was expected to finance part of these three experiments. In 2024 LEGEND was prioritised by DOE over CUPID and nEXO, although both still received R&D support. The nEXO Collaboration is now seeking funding in Canada, with a preferred deployment in the SNOLAB underground laboratory Cryopit. Meanwhile, CUPID will primarily source its funding in Europe, with core support from INFN. The LNGS will play a leading role in the next generation experiments by hosting CUPID Stages 1 and 2 (following CUORE) and LEGEND-1T (following GERDA and LEGEND-200).

All three experiments target a sensitivity to the half-life of $0\nu\beta\beta$ decay that will allow most of the inverted hierarchy prediction for the effective neutrino Majorana mass $m_{\beta\beta}$ to be investigated within the uncertainties of the nuclear matrix elements. To achieve this objective, CUPID (CUORE Upgrade with Particle IDentification) essentially builds on the success of CUORE. It addresses both the alpha background limitation by adding a coincidence light detector, and the beta background limitation by selecting an isotope with a higher $Q_{\beta\beta}$ value of 3.0 MeV, which is above the 2.6 MeV line of ^{208}Tl from natural radioactivity. In this respect, CUPID’s strength lies in its favourable ^{100}Mo phase space factor. This will enable the required sensitivity to be achieved with reduced exposure in terms of ton·year, and thus with a smaller financial investment with respect to the competition. CUPID also benefits from the existing CUORE infrastructure, that will be upgraded in the coming years. It includes the mK cryostat, which has the capacity to hold 1,596 bolometric crystals, and the clean room.

As a result, even when extrapolating the current LEGEND-200 data-taking performance and considering other experiment targets, such as AMoRE, SNO+, and KamLAND2-Zen, CUPID Stage 1 (80 kg of ^{100}Mo) should achieve some of the best $m_{\beta\beta}$ sensitivity after 3–4 years of operation, i.e. by 2033. Following this expected initial result, the full experiment will be assembled in Stage 2 (240 kg of ^{100}Mo) by 2034. It will then take a further ten years to reach the expected sensitivity.

French institutions involvement

The French teams currently involved in the project are from Irfu at CEA Saclay, as well as IJCLab Orsay (CNRS/IN2P3), IP2I Lyon (CNRS/IN2P3), and SIMaP Grenoble from CNRS. France contributes up to 20% of the Collaboration’s human resources, second only to

Italy and the US. Discussions are ongoing to establish also a possible contribution of LP2I Bordeaux (IN2P3), with a later increase of participation once SuperNEMO data collection has ended, expected in late 2026.

Both Irfu and IJClab have taken major responsibilities in the design of CUPID, since its inception in 2012, through the LUMINEU project based on the Li_2MoO_4 crystal technology. This culminated in the successful achievement of the CUPID-Mo demonstrator in 2021 and its results, and the selection of the Neganov-Trofimov-Luke technology for light detection.

Following a ten-year R&D period, the teams are now transitioning towards a mass production regime of the Li_2MoO_4 crystals and the light detectors. The procurement of the Russian crystals used for CUPID-Mo is currently impossible for geopolitical reasons. Therefore, the validation of the new Chinese baseline crystal supply chain, for which less experience has been gained with Li_2MoO_4 technology, is a critical milestone for CUPID in 2026. INFN has already secured the funding for the crystal procurement for CUPID Stage 1. IN2P3 and Irfu laboratories are both playing an active role in validating the Li_2MoO_4 crystal performance in terms of energy resolution and light yield at cryogenic temperatures in pulse tube cryostats. They are also participating in their assembly through the development of a robotic gluing station, and in the frame mounting.

Irfu and IN2P3 teams are currently investigating an alternative supply chain for enriched crystals. This alternative solution is fully based on French companies and laboratories, namely LUXIUM for radiopure crystal growth, ORANO for ^{100}Mo enrichment and SIMaP (Laboratoire de Science et Ingénierie des Matériaux et Procédés) in Grenoble for crystallization process R&D. This effort could help to speed up the production of cryogenic bolometers for the CUPID Stage 2 or CUPID-1T, and mitigate the risk of future delays to crystal delivery.

In parallel, the French teams are making great efforts to set up the cryogenic characterisation bench for the 1,710 light detectors at IJCLab, and to adapt the gluing station at Irfu. These facilities must be ready in time for the start of the procurement in 2027, and the installation at LNGS in 2029. The IJCLab team is expected to process dozens of detectors each week. To mitigate the risk of delays, part of this substantial contribution to the light detection system could be shared with US collaborators through technology transfer. Moreover, the LP2I Bordeaux team could make a valuable contribution to the light detection system by enhancing photon collection through their expertise in photon simulation. This simulation has not yet been performed, and it would fill a gap in the current modelling of the overall CUPID experiment.

In order to deliver the proposed hardware contributions for the construction commitments, the total requested French contribution amounts to 1.1 M€, split in half between IN2P3 and Irfu, and including 500 k€ for the light detectors. This is still under discussion to produce a MoU. The French contribution to CUPID also comprises key responsibilities in management (such a co-spokesperson as well as chair and members of the physics board) and in data analysis (background modelling, rejection techniques and software framework). This good level of responsibility builds on the experience and success of the CUPID-Mo project. Such positions will ensure a clear visibility of the French teams within the Collaboration over the next few years.

Looking forward to Stage 2 and beyond, three ERC projects are ongoing (CROSS, BINGO, and TINY), with the aim of further controlling and rejecting background in bolometric detectors for the $0\nu\beta\beta$ decay search, ensuring that CUPID remains a quasi-background-free experiment.

Comments

The CUPID Collaboration is developing a highly competitive $0\nu\beta\beta$ decay search experiment, in which France is playing a significant role. The planned contributions build on the key expertise acquired over more than ten years of R&D in crystal assembly, readout and data analysis. During this period, ten PhD students completed their theses, three of whom have since obtained permanent positions at IN2P3 and Irfu. A total of 24 permanent staff (researchers and engineers) are involved in the project, amounting to only 7.4 full-time equivalents (FTEs).

The establishment of a new baseline for the procurement of enriched crystals with the IPCE and SICCAS Chinese companies relies on the successful characterisation of the first four enriched crystals tested, in terms of energy resolution, light yield and signal-to-background discrimination power. These companies use the Bridgman method to grow crystals, rather than the previously used Czochralski method by NIIC for CUPID-Mo. These encouraging results obtained in preliminary tests will be further checked using three additional CUPID-like test crystals. However, the required radiopurity level still needs to be demonstrated in the final process before mid-2026, since current prototypes still feature significant alpha contamination on their surfaces. SICCAS is now addressing this requirement with a clear plan, building on its experience of producing CUORE crystals.

Regarding the light detection system, the CUPID Collaboration envisions a significant upgrade with respect to the CUPID-Mo demonstrator, with an enhanced light yield based on the Neganov-Trofimov-Luke effect. This upgrade aims to particularly address the $2\nu\beta\beta$ decay pile-up background. The anticipated performance must be confirmed in the CROSS and VSTT (Vertical Slice Test Tower) test benches within the next months.

Although the US DOE participation in $0\nu\beta\beta$ decay search now focuses on LEGEND, the CUPID US teams have recently secured recurrent funding for the next 5 years. This support is sufficient to keep a central role in the experiment. In particular, the US collaborators are now taking active part in the production of half of the light detectors, in parallel to the French contribution.

4 Recommendations made by the Scientific Councils of IN2P3 and Irfu

The Joint Scientific Council acknowledges the successful obtention of external ERC and ANR fundings by the French teams over the past 13 years, as well as the selection of their technological solutions by the CUPID Collaboration. This has enabled a highly competitive $0\nu\beta\beta$ decay search programme with cryogenic bolometric detectors to be carried out at a reasonable cost. The high level of expertise developed over the years by the French teams has been clearly presented and demonstrated, leading to many key positions in the Collaboration. The Joint Scientific Council of IN2P3 and Irfu makes the following recommendations.

- With the transition from the R&D phase to the mass production, a clear reinforcement is needed in both institutes, with different profiles according to their specific project involvement.
- Although the Chinese IPCE and SICCAS companies have already delivered four CUPID-like crystals with comparable performance, it is recommended that the teams closely pursue the validation of the procurement process at IJCLab and Irfu, and move forward

to carefully organise the assessment procedure of the achieved crystals radiopurity in light of the experience with previous NIIC crystals.

- The studies on the SICCAS light yield crystals should be continued towards full validation. In particular, this should be monitored in order to keep the lowest background in the region of interest through the surface event rejection.
- In addition to the budget requested for the construction commitments, the Joint Scientific Council recommends a financial participation in the crystal procurement for the CUPID Stage 1, commensurate with the current commitment and responsibilities of the French teams, along with an adequate human participation in the procurement follow-up process and the production monitoring.
- The Joint Scientific Council recommends that the teams further consolidate the fully French-based backup plan for light detector production in the event of a future shortage of US funding.
- Looking forward to the future, even if only considered for CUPID-1T, the Joint Scientific Council considers it strategic to pursue ongoing discussions aiming at developing a new French procurement chain for ^{100}Mo -enriched crystals with LUXIUM (crystal growth), ORANO (enrichment), and SIMaP (crystallisation R&D). The Council recommends pursuing this partnership closely.
- The Joint Scientific Council supports French institutions building on the expertise developed for the CROSS R&D in the OCTOPUS software framework, and recommends investing time in scaling it up and validating it for the large-scale experiment.
- Finally, it is recommended that the team closely follows the tight timescales and achieved milestone timeline throughout the project in particular in the context of the international competition with LEGEND, KamLAND2-Zen, AMoRE and nEXO.