CUPID

A next-generation double-beta-decay experiment prepared by the results and the activities of CUPID-Mo, CROSS, CUORE

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On behalf of the bolometric neutrinoless double-beta-decay community in France

Abstract

This document reports about an intense and successful R&D activity carried out in France from 2012 concerning the development of advanced bolometric detectors with a view to a next-generation neutrinoless double-beta-decay experiment, dubbed CUPID (CUORE Upgrade with Particle Identification). This activity was performed mainly in IN2P3 laboratories (CSNSM, LSM, IPNL and recently LAL), but in the context of a large international collaboration (Italy, US, France, Russia, Ukraine, China). An important contribution of CEA/IRFU is also to be signaled.

Two major objectives were accomplished. First, the technology of lithium molybdate (Li_2MO_4) scintillating bolometers – to be used to study the promising isotope ^{100}Mo – was fully developed, including purification of enriched material, crystal growth, and construction and validation of the detectors. The developed prototypes have shown an outstanding behavior in terms of energy resolution ($\Delta E_{FWHM} \sim 5$ keV in the region of interest for neutrinoless double beta decay), internal radiopurity (< 6 μBq/kg for ^{238}U, ^{232}Th and their daughters) and alpha-particle rejection factor (> 99.9%). (We remind that surface alpha radioactivity represents the dominant background component in CUORE, the largest current-generation double beta decay bolometric search that is collecting data in LNGS to investigate the isotope ^{130}Te.) On the wave of these results, a 20-element demonstrator, CUPID-Mo, containing ~2.5 kg of ^{100}Mo, has been built and is now installed in Modane (LSM) in the EDELWEISS cryostat, ready for data taking. A second demonstrator with additional ~4 kg of isotope, partially funded by the ERC CROSS, is planned to be installed in the LNGS in 2019. These two demonstrators have a remarkable sensitivity to the effective Majorana mass, comparable to that of the most sensitive current searches, and pave the way to a large-scale future project. A third demonstrator is planned in the Canfranc underground laboratory testing a new technology developed in CROSS and capable of rejecting surface events.

A second remarkable development of the French groups was the establishment of an innovative bolometric light-detector technology ensuring the full rejection of the alpha particle background in a large TeO_2 bolometer. (This compound is used, without alpha identification, in CUORE.) TeO_2 crystals are very week scintillators, and the alpha rejection was accomplished in our prototype via the detection of the feeble Cherenkov light emitted by beta events. This result keeps the ^{130}Te way open for the future of CUORE. A mid-scale demonstrator with several modules is planned in the next two years, to be installed in LSM in the EDELWEISS cryostat.

On the basis of the convincing results achieved in France, the CUORE collaboration decided in May 2018 to adopt the Li_2MoO_4 technology as a baseline for the proposed future experiment CUPID, and to keep TeO_2 as a valid mature alternative. CUPID will use the existing CUORE cryostat. The CUPID collaboration is in formation and a Conceptual Design Report is currently being finalized. The full CUPID experiment implies a large investment in enrichment and crystallization (at least ~250 kg of ^{100}Mo are necessary in the baseline version of CUPID), as for any future double-beta-decay experiment. However, CUPID is very cost-effective and has remarkable advantages with respect to competing next-generation experiments. The infrastructure already exists (the CUORE cryostat). The detector technology is fully developed thanks mainly to the work of the French groups. The available background model – taking advantage of the high Q-value of ^{100}Mo placed beyond the gamma environmental radioactivity – predicts safely a sensitivity to the effective Majorana mass in the range 7-20 meV. CUPID will cover therefore a large fraction of the Majorana-neutrino-mass parameter space, fully exploring the inverted-ordering region of neutrino masses. Intermediate-mass demonstrators are under study or development. For all these reasons, we strongly intend to contribute to build CUPID – a world-leading next-generation experiment – in the context of an international collaboration (France, Italy, US, China and others) with drive and leadership roles from France.

1. Scientific context and implications

The neutrinoless double beta decay (0ν2β) is a very rare hypothetical nuclear process, which, if observed, would demonstrate that the neutrino is the only fermion to be a Majorana particle (i.e. coinciding with its own antiparticle), fix the absolute neutrino mass scale and provide valuable information on the neutrino mass ordering. The possible Majorana nature of neutrinos is a fundamental open question in particle physics and cosmology, being related to the mass-generation mechanism, to CP violation and to the observed but unexplained prevalence of matter in the Universe. More in general, 0ν2β is a sensitive inclusive test of lepton number conservation, a symmetry of the Standard Model of particle physics that is expected to be violated in many extensions of this theory. The 0ν2β transition is described by

$$(A, Z) \rightarrow (A, Z+2) + 2e^- ,$$

which is energetically possible for 35 nuclei, among which ^{100}Mo and ^{130}Te are relevant here.

There are a plethora of hypothesized beyond-Standard-Model mechanisms that can induce 0ν2β. However, a by far prevalent interpretation exists: the so-called mass mechanism. It represents a minimal extension of the Standard Model and is strictly related to neutrino physics, and in particular to the effective Majorana mass $m_{\beta\beta}$, a crucial parameter that depends on the absolute neutrino mass scale and the Majorana CP-violating phases. In the mass mechanism, the 0ν2β rate $1/T_{1/2}^{0\nu}$ is proportional to $m_{\beta\beta}^2$. The sensitivity to $m_{\beta\beta}$ – for which we have only higher bounds so far as 0ν2β is not observed yet, with half-life limits around 10^{24}-10^{26} y – provides a sort of metric that defines the physics reach of the experiments and allows us to compare them on a non-ambiguous basis. The current upper limits on $m_{\beta\beta}$ are in the range of 100 meV. Next-generation experiments aim at pushing them down to ~10-20 meV, fully exploring the so-called inverted-ordering region of the neutrino mass pattern. These are the reference values to keep in mind for the evaluation of the competitiveness and the physics reach of a 0ν2β experiment.

2. The project

A very sensitive approach to the study of 0ν2β consists in developing a device which is source and detector of the phenomenon at the same time. In this method, the detector containing the candidate nuclides must be massive (of the order of 100-1000 kg for new generation experiments, which require at least 10^{27} nuclides). Furthermore, it must exhibit high energy resolution and low radioactive background. Energy resolution is very useful since the 0ν2β signal is a peak in the energy spectrum of the detector positioned exactly at the Q-value of the transition, due to the absorption of the two emitted electrons. This peak must be discriminated over the background and therefore it is convenient that it is narrow.

The bolometric technology is able to provide all the required features. Bolometers are low temperature detectors (operated at 10-20 mK in case of 0ν2β search) sensitive to single particle interactions. The deposited energy is measured as a temperature change (of the order of 0.1 mK/MeV) of the energy absorber, which is a single dielectric diamagnetic crystal. Arrays of detectors are required to get high sensitive masses.

High Q-values (in the range 2.5-4 MeV) are preferred in 0ν2β experiments, because they lead to a large phase space for the process and to lower background. We remind that the bulk of the environmental gamma radioactivity stops at the 2615 keV line of ^{208}Tl, belonging to the ^{232}Th radioactive chain. Ultra-pure crystals up to 100-1000 g can be grown for interesting materials, containing appealing high-Q value 0ν2β candidates (^{82}Se, ^{100}Mo, ^{116}Cd, ^{130}Te). Scintillating bolometers bring an additional value. In these devices the crystal containing the isotope of interest is a scintillator and an auxiliary bolometer is operated as a light detector close to it. The simultaneous detection of heat and scintillation light allows one to distinguish alpha particles from electrons or gammas thanks to the different light yield. The energy region above 2615 keV is dominated by energy-degraded alpha particles of surface origin (as shown by the CUORE experience). Scintillating bolometers containing a candidate with a Q-value higher than 2615 keV have therefore the potential to provide a background-free search even at tonne×year exposure. Candidates to 0ν2β that fit the high-Q-value requirement and can be embedded in scintillating crystals are ^{82}Se, ^{100}Mo and ^{116}Cd. The activity in France on scintillating bolometers has focused on ^{100}Mo, with a Q-value at 3034 keV.

Another isotope of interest is ^{130}Te. In this case the signal is expected at 2527 keV, just below the end point of the gamma radioactivity. However, even in this case the background is dominated by surface alpha contaminations, as observed by the currently running CUORE experiment. CUORE uses TeO_2 crystals and, in spite of the dominant alpha background, is one of the most sensitive 0ν2β experiments up to date [PRL 120(2018)132501]. (There is a small French participation to CUORE.) In future CUORE upgrades, one may think to reject alphas with a double-readout bolometer. Unfortunately TeO_2 scintillation light is too feeble to this purpose, but it is possible to exploit the Cherenkov radiation emitted from betas (and not from alphas) in order to reject the alpha background. With the typically achievable collection efficiencies, the total energy contained in a flash of collected Cherenkov photons produced by a beta energy deposition of ~2.5 MeV is only ~100 eV for TeO_2 crystals of the CUORE size (cubic 5×5×5 cm^3 shape), at least an order of magnitude less with respect to the scintillation case. Therefore, it is necessary to develop a bolometric light detector with outstanding performance to get a safe discrimination.

2.1 R&D on Mo-containing scintillating bolometers

The technology of Mo-containing scintillating bolometers was developed in the framework of the ANR-funded LUMINEU project (2012-2017). An important support came also from the ASPERA R&D project ISOTTA (2012-2014). LUMINEU has studied and developed devices based on zinc molybdate ($ZnMoO_4$) and lithium molybdate (Li_2MoO_4) crystals for the investigation of 0ν2β of ^{100}Mo, a promising candidate featuring high transition energy (Q-value=3034), reasonably high natural isotopic abundance (9.7%) and viable enrichment technology through centrifugation.

Tests of the LUMINEU detectors are ongoing since 2013 in the cryogenic laboratory of CSNSM (Orsay, France), at LSM (France) and LNGS (Italy). This activity has allowed us to reach remarkable results – listed below – that show the maturity of the LUMINEU technology [EPJC 77(2017)785].

- We have developed a purification-crystallization protocol for the production of high quality crystals (both $ZnMoO_4$ and Li_2MoO_4) implying low irrecoverable losses (< 4%) of the costly enriched molybdenum. Crystal growth is performed mainly at the Nikolaev Institute of Inorganic Chemistry (Novosibirsk, Russia).
- We have fabricated and operated several detectors from natural and ^{100}Mo-enriched molybdenum, optimizing the radiopurity, the energy resolution and the alpha/beta rejection capability.
- We have ascertained that the crystal growth is much easier for Li_2MoO_4 than for $ZnMoO_4$, providing boules with more regular shapes and less macroscopic defects and inclusions.
- We have performed a dedicated R&D to control the internal ^{40}K content in Li_2MoO_4 down to a harmless level inferior to 6 mBq/kg.

The LUMINEU activity has culminated with the production of four enriched large-volume modules (two with $ZnMoO_4$ and two with Li_2MoO_4 crystals). Enriched molybdenum was provided by the LUMINEU collaborators of ITEP (Moscow, Russia) and KINR (Kyiv, Ukraine). Though $ZnMoO_4$ is a very promising material as well, Li_2MoO_4 devices have superior performance and radiopurity ($\Delta E_{FWHM} \sim 5$ keV in the region of interest (ROI), concentration of ^{238}U, ^{232}Th and their daughters inferior to ~5 μBq/kg and alpha-particle rejection factor superior to 99.9%). Lithium molybdate was then selected in March 2016 for the construction of mid-scale demonstrators. For a closer control of the crystal growth conditions (with a view to radiopurity issues), a Li_2MoO_4 crystal growth technology has been successfully established in France in the facility Cristallinov, Sainte-Hélène-du-Lac (in the region of Grenoble), in the framework of the dedicated ANR project CLYMENE (2016-2020).

2.2 The LSM and LNGS CUPID-Mo demonstrators

The remarkable success of the R&D on Li_2MoO_4 pushed us to build demonstrators consisting of several crystals and containing in total ~10 kg of ^{100}Mo. These demonstrators intend to be a final test before the construction of CUPID, a next-generation experiment exploiting this technology. They aim at demonstrating the reproducibility at a larger scale of the energy resolution, the intrinsic radiopurity and the alpha-particle rejection factor achieved in LUMINEU. They intend also to investigate background sources, to develop background models and to finely tune the protocols for the construction of CUPID.

The first demonstrator, named CUPID-Mo-LSM consists of 20 scintillating bolometers based on cylindrical $Li_2{}^{100}MoO_4$ crystals (∅44 × 45 mm) with a mass of 210 g each and containing 2.34 kg of ^{100}Mo. The detector assembly was performed in fall 2017 and the installation in the EDELWEISS cryostat (sharing the experimental volume with modules of the EDELWEISS experiment) was done in January 2018. Unfortunately, major cryostat problems (leaks, flow blockages and the failure of a Gifford-McMahon thermal machine) have prevented a continuous data taking. These accidents are related to the relatively old age of the cryostat. Some measures have been taken in order to restart the run before the end of 2018 with duration of at least six months (minimal CUPID-Mo program). A general upgrade of the facility at a longer term is foreseen in collaboration with EDELWEISS.

A crucial parameter to evaluate the sensitivity of a $0\nu2\beta$ search, in addition to the energy resolution, is the background index b, measured usually in the units *counts/(keV kg y)* (ckky). In the current CUORE experiment, b is of the order of 10^{-2} ckky, dominated by surface-emitted alpha particles as mentioned above. Next-generation bolometric experiments like CUPID need to reach $b{\sim}10^{-4}$ ckky. The intrinsic radiopurity of Li_2MoO_4 crystals demonstrated by LUMINEU implies a crystal contribution to the background index inferior to 10^{-4} ckky, as verified by background simulations. We have performed also a study of the background induced by random coincidences of two events from the ordinary $2\nu2\beta$ of ^{100}Mo, which is challenging as the $2\nu2\beta$ half-life in ^{100}Mo is the shortest among all the double beta isotopes. We have demonstrated that pulse-shape discrimination in the heat channel can reduce this contribution down to $b{\sim}10^{-4}$ ckky, or even lower using high-performance light detectors [EPJC 77(2017)3]. However, it will not be possible to measure such a low value in CUPID-Mo at LSM because of small and not-fully-eliminable contaminated elements in the cryostat. The target in the imminent CUPID-Mo run is $10^{-3} < b < 10^{-2}$ ckky.

The preparatory phase of CUPID-Mo has allowed us to measure the half-life of the $2\nu2\beta$ of ^{100}Mo with the highest precision at the world level. A paper is in preparation. This result will be further improved by CUPID-Mo.

Thanks to the ERC Advanced-Grant project CROSS, 26 enriched Li_2MoO_4 crystals will be available in November 2018. With respect to the crystals used in CUPID-Mo-LSM, these elements have a higher mass (280 g each) and a cubic shape (45×45×45 mm) aiming at a more efficient experimental-volume utilization. In addition, a new procedure for the purification of the lithium carbonate powder (used to form the Li_2MoO_4 molecule prior to crystal growth) has been used. In order to test these innovations, a second demonstrator, dubbed CUPID-Mo-LNGS, will be assembled in LNGS in Italy. This detector will consist of 28 closely-packed crystals arranged in 7 floors of 4 crystals each, and of an equivalent number of light detectors. Imitating the CUORE structure and unlike CUPID-Mo-LSM, the crystals will be mutually visible. CUPID-Mo-LNGS will coexist with CUPID-0, an array of scintillating bolometer of ZnSe investigating the $0\nu2\beta$ of ^{82}Se. (A part of the French groups participate to this experiment.) The CUPID-Mo-LNGS run is foreseen to last about one year. Its results will very important to fix the configuration of CUPID, as scintillating bolometers have never been operated in an open structure – capable to reduce substantially charge-particle surface background by anticoincidence – but always inside optical cavities. Furthermore, the comparisons of its background level with that of CUPID-0 (based on different crystals but in the same cryostat) and with that of CUPID-Mo-LSM (based on the same crystal material but in a different environment) will be very useful to disentangle the various background components. After the operation of the two demonstrators, it will be possible to define accurately the detector structure of CUPID.

2.3 CROSS and its demonstrator

CROSS is a 5-year ERC Advanced Grant project that started in January 2018. Its purpose is to develop arrays of Li_2MoO_4 and TeO_2 bolometers enriched in the isotopes of interest ^{100}Mo and ^{130}Te, respectively. The CROSS program is in strict connection with CUPID. The key idea is to reject surface events (the currently dominant background source) by pulse-shape discrimination, obtained by exploiting solid-state-physics phenomena in superconductors. The surfaces of the crystals will be coated by an ultrapure superconductive aluminium film, which will act as a pulse-shape modifier by changing the pulse time profile in case of shallow energy depositions. This method could allow us to get rid of the light detectors, simplifying a lot the bolometric structure and achieving the additional advantage to reject in principle also beta surface events, which unfortunately persist as an ultimate background source once that alpha particles are tagged. The CROSS program is focused on a demonstrator (CROSS-DEM) with several tens of crystals, installed underground in the Canfranc laboratory. A dedicated cryostat is under construction and will be commissioned in March 2019. The first phase of CROSS-DEM will start in 2020.

2.4 CUPID

CUPID is a proposed large bolometric experiment exploiting the present CUORE infrastructure at LNGS. The CUORE cryostat has excellent performance and has proved to be able to cool down to 10 mK and successfully operate ~1000 TeO_2 macro-bolometers to investigate the isotope ^{130}Te. CUORE has set a limit of 1.5×10^{25} y on $T_{1/2}^{0v}$ of ^{130}Te, which lead to bounds on $m_{\beta\beta}$ of 110-520 meV depending on the choice of the nuclear matrix elements. The limit on $m_{\beta\beta}$ will be improved by more than a factor 2 at the conclusion of CUORE physics program in 4-5 years from now.

CUPID is supposed to explore the inverted-ordering region thanks to a background improvement with respect to CUORE by a factor 100 (from the current b~10^{-2} ckky to b~10^{-4} ckky), with a projected sensitivity to $m_{\beta\beta}$ of 7-20 meV. In the baseline CUPID configuration, this advancement is achieved by the use of luminescent (scintillation or Cherenkov) bolometers, which allow us to reject the surface alpha background that currently limits the CUORE sensitivity. The CUORE background model clearly demonstrates that, once eliminated the alpha component, b~10^{-4} ckky is expected at ~3 MeV (in the region of the ^{100}Mo Q-value), while b~2.5×10^{-2} ckky is expected at ~2.5 MeV (in the region of the ^{130}Te Q-value), because of a ^{232}Th contamination present in the cryostat inner thermal shields. Joining this safe background estimation with the outstanding results achieved in the $Li_2{}^{100}MoO_4$ technology (see Section 2.1), the CUORE/CUPID collaboration has decided – in May 2018 – to adopt as a baseline for CUPID the ^{100}Mo option with Li_2MoO_4 crystals. **This is a major success of the French bolometric 0v2β program.** However, the ^{130}Te option, due to the undoubtedly nice features of ^{130}Te and TeO_2 (low enrichment cost, easy crystallization, high density of candidate nuclei), has been kept as a valid alternative, which requires however a change in the cryostat internal shields to get rid of the observed ^{232}Th contamination.

The CUPID collaboration, in formation, is finalizing a Conceptual Design Report.

2.5 CUPID-Te demonstrator

Several promising CUPID R&D activities in France, Italy and US are focused on the development of a light detector technology capable to detect a ~100 eV flash of Cherenkov light from a large TeO_2 crystal. **The most promising results** (and the only ones that have demonstrated full alpha/beta separation with CUORE-size crystals) **have once again achieved by the French bolometric 0v2β program**. The adopted technology is based on a standard bolometric Ge light detector (like those used in LUMINEU), with a heat signal amplification by means of the so-called Neganov-Luke effect. To this aim, the Ge absorber is provided with Al electrodes on its surface, which are used to establish an electric field in the absorber volume. The proof of concept was achieved with a prototype operated in 2017 in the EDELWEISS cryostat in LSM, which exhibited outstanding performance: the main CUORE-size TeO_2 bolometer showed excellent energy resolution at the ROI of ~6 keV, while the Neganov-Luke light detector – based on a round Ge wafer – exhibited an amplification factor of ~13 and an RMS noise of 10±2 eV, resulting into 99.9% efficiency in α-event rejection with > 95% of β signal acceptance, according to the CUPID requirements [Phys.Rev.C 97(2018)032501(R)].

We plan now to move to a multi-element demonstrator, consisting of eight CUORE-size cubic crystals (or with even a larger size of 6×6×6 cm, whose development is foreseen in the CROSS program) with improved Neganov-Luke light detectors (square shape 5×5 or 6×6 cm and optimized electrode configuration). This demonstrator is dubbed CUPID-Te and its operation is foreseen in the EDELWEISS cryostat in LSM in 2020, in order to match the milestone of the final decision about the isotope for CUPID (confirmation of the Mo baseline or maintenance of Te).

3. Origin of the project and schedule

Past sub-projects and milestones

- **January 2012** – Start of the **ASPERA R&D project ISOTTA** (CSNSM, LAL, INFN Italy, NCBiR Poland) (2012-2014) – http://isotta.in2p3.fr
- **October 2012** – Start of the **ANR project LUMINEU** (CNSMS, IAS, ICMCB, CEA/IRFU, Russian, Ukrainian and German Institutions) (2012-2017) – http://lumineu.in2p3.fr/
- **2013-2016** – Fabrication and comparison of prototypes of large natural and enriched $ZnMoO_4$ and Li_2MoO_4 scintillating bolometers; in 2016, **selection of Li_2MoO_4 for the future experiments**
- **October 2016** – Start of the **ANR project CLYMENE** (CSNSM. ICMCB, ILM, SIMaP) – Development of the crystal-growth technology for Li_2MoO_4 in France

- **2016-2018** – The bolometric 0ν2β research line appears as an official project of IN2P3 with the denominations **LUCINEU** (2016-2017) and **CUPID-Mo** (2018) but with no specific funding
- **2017 – CUORE starts data taking in LNGS**
- **2017 – Full alpha/beta separation in a TeO_2 CUORE size detector** by Cherenkov effect (LSM)
- **2017 – CUPID-Mo** Collaboration Agreement – MIT (US), UCB/LBNL (US), INFN (three laboratories) Fudan Shanghai (China), USTC Hefei (China) join – In France, LAL also joins
- **2017** – Preliminary tests for CUPID-Mo – Assembly of the CUPID-Mo demonstrator in LSM
- **January 2018** – Start of the **ERC Advanced Grant project CROSS** (2018-2022)
- **2018 – Installation and commissioning of CUPID-Mo in LSM** – Cryogenics problems
- **2018 – Li_2MoO_4 technology is selected as baseline for CUPID**

Tentative future milestones

- **2019 – CUPID Conceptual Design Report** and CUPID kick-off meeting in early 2019
- **2019** – Six months' data taking of **CUPID-Mo-LSM** (January-June)
- **2019** – Assemble and start data taking of **CUPID-Mo-LNGS**
- **2019** – Commissioning of the **CROSS cryostat** in Canfranc
- **2020 – CUPID-Te** demonstrator in LSM
- **2020** – Assemble and start data taking of **CROSS-DEM** in Canfranc (First phase)
- **2020** – Final decision about **CUPID** technology – Funding request for enrichment / crystallization (**Enrichment costs: ~20 M€ – Crystallization costs: ~5 M€**)

Publications and theses

Number of publications in refereed international journals in the period 2012-2018, divided by topic:

Topic	^{100}Mo	Cherenkov (^{130}Te)	^{82}Se	CUORE (^{130}Te)	Others	**Total**
Number of papers	11	3	6	10	1	**31**

Some of the 31 papers reported above have been published in high-impact-factor journals:

Journal	Phys Rev Lett	Phys Lett B	Eur Phys J C	Astropart Phys	Phys Rev C
Number of papers	2	1	13	1	2

An incomplete list (involving ^{100}Mo mainly) is available at the LUMINEU website.

Four PhD theses have been completed and **three are ongoing** in the French institutions.

4. State-of-the-art and positioning of CUPID-Mo and CUPID

Present limits on $m_{\beta\beta}$ are in the range 60-800 meV (Fig. 1), depending on the isotope and the nuclear-matrix-element calculation used, and assuming that the axial charge g_A is equal to the free nucleon value of ~1.25 (the most common approach in the literature). None of the current experiments has the potential to explore fully the inverted-ordering region of the neutrino mass pattern (20-50 meV for $m_{\beta\beta}$), which is the objective of next-generation 0ν2β searches. The CUPID-Mo demonstrators, which aim just to validate the technology for CUPID, have also remarkable sensitivities. CUPID-Mo-LSM, even with a conservative assumption on the background level (b~10^{-2} ckky), will set the best limit on ^{100}Mo ever achieved (1.1×10^{24} y from NEMO3) in a few months' operation. The two CUPID-Mo demonstrators together compete with the most advanced running searches (see Fig. 1 and Table 1). We have assumed 5 keV energy window and 75% efficiency, and

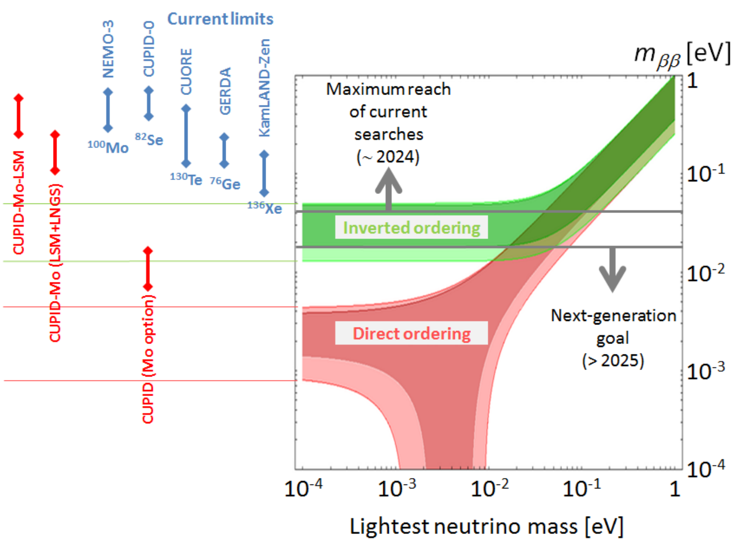

***Fig.1** – Impact of CUPID in the international scenario.*

sensitivities are at the 90% C.L. In Table 1 a reasonable configuration for CUPID – compatible with the CUORE cryostat – is considered, consisting of 1600 280-g crystals, for a total amount of 250 kg of ^{100}Mo. The sensitivity of CUPID in the baseline Mo option will fulfill the target of the next-generation experiment by fully covering the inverted-ordering region of the neutrino mass pattern and a significant part of the normal-ordering region for $m_{lightest}$ > 10 meV (Fig. 1). Other proposed projects quote of course similar sensitivities (nEXO, LEGEND 1k, KamLAND2-Zen,…), but the position of CUPID is unique: (1) the infrastructure (the CUORE cryostat) already exists and does not require substantial changes; (2) the assumed background level (b~10^{-4} ckky) is based not on simulations but on real CUORE data taken *in situ* in the final setup joined with the energy resolution, internal purity and alpha rejection demonstrated in the R&D on Li_2MoO_4 scintillating bolometers; (3) the single-module technology is fully established; (4) the cost, even though considerable, is extremely competitive. For all these reasons, we estimate that CUPID (Mo option) is probably the best placed project to explore the inverted-ordering region.

Table 1 *– CUPID sensitivity for demonstrators and final experiment*

Demonstrators / Experiment	b [ckky]	Number of ^{100}Mo nuclei	Live time [y]	Sensitivity $T_{1/2}^{0\nu}$ [y]	Sensitivity $m_{\beta\beta}$ [meV]
CUPID-Mo-LSM	b~10^{-2}	1.36×10^{25}	0.5	1.37×10^{24}	240-680
CUPID-Mo (LSM+LNGS)	b~10^{-3}	3.67×10^{25}	1	7.56×10^{24}	100-290
CUPID (Mo option)	b~10^{-4}	1.44×10^{27}	10	1.59×10^{27}	7-20

5. Resources and means

5.1 Technical resources

They consist in France of: 2 aboveground dilution refrigerators at CSNSM for bolometric optimization; 1 underground dilution refrigerator – EDELWEISS cryostat – at LSM to run demonstrators (this instrument will need an upgrade in the second half of 2019 and a major modification would be desirable at a longer time scale in the direction of a cryogenic platform to be shared with a dark-matter search program); a clean room in CSNSM with a set of thin-film evaporators for the instrumentation of the bolometers; a clean room in LAL for detector assembly. A crystal growth facility is now under optimization in the Cristallinov laboratories close to Grenoble. A new underground dilution refrigerator will be available at Canfranc in 2019 in the CROSS framework.

5.2 Financial resources

Past activities. Most of the R&D performed in 2012-2017 was funded thanks to the projects ISOTTA and LUMINEU, and from CEA/IRFU; the crystals for CUPID-Mo-LNGS have been purchased under CROSS funds (See Section 3.). Other contributions came from three international exchange programs (PICS Ukraine). Summarizing, **the total envelope in the period 2012-2018 corresponds to about 750 k€** (not including personnel). As for non-permanent personnel, LUMINEU has contributed with a PhD fellowship (100 k€), labex P2IO with ½ PhD fellowship (50 k€) and 1 y Post-doc (60 k€). IN2P3 has contributed with 2 y Post-doc (120 k€) and ½ PhD fellowship (50 k€).

Future activities. The future activities of CROSS are funded thanks to the ERC grant. On the contrary, the operation of CUPID-Mo-LSM is only partially funded. Running costs at LSM should be covered by EDELWEISS, if the request to IN2P3 for this project will be fulfilled (code 20-AC-023-001), and partially by CEA/IRFU as well as collaborators from US, INFN and China. CUPID-Mo-LNGS will be assembled and operated in strict collaboration with INFN. The mechanics will be in charge of the French groups, while detector operation in LNGS should be supported by INFN, as this demonstrator will be run together with the INFN-lead project CUPID-0, which is in continuous data taking. The fabrication costs of CUPID-Mo-LNGS in 2019 and related missions to LNGS for detector assembly and shifts are not covered. Funds have been requested for this to IN2P3 (Project CUPID-Mo, code 25-AC-138) at the level of 30 k€. The same amount has been requested by our CEA collaborators. An ANR project will be submitted in October 2018 to support the CUPID-Te program.

5.3 Human resources

Past activities. The R&D performed in the period 2012-2018 was conducted mainly by the LUMINEU collaboration and its follow-up, which included a total of 45 members, of which 28 from French institutions (CSNSM, IPNL, CEA/IRFU, ICMCB, IAS). The IN2P3 fraction was ~25% of the total.

CUPID-Mo-LSM. In 2017-2018, the LUMINEU collaboration was extended to form the CUPID-Mo collaboration, including new foreign institutions (MIT, UCB/LNBL from US, 3 INFN laboratories from Italy, Fudan Shanghai and USTC Hefei from China, other groups from Russia and Germany) with about 100 physicists/technicians. New French members, 1 research engineer and 3 technicians, belong to LAL-Orsay and therefore to IN2P3. Also a group from CEA/SPEC joined.

CUPID. The CUPID collaboration is in formation. The core will result from the current CUORE and CUPID-Mo collaborations. We count however that the strong physics case and the excellent positioning of CUPID in the global context will attract new collaborators from France and abroad. CUPID will be discussed at the next joint Scientific Committee of LAL-CSNSM-IPNO (October 23, 2018) as a candidate project of the new integrated Research Unit in formation in Orsay.

IN2P3 personnel foreseen for 2019 (names and FTE). Three IN2P3 laboratories are involved.

	CSNSM		IPNL		LAL	
	Name	FTE	Name	FTE	Name	FTE
Researchers and Professors	A. Giuliani	0.6	J. Gascon	0.15		
	S. Marnieros	0.25	C. Augier	0.2		
	P. de Marcillac	0.8	V. Sanglard	0.1		
	C. Marrache	0.2	A. Cazes	0.1		
	L. Dumoulin	0.2	J. Billard	0.1		
Research Engineers	E. Olivieri	0.5			P. Loaiza	0.5
	C. Oriol	0.2				
Technical Engineers and Technicians	L. Bergé	0.3			Ch. Bourgeois	0.05
	T. Redon	0.5			M. Brière	0.4
					E. Guerard	0.1
					B. Leluan	0.1
Post-docs	D. Poda	1.0				
	A. Zolotarova	1.0				
TOTAL FTE	5.55		0.65		1.15	

6. Technical realizations

The three main technical realizations foreseen are the three demonstrators: CUPID-Mo-LNGS, CROSS-DEM and CUPID-Te. They consist of crystals, sensors and mechanical structure. The first two elements are already available. For the mechanical structure, the design will be done in collaboration between LAL and CEA/SPEC. The LAL mechanical workshop will be in charge of the construction of the prototypes for preliminary tests, while the full fabrication will be sub-commissioned. The assembly will be done internally in the clean rooms in CSNSM and LAL.

7. SWOT self-analysis

STRENGTHS – The current project represents a coherent effort towards an extremely competitive cost-effective next-generation $0\nu2\beta$ experiment (CUPID).

WEAKNESSES – A bolometric experiment, with respect to homogenous detectors, presents an elaborated assembly procedure and depends critically on a complicated cryogenic apparatus. However, the lessons learned in CUORE will mitigate the related risks.

OPPORTUNITIES – **(1)** CUPID will exploit the present CUORE infrastructure, being therefore the only next-generation experiment able to rely on an already existing apparatus that requires minor changes. **(2)** If the CROSS program is successful, CUPID could take advantage of a technique leading to a further detector simplification and better surface background rejection.

THREATS – **(1)** CUPID needs to enlarge the collaboration attracting fresh forces, in France and abroad, and needs to be substantially funded by two or three big countries (at least) in order to share the relevant enrichment cost (~20 M€). The recent decision to fix a baseline for CUPID and to produce quickly a Conceptual Design Report should improve dramatically the visibility and the appeal of the project. **(2)** In the world, there is another bolometric experiment based on scintillating bolometers containing Mo, the Korea-lead project AMoRE. Even if technically less advanced than CUPID, AMoRE is fully funded for the purchase of ~100 kg of ^{100}Mo and for the crystal growth. This makes AMoRE a formidable competitor for CUPID. This threat would be converted into an opportunity if CUPID and AMoRE shared a joint program (similarly to what done by GERDA and MAJORANA for LEGEND) for a future combined bi-site experiment, which would be extremely powerful. An agreement should be possible once that the CUPID collaboration is fully established (2019).