Proposal for a national double-beta decay strategy

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Abstract

The search for neutrinoless double-beta decay is one of the most important topics in neutrino physics, with strong implications on particle physics and cosmology. In this document, we show the high potential of the experimental methods developed in France to play a major role at the international level for the study of this phenomenon in the next decade. We propose and discuss a national double-beta decay strategy — although in an international context — based on the current achievements of running experiments and R&D activities.

1 Introduction

Neutrinoless double-beta decay ($0\nu2\beta$) is a powerful experimental test for Lepton Number Violation and the only practical way to assess the fundamental question of the nature of neutrinos. If observed, this decay would probe that neutrinos are **Majorana** particles and would provide precious information on the **neutrino absolute mass scale** and **ordering**. Such discovery would go far beyond the neutrino physics impacting the **particle physics and cosmology** by opening new physics scenarios related to the lepton number violation as well as possible explanation of the Baryon Asymmetry of the Universe via Leptogenesis.

Many mechanisms may contribute to neutrinoless double-beta decay which can be mediated by light neutrino exchange, Rp-violating SUSY, right-hand currents or different Majoron emission modes... There is no way today to predict the most favorable process. Therefore experiments are commonly compared on their sensitivity on the light neutrino exchange mechanism. The half-life of the process depends on the effective neutrino mass parameter $m_{\beta\beta}$ whose possible values are constrained by the neutrino mass ordering and the lightest neutrino mass value (figure 1).

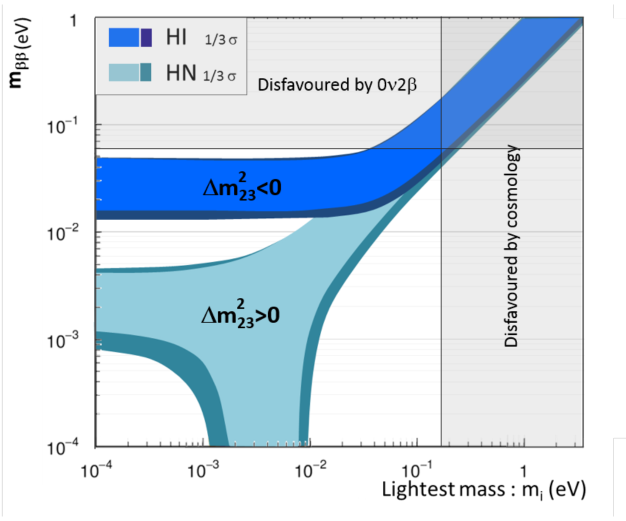

Figure 1: Allowed regions for the effective Majorana mass as a function of the lightest neutrino mass, m_1 for normal ordering (cyan, HN) and m_3 for inverted ordering (blue, HI). The oscillation parameters are varied within 3σ ranges while the Majorana CP phases are treated as free parameters. The horizontal band is the excluded region of the effective Majorana mass parameter by current neutrinoless double-beta decay measurement, while the vertical band is the excluded region of the mass scale by cosmological observations.

The experimental search is based on the detection and measurement of the sum of the kinetic energies of the two emitted electrons which must be equal to the Q-value of the transition, $Q_{2\beta}$, if the electrons are the only light particles in the final state, as happens for example in the case of light neutrino exchange mechanism. Therefore, the sensitivity of the experiments will depend on their capability to distinguish this process from the background dominated by the ambient natural radioactivity and by the allowed $2\nu2\beta$ decay. Huge efforts have been made in these last decades to improve the particle identification and the energy resolution of the detectors. In parallel, production and selection of radiopure materials as well as new anti-radon strategies continue to be developed. The detectors must also be able to accommodate large isotope masses, today typically of the order of few tens or hundreds of kilograms, depending on the experimental approach. Investigating different isotopes is also part of the strategy in a context where theoretical predictions are not reliable enough yet.

Most of the $0\nu2\beta$ experiments exploit a homogeneous approach, i.e. the detector coincides with the source, enhancing the efficiency for the collection of the electrons emitted in the decay. It is the case for the germanium semiconductors (GERDA, MAJORANA, LEGEND), bolometers (CUORE, CUPID, AMoRE), gaseous or liquid TPC (NEXT, PANDA-X-III, EXO-200, nEXO), crystals at ambient temperature (COBRA, CANDLES, AURORA) and liquid scintillators (KamLAND-Zen, SNO+). This last technology reached the best sensitivity on $m_{\beta\beta}$ — $m_{\beta\beta} < 65 - 165$ meV depending on the nuclear matrix elements — with the KamLAND-Zen experiment exploiting 1000 tons of liquid scintillator loaded with xenon-136 (350 kg). A different approach consists in separating the source and the detector. The loss of efficiency is compensated by the better topological reconstruction of the single electrons, which could be very appealing in case of discovery. The NEMO detectors are the only ones to have proven the technology feasibility with a gaseous tracker volume surrounded by a scintillator calorimeter. The already measured or expected sensitivities of most of the projects are given in Figure 2.

2 SuperNEMO

The SuperNEMO detector capitalizes on a unique tracker/calorimeter detection technique (”tracko-calo”) which was successfully operated with the NEMO-3 experiment (running from 2003-2011 at the LSM underground laboratory) [14]. This technology has been initiated in the 1980’s in France playing an important role in the development, exploitation and management of the successive NEMO projects.

Today the collaboration consists of 21 laboratories from 9 countries (France, Czech Republic, Finland, Japan, Russia, Slovakia, UK, Ukraine, US) including 6 IN2P3 laboratories: CENBG, CPPM, LAL, LAPP, LPC-Caen and LSM.

The full SuperNEMO detector has been designed to hold 100 kg of double-beta decay isotope (selenium-82 as baseline) to reach a sensitivity of the order of 10^{26} years to the half-life of decay, corresponding to a 50–100 meV effective Majorana neutrino mass (Figure 2, points SN-Se and SN-Nd for 100 kg of selenium-82 and neodymium-150 respectively).

SuperNEMO is a detector with multi-observables that allows **full topological reconstruction of events** resulting in a powerful background rejection. A background index $b \sim 8 \times 10^{-5}$ counts/(keV.kg.y) is expected in the region of interest. The topological reconstruction and the kinematic **information on individual particles** (single energy,

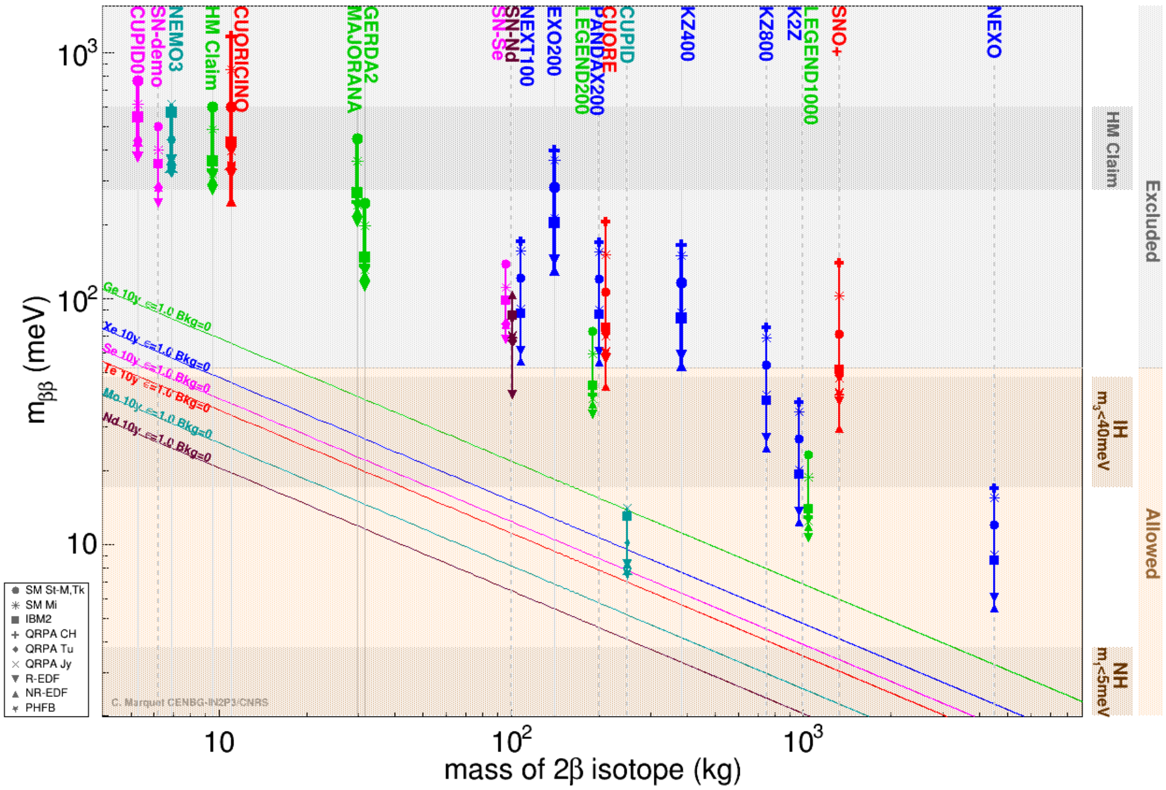

Figure 2: Sensitivity on $m_{\beta\beta}$ of past (CUORICINO, Heidelberg-Moscow:HM and NEMO3), current (CUORE, CUPID-0, EXO200, GERDA, KamLAND-Zen400:KZ400, MAJORANA, SuperNEMO:SN-demo) and future (CUPID, KamLand-Zen800:KZ800, KamLAND2-Zen:K2Z, LEGEND, nEXO, NEXT, PANDA-X-III:PANDAX, SNO+, SuperNEMO:SN-Se, SN-Nd) experiments calculated from published half-lives, phase space factors from [1] and nuclear matrix elements given in [2] (PHFB), [3] (NR-EDF), [4] (R-EDF), [5] (QRPA Jy), [6] [7] (QRPA Tu), [8] (QRPA CH), [9] (IBM 2), [10] (SM Mi), [11] (SM Tk) and [12] (M St-M). The value of the axial coupling constant is taken equal to 1.27. Colors of points relates to the 2β isotopes. Diagonal bottom lines illustrate the dependence of the $m_{\beta\beta}$ sensitivity on the (best) nuclear matrix element and phase space factor for each isotope (considering 10 years of data taking, full detection efficiency and no background).

angular correlation...) make it a unique tool to investigate new physics mechanisms involved in double beta decays, beyond the common light neutrino exchanges, with a world leading sensitivity on most of these processes. In addition to this, the SuperNEMO technology is ideal for exploring 2β decays not just in selenium-82 but in other isotopes, thanks to the modular technology which allows for the source foils to be swapped out.

The SuperNEMO demonstrator module is currently taking its first commissioning data at the LSM with 6 kg of ^{82}Se. It acts as a **proof of concept** of the technique in order to demonstrate how the tracko-calo approach could be expanded for a larger scale experiment. With 3 years of data taking (exposure of 17.5 kg·year) the demonstrator will also lead to **competitive new physics results bounded to the lepton number violation physics** and is expected to reach a sensitivity on $m_{\beta\beta}$ of 240-460 meV in the case of the light neutrino exchange process (Figure 2, SN-demo point). With its very high statistics and excellent signal over background ratio the demonstrator will also allow **precision studies of the double-beta decay with neutrinos ($2\nu2\beta$)**. Recent theoretical studies [13] have demonstrated the possibility of constraining the current effective 2β axial coupling constant g_A (entering in the fourth power in both the $2\nu2\beta$ and $0\nu2\beta$ half-lives) by measuring the shape of the individual energy of the $2\nu2\beta$ electrons and possibly their angular correlation. This measurement, which would have a large impact for the double-beta community (and for the nuclear model studies), will be carefully investigated with the demonstrator, ^{82}Se being particularly favored for this study.

The construction of a larger mass detector will have to be taken in the light of the demonstrator experience feedback, and will strongly depend on the results of the other $0\nu2\beta$ experiments. The resources requested to go beyond the current phase and overcome the inherent difficulties of the tracko-calo approach [15] will be only considered in a world wide competitiveness, notably in the case of a positive indication of a $0\nu2\beta$ decay signal. New enrichment procedures for promising isotopes like neodymium-150 or zirconium-96 (due to their high $Q_{2\beta}$, nuclear matrix elements or possible favorable decay to excited states) are currently under study within the collaboration and will also be considered as possible new phases of the experiment.

3 CUPID

CUPID (CUORE Upgrade with Particle IDentification) is a large bolometric experiment proposed mainly by French, Italian and US groups and exploiting the present CUORE infrastructure at LNGS underground laboratory [16]. 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 2.3×10^{25} y on $T_{1/2}$ of ^{130}Te, which lead to bounds on $m_{\beta\beta}$ of 90-420 meV depending on the choice of the nuclear matrix elements. The limit on $m_{\beta\beta}$ will be improved by about a factor 2 at the conclusion of the CUORE physics program in 4-5 years from now (Figure 2, CUORE point).

With respect to CUORE, CUPID is supposed to improve the background level by a factor 100, from the current background index b $\sim 10^{-2}$ counts/(keV.kg.y) to b $\sim 10^{-4}$counts/(keV.kg.y). In the baseline CUPID configuration, this advancement is achieved by the use of **scintillating bolometers**, which allow CUPID to reject the surface α background that currently limits the CUORE sensitivity. The CUORE background model clearly demonstrates that, once eliminated the α component, b $\sim 10^{-4}$counts/(keV.kg.y) is expected at $\sim$3 MeV (in the region of the ^{100}Mo Q-value), while b $\sim 10^{-3}$counts/(keV.kg.y) is expected at $\sim$ 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**, the CUORE/CUPID collaboration has decided — in May 2018 — to abandon ^{130}Te and adopt the ^{100}Mo option with Li_2MoO_4 crystals as a baseline for CUPID. **This is a major success of the French $0\nu2\beta$ decay bolometric program**.

In fact, the $Li_2^{100}MoO_4$ technology was developed in France starting from 2014, mainly in IN2P3 laboratories (CSNSM, LSM, IPNL and LAL), but in the context of an international collaboration with 15 laboratories in 7 countries (France, Ukraine, Italy, Russia, Germany, US and China). The developed prototypes have shown an excellent behavior in terms of energy resolution ($\Delta E_{FWHM} \sim 5$ keV in the region of interest for $0\nu2\beta$), internal radiopurity (< 3 μBq/kg for ^{226}Ra, ^{232}Th and their daughters) and α-particle rejection factor ($> 99.9\%$). 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 LSM in the EDELWEISS cryostat. CUPID-Mo is in physics data taking and it is by itself a very sensitive $0\nu2\beta$ experiment at the international level, as well as the most important demonstrator for CUPID.

The CUPID single-detector module will follow closely the CUPID-Mo structure. The full array, to be operated at 10-20 mK in the CUORE cryostat, will contain $\sim$ 1500 crystals corresponding to about $\sim$ 250 kg of ^{100}Mo. The CUPID projected sensitivity to $m_{\beta\beta}$ is 8-14 meV in ten-years' data taking (Figure 2, CUPID point), exploring the full inverted ordering region and a significant part of the normal one. CUPID is one of the most promising options for next-generation experiments (Figure 2).

The **strong points of CUPID** are the following: it is **technologically ready** in terms of detector performance; it is based on an existing infrastructure; it is **data driven**, as the background model is based on a working demonstrator and on the results achieved by CUORE directly inside the final CUPID infrastructure; it is **extremely cost-effective** with respect to other experiment as the cost is dominated by the isotope production. A CUPID CDR [17] — signed by the CUPID group of Interest which includes 5 French laboratories (3 of IN2P3) and about 35 French researchers (25 from IN2P3) — is ready and CUPID has passed the DoE selection step CD0 in the US, together with two more $0\nu2\beta$ experiments (nEXO and LEGEND). According to the current schedule of the experiment, if funding for the isotope is secured, data taking is foreseen to start 6 years from now.

4 Prospects and strategy

The French double-beta decay community plays today a relevant role at the international level thanks to two original approaches conceived and developed in France: the tracko-calo technique (NEMO-3, SuperNEMO) and the Mo-based scintillating bolometers (LUMINEU, CUPID-Mo). These strength points should be reinforced in the future, developing synergies and defining a precise strategy. In addition, new original ideas that could affect the scenario of the $0\nu2\beta$ decay search at a 10 year time scale can benefit from the French expertise on this topic. The prospects of the search for $0\nu2\beta$ decay, with special regard to the role of the French groups, are examined below, over a three-step time scale matching an increasing sensitivity to $m_{\beta\beta}$. Subsequently, new ideas that are explored in the IN2P3 laboratories are mentioned and synergies among the various projects are discussed.

Current situation — $m_{\beta\beta} \sim 50 - 500$ meV. Several experiments worldwide are now exploring this range. The two French demonstrators, SuperNEMO and CUPID-Mo, both installed in Modane, have a sensitivity at best of $\sim$ 200 meV on a 2-3 year time scale. If $0\nu2\beta$ decay is discovered at this level, it becomes important to confirm its observation and to investigate the mechanism inducing the process. As for the latter point, the SuperNEMO technology is unique in the world (see Section 2). It is therefore very important to keep this technology ready and available. A multi-isotope confirmation will also be mandatory. Both tracko-calo and bolometers can explore different isotopes in this range of $m_{\beta\beta}$ values.

5 year time scale — $m_{\beta\beta} \sim 10 - 50$ meV. A few projects worldwide are proposed to cover this interval, as discussed in Section 1. Among them CUPID is very well positioned (see Section 3 and Figure 2). This experiment is one of the most sensitive in the next generation and could dominate the scenario of the $0\nu2\beta$ decay search in the next decade. France's role in CUPID is expected to be major, given the contribution provided by the French groups in the definition of the basic CUPID technology and the support that can come from all the double-beta decay French community to the construction of the experiment. CUPID is naturally part of the French strategy for the search for $0\nu2\beta$ decay down to 10-20 meV sensitivity on $m_{\beta\beta}$.

10 year time scale — $m_{\beta\beta} < 10$ meV. To discover Majorana neutrinos in this mass range is a major challenge. This can be done with an isotope mass of the order of 10 tons and background close to zero. R&D is mandatory to achieve these goals.

Crucial elements for a next-to-next generation experiment with such a sensitivity are the followings:

- Possibility to achieve the **multi-ton scale** in terms of isotope mass
- Sophisticated methods of background rejection providing **particle identification**
- Use of a **well-established technology** even if developed along innovative lines
- Possibility to **study different isotopes** to confirm possible claims and to improve the extraction of the physical parameters given the uncertainty of the nuclear calculations

In addition to these features, detectors will have to be installed underground in low background environment. The depth of the laboratory becomes a key parameter to tackle the cosmogenic background already an issue for large mass project (such as ^{137}Xe for xenon experiment like DARWIN in LNGS [18]). IN2P3 has a major asset with the LSM, the deepest European laboratory, and the possible new laboratory under discussion in proximity of the Lyon-Turin tunnel.

An evolution of the bolometric technology can in principle provide an adequate sensitivity if new methods are set up to decrease the background level by a further order of magnitude with respect to CUPID, achieving $b < 10^{-5}$ counts/(keV.kg.y). This implies the development of technologies capable to fully reject the surface radioactivity in bolometers, including the β-particle component, as those studied in the ERC project CROSS. Proposed follows-ups of CUPID, discussed in the CUPID CDR and named CUPID-reach and CUPID-1T [17], can be considered as significant steps to extend the reach of the bolometric technologies. In particular, CUPID-1T will have an active mass of 1 ton and would need a new cryostat — larger than the one used by CUORE — and a deeper underground site. The new French underground laboratory would be ideal in terms of depth. An extreme bolometric experiment at the 10-ton-scale level is conceivable using natural tellurium if a background index $b < 10^{-5}$ counts/(keV.kg.y) can be demonstrated. This experiment would reach a sensitivity of 3 meV on $m_{\beta\beta}$ in 10-years' data taking for the most favorable nuclear matrix elements.

Other possible developments. Other approaches to the search for $0\nu2\beta$ are pursued in the French landscape through dedicated $0\nu2\beta$ R&D or possible applications in detectors initially conceptualized for other physics case:

- LiquidO is and R&D activity based on the well-known liquid scintillator technology where the conventional paradigm of transparency is abandoned and scintillation light is confined and collected near its creation point with an opaque scintillator and a tight array of fibres. This helps particle identification and background rejection. In addition the liquid should be loaded with any interesting $0\nu2\beta$ decay isotope at high concentration ($> 10\%$), since transparency is not a requirement, opening the way to multi-ton multi-isotope experiment without isotope enrichment [19].
- R2D2 is a dedicated $0\nu2\beta$ R&D which explores a new high pressure xenon TPC consisting in a sphere with a single (or few) central electrode aiming at more compactness geometry and readout compared to existing TPC. The main feature is to gain on the radiopurity levels and cost of the instrument minimizing the mass of materials and number of channels. A final ton scale detector is considered to cover the inverted mass hierarchy region [20].
- DARWIN is a long-term evolution of the XENON-1T and XENON-nT experiments. These searches, based on double-phase liquid-xenon TPCs, aim at the detection of WIMPs. However, this technology could also be interesting for $0\nu2\beta$ decay in the future [21]. In particular, the DARWIN project envisions an active mass of 50 tons of natural xenon, corresponding to more than 3.5 (active) tons of ^{136}Xe. If a reduction of the background by a factor 10^4 can be demonstrated with respect to XENON-1T, DARWIN can be a competitive $0\nu2\beta$ decay experiment constraining $m_{\beta\beta}$ at the level of 20 meV.
- Finally the JUNO experiment, a multi-purpose neutrino observatory with an important participation of IN2P3 laboratories, can in principle improve the sensitivity to $0\nu2\beta$ up to a few meV with $\sim$50 tons of fiducial ^{136}Xe and 5 years exposure after the reactor running phase ($\sim$ 2030) [22]. It is not yet an approved part of JUNO.

Synergies. The two main double-beta research lines in France, SuperNEMO and CUPID, differ in terms of basic technologies. However, there are important aspects where they can benefit one from the other. The SuperNEMO collaboration has developed a special detector — BiPo, installed in the Canfranc underground laboratory in Spain — that has unique capabilities in measuring surface radioactive contamination. This device is very useful also for the development of radiopure bolometers. The SuperNEMO expertise in radon control — anti-Rn factory, Rn detection, Rn line concentration — can be useful for bolometer assembly and storage as well. More generally, synergies can be developed between all the mentioned projects. Radio-clean crystals containing double-beta decay sources and developed to fabricate bolometric prototypes can in principle be made available to the Liquid0 collaboration to produce powders to be loaded in the opaque scintillator. Expertise on scintillation and light detection developed within the SuperNEMO, CUPID and LiquidO communities could also be shared. The precise measurements of several $2\nu2\beta$ processes in NEMO-3 and possible unique constraint on g_A quenching from SuperNEMO are also useful to the whole community for a better definition of the nuclear models. Common pieces of expertise that could be enhanced by exchanges are radiopurity databases, purification techniques, construction of mechanical pieces without introducing impurities, clean-room methodologies, $\beta\beta$ isotope manipulation and others related to low-radioactivity methods. New technologies can also be seen as possible improvements of current approaches, opaque scintillator may for example benefit to the "tracko-calo" technique.

We consider expertise exchanges inside the double-beta decay and — more in general – the rare-event communities in France as a fundamental part of the future strategy. The DULP (Deep Underground Laboratory Physics) GDR, bringing together the different communities of underground physics, will play a major role to initiate and develop these synergies.

In conclusion, we remark that there are all the elements for France to play a leading role in the search for $0\nu2\beta$ decay in the next decade. It is important that the pieces of expertise accumulated by the various collaborations are not lost and that they are used for future developments. A clear strategy for the search for $0\nu2\beta$ decay would help to structure the French double-beta community.

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