COMITÉ NATIONAL DE LA RECHERCHE SCIENTIFIQUE
CONSEIL SCIENTIFIQUE D'INSTITUT

REPORT

Scientific Council of IN2P3

Session of October 6-7, 2025

IN2P3
Institut national de physique nucléaire
et de physique des particules

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Participants

IN2P3 Scientific Committee members

Navin Alahari, Auguste Besson, Olivier Bourrion, Cristina Cârloganu, Barbara Clerbaux, Maria De Los Angeles Faus-Golfe (on October 2^{nd}), Maria José Garcia Borge, Jules Gascon, Leïla Haegel, Andrea Jeremie, Yoann Kermaïdic, Iro Koletsou, Bogna Kubik, Aleandro Nisati, Luc Perrot (on October 2^{nd}), Guillaume Pignol, Isabelle Ripp-Baudot, Laurent Serin, Vincent Tatischeff, Régis Terrier, Dominique Thers.

Excused: Maria De Los Angeles Faus-Golfe (on October 3^{rd}), Didier Laporte, Luc Perrot (on October 3^{rd}).

Invited members

Stéphane Grévy (president of the *Section 04* of the National Committee of CNRS).

IN2P3 management

Christelle Roy (director of IN2P3), Jean-Luc Biarrotte (deputy director of IN2P3), Marcella Grasso (scientific deputy director of IN2P3 in charge of nuclear physics), Laurent Vacavant (scientific deputy director of IN2P3 in charge of particle physics).

Invited experts

Patrick Decowski (NIKHEF), Esther Ferrer-Ribas (DEDIP, Irfu), Aldo Ianni (LNGS, INFN, remote), Michel Sorel (IFIC).

Speakers

Andrea Giuliani (IJCLab, IN2P3), Christine Marquet (LP2i, IN2P3), Javier Menéndez (IFIC), Anselmo Meregaglia (LP2i, IN2P3), Claudia Nones (DPhP, Irfu), Benjamin Schmidt (DPhP, Irfu).

1 Framework

The meeting of the Scientific Council was held on 6 and 7 October 2025 at the CNRS headquarters in Paris. Part of it was led jointly with the Scientific Council of the Particle Physics Department at Irfu, CEA. The first day was dedicated to the presentation of the projects 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 purpose of this session was to review French activities in neutrinoless double beta decay searches ($0\nu\beta\beta$), and to assess their current status in terms of involvement, maturity, competitiveness, collaboration, and expected scientific return.

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, mainly the following Science Drivers (SD):

- SD #2 Study matter-antimatter asymmetry and flavor transitions
- SD #3 Pursue searches for unknown particles and interactions
- SD #11: 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 ($0\nu\beta\beta$), 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 signature relies on the specific kinematics of the two electrons in the final state, and on the ability to distinguish the neutrinoless decay signal from the continuous electron energy spectrum of the SM. This requires an excellent electron energy measurement resolution, an extremely low background, and, potentially, event topology reconstruction 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.

French teams are currently involved in three distinct projects, each of which is at a different stage of development. They were all presented during the session, namely:

- The SuperNEMO Demonstrator, with contributions from IN2P3 laboratories in Annecy, Bordeaux, Caen, Marseille, and Orsay. This activity was approved by IN2P3 management 20 years ago and has been reviewed in 2005, 2011, and 2018 by the IN2P3 Scientific Council. In this session, SuperNEMO is simply being presented for information about its expected completion and final results. No recommendations are asked by the management to the Scientific Council.
- The R2D2 R&D project, led by IN2P3 laboratories in Bordeaux, Marseille, and Nantes. It was presented to the Scientific Council in 2018 for information purposes only, while this time a full scientific evaluation with recommendations from the Scientific Council is asked by the management. The specific questions posed by the management are presented in Section 2.
- The CUPID experiment, with the contribution from both Irfu, and IN2P3 laboratories in Lyon and Orsay. IN2P3 activities were previously reviewed by the Scientific Council in 2018, and a full scientific evaluation with recommendations from the Scientific Council is again requested this time.

The rest of this document comprises the parts dealing with SuperNEMO and R2D2, which were reviewed exclusively by the Scientific Council of IN2P3, while CUPID is covered in a distinct joint IN2P3-Irfu report.

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 management on R2D2

In recent years, the international community interested in measuring neutrinoless double beta decay has mainly focused on three next-generation experimental projects. These projects, LEGEND, nEXO and CUPID, have since reached and demonstrated a certain degree of maturity, and brought communities from different countries together. Each of these experiments focuses on a specific emitter (^{76}Ge, ^{136}Xe and ^{100}Mo, respectively) and uses a different detector technology.

New-generation projects for neutrinoless double beta decay measurements are indeed very ambitious and expensive, and for several years there has been a perceived need to structure and optimise international efforts, expertise and resources. It has therefore become clear that human and financial resources should be concentrated on a smaller number of projects in order for these projects to be carried out and completed.

The international context subsequently evolved at the end of last year when the United States chose to support only LEGEND (of the two new-generation experiments known as “ton-scale”, nEXO and LEGEND). In this context, the Institute proposes, in particular, that the Scientific Council analyses and gives its assessment on the following points:

- Are the technical or technological achievements of R2D2 R&D properly identified? What are the conclusions of this R&D, particularly in terms of expected performance and sensitivity?
- How were these achievements and findings promoted (publications or other) and how is their transmission within the institute implemented with a view to possible reuse?
- What are the resources and involvement of the R2D2 teams today? How does this involvement fit into IN2P3 laboratories and match their local situation? Is it compatible with each team’s other existing commitments to other projects at the Institute?
- What is the current status of this proposed double beta decay measurement (choice of emitter and technology), and how does it compare in terms of competitiveness, ability to bring together an international community, sensitivity, timetable and degree of maturity, in the international context described above?
- Taking also into account the available resources and capabilities, what scientific returns and impact could be expected?

3 Comments and recommendations on R2D2

Introduction and highlights

The goal of R2D2 is to study neutrinoless double beta decay with sensitivity to the effective Majorana neutrino mass down to a few 10 meV. In order to achieve this, the detector must have an excellent energy resolution, allow topological identification of the two-electron signal, present ultra-low backgrounds in the region of interest, and allow scalability to large isotopic masses. R2D2 addresses these requirements with a high-pressure xenon gas TPC in a cylindrical geometry, operated in ionisation mode with a central charge collection anode. A single module (2.5 m long, 1 m diameter) can host approximately 600 kg of xenon at a pressure of 40 bar. The planned use of a composite material vessel would allow a minimal material budget, with wall thicknesses of a few millimetres, thereby reducing external backgrounds.

The combination of topological discrimination and an energy resolution of 1% FWHM at 2.5 MeV, alongside the minimal use of passive materials, makes R2D2 a promising candidate for next-generation or next-to-next-generation experiments. If an extremely low radiopurity of the composite vessel is achieved, R2D2 would make a full and efficient use of the xenon mass, avoiding costly fiducialisation. Consequently, R2D2’s focus is on minimising the material budget to suppress backgrounds from radiactivity.

Comments

In the international context, several competitive staged experiments are already more advanced in principle, though at different levels of maturity with respect to each other. Most of them have entered an upgrade phase (CUORE towards CUPID, LEGEND towards ton scale, KamLAND), while some are not yet funded (nEXO) or still require R&D work (NEXT). However, to date, none of these next-generation experiments has yet delivered the final detector. In this context, R2D2 presents a novel, cost-effective exploratory approach that still has the potential to be relevant in the future.

The R2D2 team comprises 2.6 full-time equivalents (FTEs) and is based entirely within the institute. The team has just completed an eight-year research and technology (R&T) programme led by IN2P3. The objective was to establish the proposed detector concept, with good energy resolution. Several papers reporting significant milestones have been published, including stable resolution under different conditions, and comparable resolution in argon and xenon. A number of technological advances were also achieved. These include electronic noise reduction, gas purification and recuperation, and signal processing.
However, the feasibility of the real-scale experiment still needs to be demonstrated. This proof of concept is expected to be achieved by 2028. Firstly, this means completing the composite material vessel, which must demonstrate excellent radiopurity and be able to withstand the high xenon pressure. Secondly, the team must prove that their previous progress can be replicated under nominal conditions. Notably, they must demonstrate their ability to build a composite material vessel with the necessary radiopurity properties to meet the required background level of 10 μBq/kg, while ensuring safety with vacuum and at a gas pressure of 40 bars. Additionally, the background suppression capability should be demonstrated at high pressure. Finally, the topological approach must be validated experimentally.

One concern is the very small size of the team. Further human resources will be required to complete the radiopurity screening procedure for the feasibility study. Discussions with potential partners have begun. In the longer term, beyond 2028, achieving critical collaboration mass for an experiment will be a significant challenge. A successful prototype that addresses all the aforementioned technological steps could generate interest from the international community. The team has already started communicating and exploring possible future collaborations.

Recommendations

The Scientific Council is of the opinion that a successful R2D2 R&D phase could be a game changer for future low background experiments. It could allow the construction of an original, low-cost, and easy-to-operate at room temperature neutrinoless double beta decay experiment. Furthermore, it could be easily duplicated using multiple vessels in different locations. Ultimately, this technological achievement would transform the landscape of low-background experiments.
The Scientific Council of IN2P3 therefore recommends supporting an additional three years of R&D, in order to validate or refute the scientific potential of R2D2. This would require the team to find the appropriate budget to complete the vessel, either through ANR or ERC calls for proposals, or through contributions from their partners. A final evaluation of the scientific outcome and technical feasibility should be conducted by the end of 2028 or the beginning of 2029.

Once the detector feasibility in realistic experimental conditions has been demonstrated, and the level of interest from the international community has been established, it will be important to investigate the possibility of hosting the R2D2 experiment at LNGS or at the Boulby Undeground Laboratory. The release of a Conceptual Design Report demonstrating the feasibility will be necessary in order to proceed to the next stage.

4 Comments on SuperNEMO

General context

The SuperNEMO experiment employs a unique technological concept combining a thin, independent double beta decay source, composed of 6.11 kg of ^{82}Se, with an extremely low-background setup. The source is separated from the detector. It is positioned at the center of a tracking chamber, which records the trajectories of charged particles, and is surrounded by a segmented calorimeter that measures the energy and timing of each individual particle. A distinctive feature of SuperNEMO lies in its capability not only to detect a potential $0\nu\beta\beta$ signal, but also to reconstruct the full event topology and identify the emitted particles, thereby providing unique information to investigate the underlying decay mechanism and disentangle for instance Left-Right symmetry, Majoron emission or Light neutrino exchange. In addition, SuperNEMO is able to perform high-precision measurements of the Standard Model $2\nu\beta\beta$ decay, offering valuable insights into the kinematics and nuclear physics of the process.

Status of the SuperNEMO experiment

The full construction of the SuperNEMO Demonstrator, including its shielding, was completed in October 2024. Data taking began in April 2025 at the IN2P3 Fréjus underground facility (LSM). During this initial phase, the absence of an anti-radon facility resulted in the presence of a dominant radon background, preventing a reliable analysis of background sources in the summer 2025 data. While writing this document, the detector started data taking with the LSM anti-radon facility on October 16, 2025. According to the collaboration's nominal plan, based on the expected sensitivity, the target exposure for the full detector should be approximately 17.5 kg·year, corresponding to 2.86 years (34.3 months) of double beta data taking. However, the end of data taking is currently constrained by space limitations at the LSM, which requires the SuperNEMO area to be vacated by January 2028 to install another experiment. A dismantling plan, including a 12-month period with a three-month contingency, has been approved by the LSM. Under the present schedule and assuming a 90% duty cycle, the total double beta physics data would correspond to approximately 1.1 years of operation, starting from October 2025 when the anti-radon facility is available.

As a Demonstrator, the current SuperNEMO detector has the primary goal of validating the feasibility and performance of the experimental approach for a possible next-generation neutrinoless double $0\nu\beta\beta$ beta decay experiment. At the same time, its scale allows it to conduct also competitive physics measurements. For the standard $0\nu\beta\beta$ decay mode mediated by light Majorana neutrino exchange, the Demonstrator's 6.11 kg of ^{82}Se cannot reach the half-life sensitivities expected from larger calorimetric experiments using ^{136}Xe, ^{76}Ge, or ^{130}Te. Nevertheless, it can improve the current limit for ^{82}Se, which remains a valuable input, since exploring multiple isotopes remains crucial given the current uncertainties on nuclear matrix elements. The key strength of SuperNEMO lies in its capability to reconstruct the full event topology, which allows the investigation of underlying $0\nu\beta\beta$ mechanisms such as those mediated by right-handed currents. In addition, SuperNEMO will perform high-statistics measurements of the standard $2\nu\beta\beta$ process. For an exposure of 17.5 kg·year with ^{82}Se, about 10^5 fully reconstructed $2\nu\beta\beta$ events are expected, enabling a detailed topological study that will provide valuable input for nuclear structure calculations. Beyond-Standard-Model effects could also be probed through precise analysis of the $2\nu\beta\beta$ spectral and angular distributions. A very preliminary analysis of 64.8 days of data recorded up to summer 2025 shows overall good agreement between the observed energy spectrum and Monte Carlo predictions.

IN2P3 involvement

IN2P3 is a leading contributor to the SuperNEMO project. The experiment is hosted at the LSM and IN2P3 laboratories and personnel have played key roles in the development of the experiment, from the early R&D phases through detector construction and now during its operational and data exploitation stages. IN2P3 scientists have held numerous leadership responsibilities within the collaboration since its inception, including positions such as spokesperson, technical coordinator, physics coordinator, run coordinator, and chair of the Institutional board. SuperNEMO has also provided strong support for education and training: about twenty PhD theses have been completed within the collaboration in France, and three PhD students are currently active. A significant part of the French contribution has relied on IN2P3's expertise in areas that are critical for double beta decay research, including ultra-low radioactivity measurements, calorimetry, tracking technologies, simulation, and data analysis.

Comments

The Scientific Council acknowledges the successful start of the SuperNEMO data-taking phase and congratulates the collaboration for the completion of the Demonstrator and the beginning of operations at the LSM. Regardless the duration of the data taking period, the experiment will leave a strong scientific legacy through the precise measurement of the $2\nu\beta\beta$ spectrum of ^{82}Se, which will be of lasting value to the nuclear physics community. This Demonstrator is the only currently competitive experiment dedicated to the study of the ^{82}Se isotope. Any discoveries and measurements made with SuperNEMO will remain the reference for the field for the foreseeable future, as there is currently no plan for another similar detector. If SuperNEMO demonstrates the expected performance, which should be established within approximately two months after the commissioning of the anti-radon facility, an active support to the project, including adequate human resources for the continuation of data taking towards a possible extension of the data-taking period would significantly enhance the potential scientific return of the experiment and be highly valuable.

With its nominal exposure (17.5 kg·yr) and expected background, the SuperNEMO Demonstrator could achieve up to 9 world-leading results in various $0\nu\beta\beta$ and $2\nu\beta\beta$ channels for ^{82}Se, including the best sensitivities worldwide across all isotopes for the $0\nu\beta\beta$ (V+A) modes ($\langle\eta\rangle$ and $\langle\lambda\rangle$). These results would cover the most common (V–A) decay mode and would provide unique and valuable inputs for nuclear matrix element (NME) calculations through detailed kinematic studies. With the currently allocated exposure of $\sim$ 7 kg·year, sensitivities to $0\nu\beta\beta$ decays would only be able to surpass existing limits for ^{82}Se for three mechanisms, involving Majoron emission and (V+A) currents. An intermediate running scenario, with one additional year of data taking (until the end of 2027), would still be beneficial, allowing for the inclusion of new, albeit limited, and valuable results, particularly contributing to improved NME constraints.

Furthermore, the technological developments achieved within SuperNEMO represent a valuable R&D contribution to the experimental community that should be further exploited in future projects. Its unique approach remains a promising and complementary strategy for studying the underlying physics of double-beta decay once it is discovered, and other rare processes.