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Latest results from NEMO-3 and commissioning status of the SuperNEMO demonstrator

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Abstract. The NEMO-3 experience was dedicated to the search for neutrinoless double beta decays $(0\nu\beta\beta)$ and to the precise measurements of the two neutrino double beta decays $(2\nu\beta\beta)$. The detector was installed at Laboratoire Souterrain de Modane (LSM) and investigated $\beta\beta$ decays among seven isotopes from 2003 to 2011. Its unique approach combining a calorimetric and a tracking measurement allows to fully reconstruct the $\beta\beta$ event topology with a very low background level. This feature also permits original searches such as the investigation of the hypothetical quadruple beta decay $(0\nu 4\beta)$. Its successor, SuperNEMO, is currently under construction at LSM and will extend the sensitivity of the $0\nu\beta\beta$ search. The latest results from NEMO-3 concerning the ¹⁵⁰Nd and ¹¹⁶Cd isotopes are presented as well as the installation status of the first SuperNEMO module.

1. Introduction

Experimental $0\nu\beta\beta$ decay search is one of the most active research topics in neutrino physics [1]. Its observation is of major importance since it can prove the Majorana nature of the neutrino and could give access to their mass scale. In the framework of a Majorana neutrino, the total lepton number is not conserved and could be linked to the matter-antimatter asymmetry in Universe. In parallel, the precise half-life measurements of the corresponding $2\nu\beta\beta$ decay mode provide valuable inputs for nuclear matrix elements (NME) calculations [2, 3] and is also of great interest as the $2\nu\beta\beta$ decay is the ultimate background for the $0\nu\beta\beta$ search.

1.1. Double beta decay

The $2\nu\beta\beta$ decay is a second order process allowed in the Standard Model (SM) in which two neutrons simultaneously convert into two protons with the emission of two electrons and two antineutrinos $(2n \rightarrow 2p + 2e^- + 2\bar{\nu}_e)$. These decays are very rare and have been experimentally observed for 12 isotopes. The typical half-lives have been measured in the range $[10^{18} 10^{24}$ years depending on the isotope. The total energy of the two emitted electrons is a continuous spectrum with an end-point at the nuclear transition energy $Q_{\beta\beta}$.

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The $0\nu\beta\beta$ decay is a hypothetical process in which two β decays occur simultaneously and no antineutrino is emitted $(2n \rightarrow 2p + 2e^{-})$. This decay is forbidden in the SM as it violates the lepton number conservation and has never been observed. The half-life of the process can be parametrised as :

$$[T_{1/2}^{0\nu}(A,Z)]^{-1} = g_A^4 \ G_{0\nu}(Q_{\beta\beta},Z) \ |M_{0\nu}(A,Z)|^2 \ \eta^2 \tag{1}$$

where g_A is the axial coupling constant, $G_{0\nu}$ the kinematical phase space, $M_{0\nu}$ the nuclear matrix element and η is a lepton violating number parameter which takes into account all the physics behind the $0\nu\beta\beta$ mechanism. The expected signal of this decay is an excess of events at the $Q_{\beta\beta}$ value in the energy sum spectrum of the two electrons.

1.2. The tracker-calorimeter technique

The NEMO detectors are based on the so-called tracker-calorimeter technique consisting of the separation of the $\beta\beta$ isotopes from the rest of the detector. The $\beta\beta$ isotopes are in shape of thin foils which are surrounded by a tracking and a calorimeter device immersed in a magnetic field allowing the particle identification and the full reconstruction of event topology. This technique has the advantage that many $\beta\beta$ isotopes can be investigated simoultaneously and could distinguish between the possible mechanisms underlying the $0\nu\beta\beta$ process. The experimental principle and an example of a $\beta\beta$ event in the NEMO-3 detector are presented in Figure 1.



Figure 1: Left: Principle of the tracker-calorimeter technique used by the NEMO detectors. Right: Top view of the NEMO-3 detector where 2 electrons have been detected. The small blue circles correspond to hits into the tracker, the two red rectangles correspond to the hit into the calorimeter and the red lines represent the reconstructed electron trajectories.

1.3. Sources of background

The backgrounds for the $0\nu\beta\beta$ search are any processes in which two electrons with an energy sum close to the $Q_{\beta\beta}$ value are produced. They are mainly induced by the natural radioactivity coming from the laboratory environment and from the detector materials. The isotopes with a very long half-life such as ²³⁸U and ²³²Th and the isotopes produced in their decay chain (²¹⁴Bi and ²⁰⁸Tl) are particularly problematic. The β and/or γ particles emitted during their decay can mimic the $\beta\beta$ signal by different processes such as Møller or Compton scatterings. As the tracker-calorimeter technique allows the identification of different particles and topologies, the origin of the background contamination can be determined. Different analysis channels can be defined to measure the different background contributions [4].

2. Latest results from NEMO-3

NEMO-3 was a tracking calorimeter detector arranged in a cylindrical geometry with a height of 3 m, a diameter of 5 m and divided into 20 equal sectors [5]. Thin source foils with a thickness of 40-60 mg/cm² are made with seven different $\beta\beta$ isotopes and distributed around the different sectors at a fixed radius of ~155 cm. The source foils are surrounded by a tracking chamber composed of 6180 drift cells working in Geiger mode. This tracking device provides three-dimensional measurements of trajectories and vertex reconstruction of charged particles on the source foil with a resolution of 0.5 cm in the transverse plane (xy coordinate) and 0.8 cm in the longitudinal axis (z coordinate) for 1 MeV electrons. The tracking chamber is enclosed on all sides by calorimeter walls made of 1940 scintillator blocks coupled to 3" and 5" photomultiplier tubes (PMT) providing both timing and energy measurements. For 1 MeV electrons, the energy resolution has been determined to be (14-17)% FWHM for the optical module with 3" and 5" PMTs respectively, and the average time resolution to be ~250 ps. A solenoid coil surrounding the calorimeter produced a 25 G magnetic field allowing particle charge discrimination.

2.1. ^{150}Nd results

36.6 g of ¹⁵⁰Nd has been introduced in NEMO-3. ¹⁵⁰Nd is a very interesting nucleus as it has the largest phase space factor of any other $\beta\beta$ isotopes and possesses a high $Q_{\beta\beta}$ value at 3.4 MeV above the bulk of naturally occurring radioactive backgrounds. By using the full data set, corresponding to 5.25 years, the half-life has been measured to be: $T_{1/2}^{2\nu} = [9.34 \pm 0.22 \text{ (stat.)} +0.62 \text{ (syst.)}] \times 10^{18}$ y, representing the most accurate result to date for this isotope. A multivariate analysis has been performed to search for $0\nu\beta\beta$. As no excess has been observed in the $Q_{\beta\beta}$ region (Figure 2), a lower limit on the half-life has been derived to $T_{1/2}^{0\nu} > 2.0 \times 10^{22}$ y at the 90% C.L. which corresponds to $\langle m_{\beta\beta} \rangle < (1.6-5.3)$ eV assuming the process is mediated by a light Majorana neutrino exchange [6].

2.2. ¹¹⁶Cd results

410 g of ¹¹⁶Cd ($Q_{\beta\beta} = 2.8$ MeV) contained in five foils were installed in the detector. After an exposure of 5.26 years, (4968 ± 74) events corresponding to the ¹¹⁶Cd $2\nu\beta\beta$ decay have been observed with a signal to background ratio of about 12. The $2\nu\beta\beta$ half-life has been measured to be $T_{1/2}^{2\nu} = [2.74 \pm 0.04 \text{ (stat.)} \pm 0.18 \text{ (syst.)}] \times 10^{19} \text{ y}$ The search for $0\nu\beta\beta$ decay has (Figure 3). been performed using a multivariate analysis. No signal has been observed, a limit has been set to $T_{1/2}^{0\nu} > 1.0 \times 10^{23}$ y at the 90% C.L. corresponding to $\langle m_{\beta\beta} \rangle < (1.4-2.5)$ eV in the hypothesis of light Majorana neutrino exchange. Limits on other mechanisms generating $0\nu\beta\beta$ have also been obtained [7].



Figure 2: Total energy distribution of the $2\nu\beta\beta$ events in ¹⁵⁰Nd foil for the data and expected background [6].



Figure 3: Total energy distribution of the $2\nu\beta\beta$ events in ¹¹⁶Cd foil for the data and expected background [7].

2.3. $0\nu4\beta$ results

Heeck and Rodejohann pointed out that lepton violation is possible even if neutrinos are Dirac particles [8]. Constructing a model with a violation of the lepton number by four units, the $0\nu4\beta$ decay is allowed contrary to the $0\nu\beta\beta$ process. The best candidate for the $0\nu4\beta$ decay is the ¹⁵⁰Nd (¹⁵⁰Nd \rightarrow ¹⁵⁰Gd + 4e) which has the highest $Q_{4\beta}$ at 2.084 MeV. This search can be realized by using the unique ability of NEMO-3 to reconstruct the kinematics of each electron. After a total exposure of 0.19 kg·y no evidence of lepton violation process by four units has been observed (Figure 4). Lower limits on the half-life in the range $T_{1/2}^{0\nu4\beta} > (1.1 - 3.2) \times 10^{21}$ y at 90% C.L. have been set depending on the model used for the kinematic distributions of the emitted electrons.



Figure 4: Total energy distribution of the 4-e events in ¹⁵⁰Nd foil for the data and expected signal and background [9].

3. Installation status of the SuperNEMO demonstrator module

SuperNEMO is the successor of the NEMO-3 detector [10]. Its goal is to search for $0\nu\beta\beta$ decays with a sensitivity of 10^{26} y corresponding to $\langle m_{\beta\beta} \rangle < (0.04\text{-}0.1)$ eV. After an extended R&D program to improve the detector design and its radiopurity, the construction of the first module, called demonstrator, is ongoing at LSM. The goals of this demonstrator module which will contain 7 kg of ⁸²Se are multiple : validate the detector improvements, verify that a very low level of background is achievable (10^{-4} events/keV/kg/y in the region of interest) and reach a sensitivity of ~ 6 × 10^{24} y after 2.5 y of data taking.

3.1. Tracker and calorimeter installation

The SuperNEMO calorimeter consists of 712 optical modules distributed in six walls. Each optical module is made of a polystyrene cubic scintillator block directly coupled to 8" PMTs (440) or 5" PMTs (272). The optical module of the two main calorimeter walls have been built in France and have all been assembled at LSM. A photo of one of the two assembled main walls is shown in Figure 5 (right).



Figure 5: SuperNEMO demonstrator module installation at LSM. Left: photo of one half of the tracker. Right: photo of one of the calorimeter main wall.

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The SuperNEMO tracker consists of 2034 drift cells working in Geiger mode. The four C-shape sections of the tracker has been constructed with ultrapure materials (copper, steel, duracon), commissioned in the UK and moved to LSM by December 2016. The two first C-sections have been joined (left photo of Figure 5) and coupled to the first calorimeter wall to form half of the demonstrator module. The commissioning of this half detector started in February 2017.

3.2. Source foil mounting

The SuperNEMO demonstrator module will contain 7 kg of ⁸²Se ($Q_{\beta\beta} = 2.998$ MeV) distributed in 36 foils of 2.7 m long and 13.5 cm wide. Foils are made of selenium powder mixed with a radiopure glue and water inserted between two Mylar films providing mechanical strength. Different methods for the selenium purification have been tested such as distillation, chromatography or chemical precipitation. In order to verify the very challenging requirements on foil contamination, 10 μ Bq/kg and 2 μ Bq/kg for the ²¹⁴Bi and ²⁰⁸Tl respectively, the radiopurity of the source foils is measured in a dedicated detector called BiPo [11] built at *Laboratorio Subterràneo de Canfranc* (LSC). All the source foils have been made and will be installed in the detector during fall 2017.

3.3. Calibration

The detector calibration system is composed of two parts. The first one allows to get monthly measurements of the absolute energy by introducing ²⁰⁷Bi sources into the detector via a system of weights and stepper motors. The second one is a light injection system which will be used daily to guarantee the stability of the calorimetric response to 1%.

4. Conclusion

From 2003 to 2011, the NEMO-3 experiment searched for $0\nu\beta\beta$ decay and took data allowing high presicion measurements of $2\nu\beta\beta$ decay among seven isotopes. The latest results concerning the ¹⁵⁰Nd and ¹¹⁶Cd isotopes have been presented. After an exposure of 5.25 y investigating 36.6 g of ¹⁵⁰Nd, no signal has been found and a limit has been set to $T_{1/2}^{0\nu}$ (¹⁵⁰Nd)> 2.0 × 10²² y at the 90% C.L. With 410 g of ¹¹⁶Cd investigated during 5.26 y, no $0\nu\beta\beta$ signal has been found and a limit has been derived to $T_{1/2}^{0\nu}$ (¹¹⁶Cd)> 1.0 × 10²³ y at the 90% C.L. The search for quadruple beta decay in the ¹⁵⁰Nd sample has been performed for the first time. No signal of $0\nu4\beta$ has been found and limits have been set on the process half-life to $T_{1/2}^{0\nu4\beta} > (1.1 - 3.2) \times 10^{21}$ y at 90% C.L depending on the model. The SuperNEMO demonstrator module is currently installed and commissioned at LSM. The first physics data are expected at the beginning of 2018.

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