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THE NEMO-3 EXPERIMENT AND THE SUPERNEMO PROJECT

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The NEMO experiment is investigating the neutrinoless double beta decay. The NEMO-3 detector is taking data in the Frejus Underground Laboratory.

The goal of the SuperNEMO detector is to reach a sensitivity on the order of 10^{26} year on the half-life of the $\beta\beta_{0\nu}$ process. The chosen isotopes for the future detector are ^{82}Se and ^{150}Nd , because of the reduced background. The collaboration has started a 3-year R&D development on all components : tracking detector, calorimeter, source enrichment and purification, radiopurity measurements.

1. THE NEMO 3 DETECTOR

The NEMO 3 has been taking data since 2003 in the Modane underground laboratory located in the Frejus tunnel at the depth of 4800 m w.e. Its method of $\beta\beta$ -decay study is based on the detection of the electron tracks in a tracking device and the energy measurement in a calorimeter.

The detector [1] has a cylindrical shape. Thin source foils ($\sim 50 \text{ mg/cm}^2$) are located in the middle of the tracking volume surrounded by the calorimeter. Almost 10kg of enriched $\beta\beta$ isotopes (listed in Table I) were used to produce the source foils. The tracking chamber contains 6180 open drift cells operating in the Geiger mode. It provides a vertex resolution of about 1 cm. The calorimeter consists of 1940 plastic scintillator blocks with photomultiplier readout. The energy resolution is $14\text{-}17\%/\sqrt{E}$ FWHM. The time resolution of 250 ps allows excellent suppression of the crossing electron background. A 25 G magnetic field is used for charge identification.

The detector is capable of identifying e^- , e^+ , γ and α particles and allows good discrimination between signal and background events.

2. NEMO 3 RESULTS

2.1. MEASUREMENT OF $2\nu\beta\beta$ HALF-LIVES

Measurements of the $2\nu\beta\beta$ decay half-lives were performed for 7 isotopes available in NEMO 3 (see Table I). New preliminary results based on higher statistics than previously are presented here for two of these isotopes: ^{48}Ca and ^{96}Zr .

Table I: NEMO 3 results of half-life measurement.

Isotope	Mass (g)	$Q_{\beta\beta}$ (keV)	Signal/Background	$T_{1/2}$ [10^{19} years]
^{100}Mo	6914	3034	40	0.711 ± 0.002 (stat) ± 0.054 (syst) [2]
^{82}Se	932	2995	4	9.6 ± 0.3 (stat) ± 1.0 (syst) [2]
^{116}Cd	405	2805	7.5	2.8 ± 0.1 (stat) ± 0.3 (syst)
^{150}Nd	37.0	3367	2.8	$0.920^{+0.025}_{-0.022}$ (stat) ± 0.062 (syst)
^{96}Zr	9.4	3350	1.	2.3 ± 0.2 (stat) ± 0.3 (syst)
^{48}Ca	7.0	4772	6.8	$4.4^{+0.5}_{-0.4}$ (stat) ± 0.4 (syst)
^{130}Te	454	2529	0.25	76 ± 15 (stat) ± 8 (syst)

The measurement of the ^{96}Zr half-life was performed using the data collected within 925 days. A total of 678 events were selected, with the expected 328 background events. The largest background contribution is due to the

internal ^{40}K contamination of the sample. The distribution of the energy sum of two electrons and their angular distribution are shown in Fig. 1, demonstrating good agreement of the data with the Monte Carlo simulation. The $2\nu\beta\beta$ efficiency is estimated to be 7.6%. The measured half-life is $T_{1/2}^{2\nu}(^{96}\text{Zr}) = [2.3 \pm 0.2(\text{stat}) \pm 0.3(\text{syst})] \cdot 10^{19}\text{y}$.

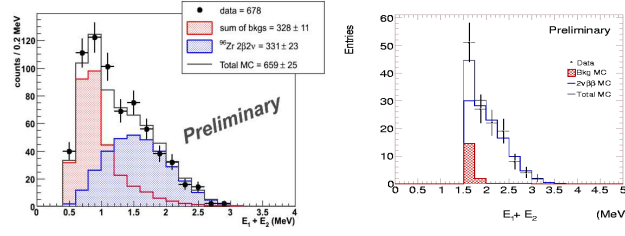


Figure 1: The energy sum and for two-electron events from ^{96}Zr and ^{48}Ca .

The ^{48}Ca sample used in NEMO 3 is known to be contaminated by ^{90}Sr ($T_{1/2}=28.79\text{ y}$, $Q_{\beta}=0.546\text{ MeV}$). Its daughter ^{90}Y ($T_{1/2}=3.19\text{ h}$, $Q_{\beta}=2.282\text{ MeV}$) is the major background source in this case. An activity of $1699 \pm 3\text{ mBq/kg}$ was measured for ^{90}Y using single-electron events. Both ^{90}Sr and ^{90}Y are essentially pure β^{-} emitters and imitate $\beta\beta$ events through Möller scattering. To suppress this background contribution, events with the energy sum greater than 1.5 MeV and $\cos(\Theta_{ee}) < 0$ are selected. Finally, with 943 days of data taking, there are a total of 133 two-electron events, with an evaluated residual background contribution of 17 events. Their two-electron energy sum distribution is presented in Fig. 1. The $2\nu\beta\beta$ efficiency is 3.3%, and the measured half-life is $T_{1/2}^{2\nu}(^{48}\text{Ca}) = [4.4_{-0.4}^{+0.5}(\text{stat}) \pm 0.4(\text{syst})] \cdot 10^{19}\text{y}$.

2.2. SEARCH FOR $0\nu\beta\beta$ DECAY

In the case of the mass mechanism, the $0\nu\beta\beta$ -decay signal is expected to be a peak in the energy sum distribution at the position of the transition energy $Q_{\beta\beta}$. Since no excess is observed at the tail of the distribution for ^{96}Zr , see Fig. 1 (left), nor for ^{48}Ca , Fig. 1 (right), limits are set on the neutrinoless double beta decay $T_{1/2}^{0\nu}$ using the CLs method [3]. A lower half-life limit is translated into an upper limit on the effective Majorana neutrino mass $\langle m_{\nu} \rangle$. The following results are obtained using the NME values from papers [4], [5] for ^{96}Zr and from paper [6] for ^{48}Ca

$$T_{1/2}^{0\nu}(^{96}\text{Zr}) > 8.6 \cdot 10^{21}\text{y} \quad (90\% \text{ C.L.}) \quad \langle m_{\nu} \rangle < 7.4 - 20.1 \text{ eV}$$

$$T_{1/2}^{0\nu}(^{48}\text{Ca}) > 1.3 \cdot 10^{22}\text{y} \quad (90\% \text{ C.L.}) \quad \langle m_{\nu} \rangle < 29.7 \text{ eV}.$$

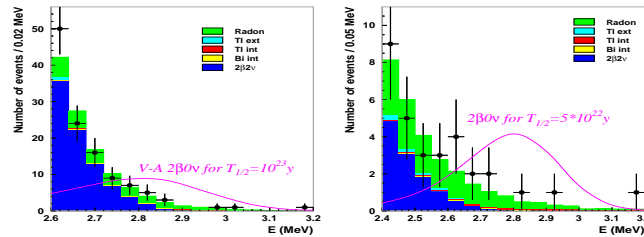


Figure 2: Distribution of the energy sum of two electrons for ^{100}Mo (left) and ^{82}Se (right).

The $0\nu\beta\beta$ -decay search in NEMO 3 is most promising with ^{100}Mo and ^{82}Se because of the larger available isotope mass and high enough $Q_{\beta\beta} \sim 3\text{ MeV}$. The two-electron energy sum spectra obtained from the analysis of the data taken within 693 days are shown in Fig. 2. For ^{100}Mo there are 14 events observed in the 0ν search window [2.78-3.20] MeV in good agreement with the expected background of 13.4 events. For ^{82}Se there are 7 events found in the energy

sum interval [2.62-3.20] MeV, compared to the expected background of 6.4 events. The limits on the $T_{1/2}^{0\nu}$ and the corresponding $\langle m_\nu \rangle$ limits calculated using the recent NME values [4]: [5] are

$$\begin{aligned} T_{1/2}^{0\nu}(^{100}\text{Mo}) > 5.8 \cdot 10^{23} \text{y} \quad (90\% \text{ C.L.}) & \quad \langle m_\nu \rangle < 0.61\text{--}1.26 \text{ eV} \\ T_{1/2}^{0\nu}(^{82}\text{Se}) > 2.1 \cdot 10^{23} \text{y} \quad (90\% \text{ C.L.}) & \quad \langle m_\nu \rangle < 1.4\text{--}2.2 \text{ eV}. \end{aligned}$$

3. THE PRINCIPLE AND CHARACTERISTICS OF THE SUPERNEMO DETECTOR

The SuperNEMO collaboration has started in February 2006 a 3-year R&D phase; the goals of this R&D are summarized in table II. This R&D phase has been approved in France, UK and Spain. Similar proposals are under consideration in Russia, Czech Republic and Japan. The method is to have R&D tasks on critical components (obtain a 4 % FWHM for the calorimeter energy resolution for 3 MeV electrons, optimize the tracking detector, develop a wiring automation, produce ultrapure sources and control their purity, simulate the sensitivity of the detector). At the end of the R&D phase, a Technical Design Report will be written and the experimental site (Modane(Frejus), Canfranc, Gran Sasso or Boulby) will be selected.

Experiment	NEMO-3	SuperNEMO
Choice of isotope	¹⁰⁰ Mo	¹⁵⁰ Nd or ⁸² Se
Isotop mass	7 kg	100-200 kg
Internal contaminations	²⁰⁸ Tl < 20 μBq/kg	²⁰⁸ Tl < 2 μBq/kg
²⁰⁸ Tl and ²¹⁴ Bi in the foil	²¹⁴ Bi < 300 μBq/kg	²⁰⁸ Tl < 10 μBq/kg
Energy resolution FWHM (calorimeter)	8% at 3 MeV	4% at 3 MeV
Sensitivity $T_{1/2}(\beta\beta 0\nu) > 2 \cdot 10^{24} \text{y}$		$T_{1/2}(\beta\beta 0\nu) > 10^{26} \text{y}$
	$\langle m_\nu \rangle < 0.3\text{--}0.9 \text{ eV}$	$\langle m_\nu \rangle < 40\text{--}110 \text{ meV}$

Table II: Characteristics of the running experiment NEMO-3 and of the project of future detector SuperNEMO.

A possible design for the SuperNEMO detector [7] could be planar and modular : the 100 kg of enriched isotopes could be placed in 20 modules each containing 5 kg of isotopes. Each source could have a thickness of 40 mg/cm² and a surface of 4 x 3 m². For each module, the tracking device could be a drift chamber made of around 3000 cells, operating in Geiger mode. For each module, the calorimeter could either be made of around 1000 scintillators blocks coupled to low-radioactivity PMTs, or of scintillators bars, coupled to around 100 PMTs (see figure 3).

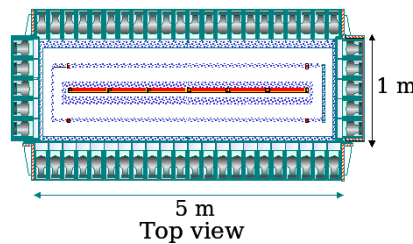


Figure 3: Top view of a module in a possible design of the SuperNEMO detector. The source shown in red is surrounded by Geiger cells shown in dark blue and by plastic scintillators blocks coupled to low radioactivity PMTs.

4. THE R&D TASKS

4.1. R&D ON MEASUREMENT OF MATERIAL RADIOPURITIES

The best sensitivity for the high-purity Germanium detectors used for NEMO-3 is 60 μBq/kg for ²⁰⁸Tl and 200 μBq/kg for ²¹⁴Bi. The goal of the R&D phase is to improve the sensitivity by developing 800 cm³ high

purity Germanium (with Canberra-Eurisys) with shields improvement and a new ultra-pure cryostat. A new planar Germanium detector with a resolution of 0.5 keV at 40 keV is also in development.

The BiPo detector [8] has been developed to measure the radiopurity in ^{208}Tl and in ^{214}Bi of the source foils before their installation in the SuperNEMO detector. The goal is to measure 5 kg of foils in 1 month with a sensitivity of 2 $\mu\text{Bq/kg}$ in ^{208}Tl and of 10 $\mu\text{Bq/kg}$ in ^{214}Bi . The principle is to tag the electron emitted by the beta desintegration of ^{212}Bi or of ^{214}Bi , then to tag the alpha emitted by the desintegration of ^{212}Po or of ^{214}Po (with a decay half-time of 300 ns or of 164 μs). The thin source can be put in a sandwich of scintillators. For the measurement of the source contained in one module of the SuperNEMO detector (12 m²), the background has to be very low, less than 1 event per month. Already, a prototype using 20cm x 20 cm x 3 mm plastic scintillators has been developed and installed in the Frejus Underground Laboratory; with the measured background, the expected sensitivity extrapolated for the full BiPo detector is of the order of 5 $\mu\text{Bq/kg}$ in ^{208}Tl .

4.2. R&D ON CALORIMETER

The goal of the calorimeter R&D is to reach a FWHM energy resolution of 4% for 3 MeV electrons (7% for 1 MeV electrons) and to optimize the number of channels and the detector geometry.

The goal of the R&D for scintillators is to improve the light yield and the homogeneity. Plastic scintillators are developed in collaboration with Kharkhov and Dubna, trying to improve the performances of polystyrene and to develop polyvinylxylene. Already, a FWHM of $(8.2 \pm 0.1) \%$ for 1 MeV electrons has been obtained for 10 cm thick plastic scintillator coupled to a 8'' PMT. Tests with different wrappings of the scintillators are also proceeded in Kharkhov. Liquid scintillators are also studied : their advantages are the high light yield, the very good uniformity and transparency; the challenge is to satisfy the mechanical constraints, especially for the entrance window, which has to be as thin as possible, in order not to degrade the electron energy.

The aim of the R&D for PMTs is to improve the quantum efficiency, the collection efficiency and to develop low radioactivity PMTs : an agreement between PHOTONIS and IN2P3 has been signed, tests are also done with Hamamatsu and ETL. Already, PMTs with very high quantum efficiencies (43% for 3 inches and 35% for 8 inches) have been developed. Slow and fast PMTs are also studied. The goal is also to have a higher compacity by reducing the number of channels, without reducing too much the light collection. The energy measurement with scintillator bars with 2 PMTs or with optical fibers is also studied.

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