Topological detection of double beta decay with NEMO3 and SuperNEMO

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Abstract.

Since 2003 NEMO3 experiment has been searching for neutrinoless ($0\nu\beta\beta$) and two neutrino ($2\nu\beta\beta$) double beta decay using about 10 kg of enriched isotopes. A limit on the Majorana effective mass ($< m_\nu >$) has been obtained and several measurements of $2\nu\beta\beta$ decays have been performed. The results are reported here. In parallel, there is an active R&D programme for the SuperNEMO experiment which is expected to commence data taking in 2012-2013 and will use 100 kg of enriched isotope to reach a sensitivity to $< m_\nu >$ at the level of $50-100$ meV by 2017. The unique approach of these experiments is a tracking plus calorimetry technique which allows a topological signature of $\beta\beta$ events to be detected.

1. Introduction

Neutrinoless double beta decay ($0\nu\beta\beta$) leads to the decay of a nucleus of charge Z and atomic number A via the process $(Z,A) \rightarrow (Z+2,A) + 2e^-$. This decay violates total lepton number L and its observation would therefore be a direct indication for physics beyond the Standard Model. Neutrinos would be Majorana and not Dirac particles, thereby solving one of the fundamental questions of particle physics. The $0\nu\beta\beta$ half-life is given by

$$[T^{0\nu}_{1/2}(A,Z)]^{-1} = |\eta|^2 \cdot |M^{0\nu}(A,Z)|^2 \cdot G^{0\nu}(Q_{\beta\beta},Z), \tag{1}$$

where η is a lepton number violating parameter, $M^{0\nu}$ is the nuclear matrix element (NME) and $G^{0\nu}$ is a known phase space factor. The mechanism most commonly discussed is the one shown in Fig. 1 where a light Majorana neutrino is exchanged in which case $|\eta| = \langle m_\nu \rangle$. However many other mechanisms are possible: V+A currents, Majoron emission, R-parity violating SUSY, to name a few.

Observation of the topological signature of the $\beta\beta$ decay, the angular distribution between the emitted electrons and their individual energies provides a way of discriminating the underlying physics mechanism. In addition the $\beta\beta$ topological signature observed in a tracking detector provides an unambiguous signature of the process ("smoking gun"). The unique feature of the NEMO3 and SuperNEMO experiments is a tracking plus calorimetry technique which allows a topological signature of $\beta\beta$ events to be detected.

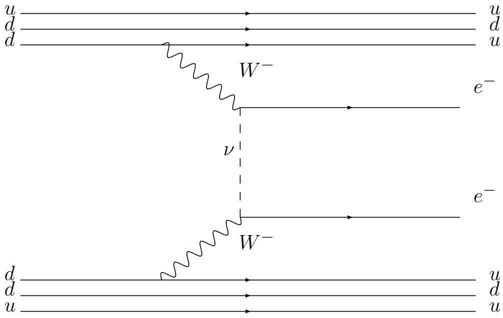

Figure 1. Feynman diagram of $0\nu\beta\beta$ decay via light Majorana neutrino exchange.

2. NEMO3

The NEMO3 detector is situated in the Modane underground laboratory (LSM) in the Frejus tunnel between France and Italy. The underground laboratory is shielded from cosmic rays by 1700 m of rock overburden, corresponding to 4800 m of water equivalent. The NEMO3 detector consists of a cylinder made of detector segments containing different samples of double beta decay enriched isotopes.

The source foils of $\beta\beta$ emitters were constructed from either a metal film or powder bound by an organic glue to mylar strips. The source hangs between two concentric cylindrical tracking volumes consisting of open octagonal drift cells operating in Geiger mode (6180 cells).

The external walls of these tracking volumes are covered by calorimeters made of large blocks of plastic scintillator (1940 blocks in total) coupled to low radioactivity PMTs. The electron tracks curve under the influence of a 25 G magnetic field to reject pair production events. The detector is substantially shielded from the external gamma ray background by 20 cm of low activity iron and 30 cm of water with boron acid to suppress the neutron flux.

There are seven different isotopes studied in NEMO3. The two isotopes with the largest mass are ^{100}Mo (6.9 kg) and ^{82}Se (0.93 kg). The other five isotopes are ^{130}Te (454g), ^{116}Cd (405 g), ^{150}Nd (37 g), ^{96}Zr (9.4 g), ^{48}Ca (7 g) which are used for $2\nu\beta\beta$ decay and background studies. NEMO3 has been taking physics data since February 2003.

The $\beta\beta$ events are selected by requiring two reconstructed electron tracks with a curvature corresponding to the negative charge, originating from a common vertex in the source foil (see Fig. 2). The detection of a clear topological signature allows unambiguous reconstruction of $\beta\beta$ events and a powerful background rejection.

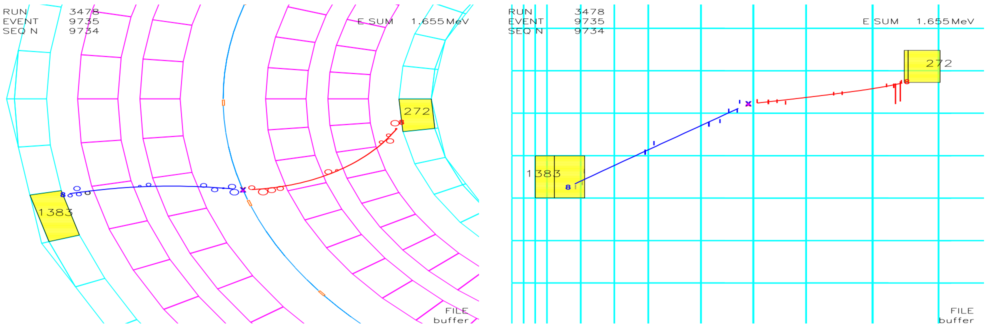

Figure 2. A $\beta\beta$ event signature observed in the NEMO3 detector. Left: top view, right: side view.

A detailed description of the NEMO3 detector and its performance can be found in [1].

2.1. NEMO3 results.

Measurements of the $2\nu\beta\beta$ decay half-lives have been performed with unprecedented precision for the seven isotopes available in NEMO3. The results are shown in Table 1.

Table 1. NEMO-3 results of $2\nu\beta\beta$ decay half-life measurements for seven isotopes.

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) $\pm\ 0.054$ (syst) [2]
^{82}Se	932	2995	4	9.6 ± 0.3 (stat) $\pm\ 1.0$ (syst) [2]
^{116}Cd	405	2805	7.5	2.8 ± 0.1 (stat) $\pm\ 0.3$ (syst) [3]
^{150}Nd	37.0	3367	2.8	$0.920^{+0.025}_{-0.022}$(stat) $\pm\ 0.072$ (syst) [4]
^{96}Zr	9.4	3350	1.	2.3 ± 0.2 (stat) $\pm\ 0.3$ (syst) [4]
^{48}Ca	7.0	4272	6.8	$4.4^{+0.5}_{-0.4}$(stat) $\pm\ 0.4$ (syst) [4]
^{130}Te	454	2529	0.25	76 ± 15 (stat) $\pm\ 8$ (syst) [3]

The most precise measurements were obtained for ^{100}Mo and ^{82}Se but the results for other isotopes are also most accurate to date. Fig. 3 shows one of the most recent results, the ^{96}Zr-isotope half-life measurement.

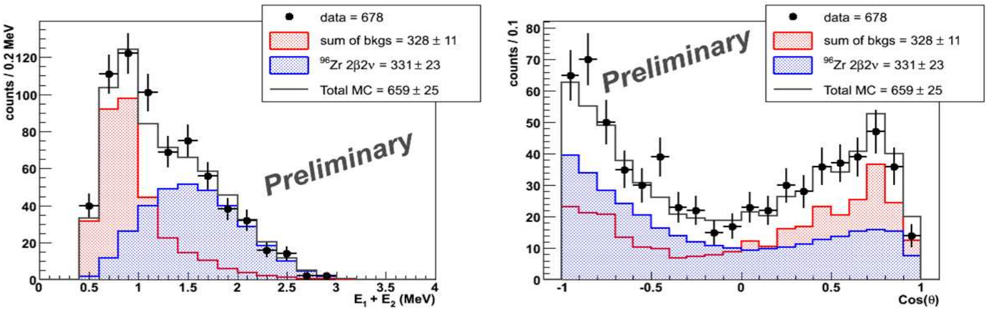

Figure 3. The sum of the energies of the two electrons and their angular separation for two-electron events for ^{96}Zr.

The distribution of the energy sums of the two electrons around the $Q_{\beta\beta}$ value was used to search for $0\nu\beta\beta$ in all isotopes. The best sensitivity was obtained with the ^{100}Mo data. Using the data until spring 2006 a limit on the $0\nu\beta\beta$ half-life of ^{100}Mo was set to be $T^{0\nu}_{1/2} > 5.8 \cdot 10^{23}$ yr at 90% CL which translates into a limit on the neutrino mass of $< m_\nu > <$ 0.8–1.3 eV. The half-life limit was also used to obtain the best constrain on Majoron-neutrino coupling to date , $\langle g_{ee} \rangle < (0.4 - 1.8) \cdot 10^{-4}$ [5]. The ranges in the values of $< m_\nu >$ and $\langle g_{ee} \rangle$ are due to uncertainties in NME calculations. The collaboration will release a new result covering the entire data taking period in summer 2009 and once again at the end of running in 2011. The final sensitivity of NEMO3 will be $< m_\nu > <$ 0.4–0.8 eV.

3. SuperNEMO

SuperNEMO aims to extend and improve the experimental techniques used by NEMO3 to search for neutrinoless double beta decay. It will extrapolate the successful NEMO3 technology over one order of magnitude by studying about 100 kg of double beta decay isotopes. The detector's ability to measure any $\beta\beta$ isotope and the topological signature are distinct features of SuperNEMO. The baseline isotope choice for SuperNEMO is ^{82}Se and ^{150}Nd , if the enrichment of the latter proves to be feasible. The experiment will reach a sensitivity to the Majorana neutrino mass,$< m_\nu >$, of 50-100 meV in 5 years of running which, according to the current schedule, will start in 2012.

3.1. SuperNEMO detector design.

The baseline SuperNEMO design envisages about twenty identical modules, each housing around 5 kg of isotope. A preliminary design of a SuperNEMO detector module is shown in Fig. 4.

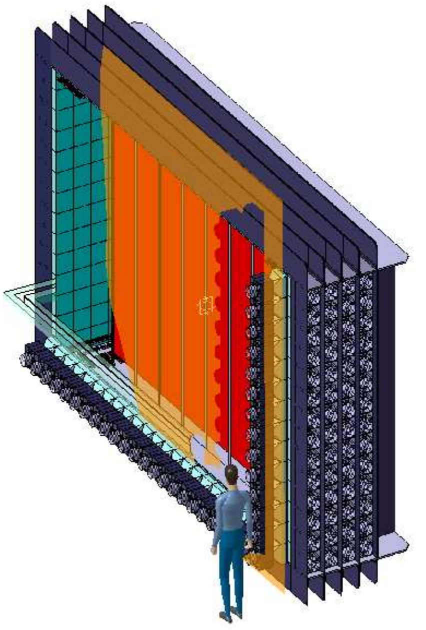

Figure 4. Schematic of a proposed SuperNEMO module showing the source foil surrounded by a tracking volume and scintillator blocks read out by PMTs.

The source is a thin ($\sim$ 40 mg/cm^2) foil inside the detector. It is surrounded by a gas tracking chamber followed by calorimeter walls. The tracking volume contains around 2000 wire drift cells operated in Geiger mode which are arranged in nine layers parallel to the foil. The calorimeter is divided into 700 plastic scintillator hexagonal blocks (25 cm diameter) which cover most of the detector outer area and are coupled to low radioactive 8-inch PMTs. In parallel with the baseline design, an alternative design is being investigated. The latter is based on long (2 m) scintillator bars read out from both ends by two 3-inch PMTs. In this case, the entire detector is built as a single module with calorimeter walls and source foils "sandwiched" between each other.

3.2. SuperNEMO design study

The SuperNEMO R&D programme (2006–2009) is currently underway, supported by funding agencies in the UK, France, Russia, Czech Republic, Spain and other countries. The programme addresses three main challenges: improvement of the calorimeter energy resolution, radio-purity of the source foils and optimisation of the tracker detector for large-scale production under low background requirements.

The expected improvement in performance of SuperNEMO compared to its predecessor NEMO3 is shown in Table 2. The most important design study tasks are described in the sections that follow.

Table 2. Comparison of the main NEMO 3 and SuperNEMO parameters.

	NEMO 3	SuperNEMO
Isotope	^{100}Mo	^{82}Se or ^{150}Nd
Mass	7 kg	100 kg
Detection efficiency	18%	$> 30\%$
^{208}Tl in foil	$< 20\mu$Bq/kg	$< 2\mu$Bq/kg
^{214}Bi in foil	$< 300\mu$Bq/kg	$< 10\mu$Bq/kg (^{82}Se)
energy resolution at 3 MeV	8% (FWHM)	4% (FWHM)
half-life	$T^{0\nu}_{1/2} > 1.5 \cdot 10^{24}$ years	$T^{0\nu}_{1/2} > 10^{26}$ years
neutrino mass	$\langle m_{\beta\beta}\rangle < 0.4 - 0.8$ eV	$\langle m_{\beta\beta}\rangle < 0.05 - 0.1$ eV

3.3. Energy resolution

An excellent energy resolution is vital for discriminating the $0\nu\beta\beta$ peak in the energy sum of the two electrons from the background of two-neutrino beta decay. The energy resolution is determined by two factors, the electron energy losses in the foil and the calorimeter resolution.

SuperNEMO aims to improve the calorimeter energy resolution to $7\%/\sqrt{E}$ at FWHM (compared to the NEMO3 resolution of $\sim 14\%/\sqrt{E}$).

A large number of studies have been carried out investigating the choice of calorimeter parameters such as scintillator material (organic plastic, liquid, or non-organic), and the shape, size and coating of calorimeter blocks. These are combined with dedicated development of PMTs with low radioactivity and high quantum efficiency. The target energy resolution (7% at 1 MeV) has been demonstrated with large hexagonal (25 cm diameter) PVT-based plastic scintillator blocks coupled to high-QE low radioactive 8" PMTs. In addition a record energy resolution has been obtained for the bar design (10% at 1 MeV). The final choice between the two designs will be made in June 2009. The next step is to demonstrate that these detector parameters can be maintained during mass production of the detector components.

3.4. Radiopurity of the source

SuperNEMO will search for a very rare process, therefore it must maintain ultra-low background levels. The source foils must be radiopure, and their contamination with naturally radioactive elements must be precisely measured. The most important source contaminants are ^{208}Tl and ^{214}Bi, whose decay energies are close to the neutrinoless signal region. In order to evaluate their activities, a dedicated BiPo detector has being developed which can measure their signature of an electron followed by a delayed alpha particle. The detector has been demonstrated to have the required sensitivity at the level of $\sim 10\ \mu$Bq/kg.

3.5. Tracker design

The SuperNEMO tracker consists of octagonal wire drift cells operated in Geiger mode. Each cell is around 4 m long and has a central anode wire surrounded by 8–12 ground wires, with cathode pickup rings at both ends. Signals can be read out from the anode and/or cathodes to determine the position at which the ionising particle crossed the cell.

The tracking detector design study looks at optimising its parameters to obtain high efficiency and resolution in measuring the trajectories of double beta decay electrons, as well as of alpha particles for the purpose of background rejection. The tracking chamber geometry is being investigated with the help of detector simulations to compare the different possible layouts. In addition, several prototypes have been built to study the drift chamber cell design and size, wire length, diameter and material, and gas mixture.

A large 90-cell prototype has been constructed and commissioned in January 2009. It will be used to finalise the tracker design and to test the mechanics and large-scale operation of the drift cell system.

A single SuperNEMO module will contain about 2000 drift cells with 8–12 wires each. The large total number of wires has lead to the need of automated wiring. A dedicated wiring robot is being developed for the mass production of drift cells.

3.6. SuperNEMO sensitivity

The sensitivity of SuperNEMO has been studied extensively during the current design study phase. A full chain of GEANT4 based simulation software has been developed and commissioned and the sensitivity was studied as a function of various detector parameters such as the calorimeter energy resolution, source foil radio-purity, tracking detector configuration, etc. A summary of these studies is shown in Fig. 5. With the target detector parameters and 500 kg-yr exposure (100 kg of ^{82}Se for 5 years of running), the calculated sensitivity is $\sim 10^{26}$ yrs at 90% CL which corresponds to an upper limit on $< m_\nu >$ of 50–110 meV depending on the NME used. This sensitivity is expected to be reached by 2017.

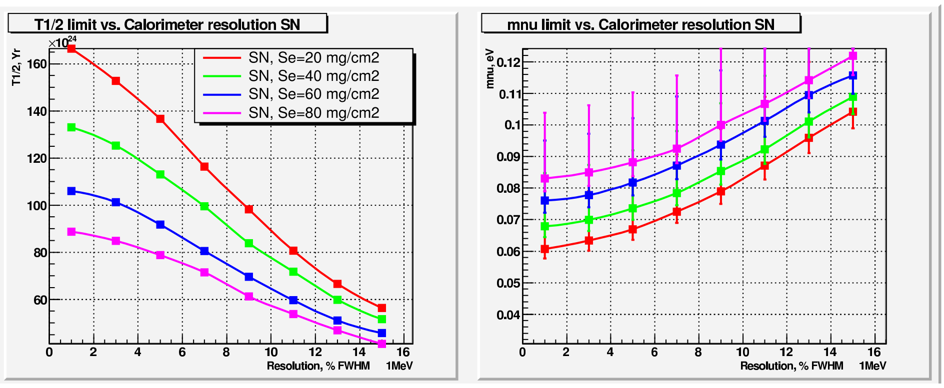

Figure 5. MC simulations of the SuperNEMO sensitivity obtained with 100 kg of ^{82}Se and 5 yr of data taking in terms of half-life (left) and Majorana neutrino mass $< m_\nu >$ (right). NME calculations from [6] are used for the $< m_\nu >$ sensitivity plot. Target values for source contamination are assumed (10 μBq/kg for ^{214}Bi and 2 μBq/kg for ^{208}Tl).

4. Summary

The NEMO approach of using tracking plus calorimetry is unique for a $\beta\beta$ experiment and allows for excellent background rejection, choice of multiple isotopes and full kinematic reconstruction leading to an observation of a “smoking gun” signature of the process. NEMO3 is taking data and have measured the $2\nu\beta\beta$ processes for several nuclei with unprecedented precision. These results provide an experimental input to nuclear matrix element calculations. In addition precise measurements of $2\nu\beta\beta$ processes are important as they provide information on this ultimate background component to $0\nu\beta\beta$. NEMO3 will run until 2011 focusing on $0\nu\beta\beta$ search and will reach a sensitivity to $< m_\nu >$ at the level of 400-800 meV.

At the same time an active R&D programme for the next-generation experiment SuperNEMO which will accommodate a 100 kg of isotope has yielded promising results. The next step is to build a first demonstrator module and install it in 2012 in LSM in place of the NEMO3 detector. The goal of this first module is to demonstrate feasibility of the target detector performance parameters, most importantly the background levels and calorimeter energy resolution. It will also produce a competitive physics measurements improving on the NEMO3 results. The rest of the modules are expected to be installed in the new-LSM underground lab (subject to availability) starting from 2013. SuperNEMO will reach a sensitivity to $< m_\nu >$ at the level of 50–100 meV by 2017.

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