Investigating $\beta\beta$ decay with the NEMO-3 and SuperNEMO experiments

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Abstract. The NEMO-3 and SuperNEMO experiments search for neutrinoless double beta decay (0$\nu\beta\beta$). Detection of 0$\nu\beta\beta$ decay would provide direct evidence that neutrinos are Majorana particles and lepton number is not conserved. In these experiments, the isotopes of interest are separated from the active detector region, allowing for reconstruction of the full event topology. This aids in background suppression and discrimination between underlying 0$\nu\beta\beta$ decay mechanisms. The NEMO-3 experiment investigated a total of seven 0$\nu\beta\beta$ decay isotopes. The SuperNEMO experiment builds upon the design of NEMO-3. Upgrades to the detector technologies and radiopurity, as well as an increase in isotope mass will allow SuperNEMO to improve 0$\nu\beta\beta$ half-life sensitivities by two orders of magnitude. The latest result from NEMO-3 is summarized, and an overview of the progress in the construction of the SuperNEMO demonstrator module is presented.

1. Introduction

Double-$\beta$ decay is a form of nuclear decay that occurs in select isotopes where single $\beta$ decay is energetically forbidden or kinematically suppressed [1]. The Standard Model (SM) allows for $\beta\beta$ decay with the emission of two neutrinos (2$\nu\beta\beta$) [2]. In this process two neutrons decay to protons with the emission of two electrons and two anti-electron neutrinos. This is a second order weak decay characterized by extremely long half-lives spanning a range of $10^{18}$–$10^{21}$ years, depending on the isotope. This process has been directly observed in nine isotopes to date, where the most accurate 2$\nu\beta\beta$ decay half-life measurements for seven of these isotopes come from the NEMO-3 experiment.

Several beyond SM theories postulate that a neutrinoless form of $\beta\beta$ decay may also occur in isotopes where the SM 2$\nu\beta\beta$ decay is possible. Observation of 0$\nu\beta\beta$ decay would provide evidence of lepton number violation, which is a necessary condition for leptogenesis and baryogenesis theories that explain the matter-antimatter asymmetry of the observable universe [1]. Moreover, for 0$\nu\beta\beta$ decay to occur the neutrino ($\nu$) must be a Majorana particle, such that $\nu = \bar{\nu}$ [3, 4]. Therefore observation of this decay would demonstrate that the neutrino is a Majorana particle and therefore fundamentally different from all other fermions, which are Dirac particles.

Several underlying mechanisms can mediate 0$\nu\beta\beta$ decay. The half-life ($T_{1/2}^{0\nu}$) is related to a parameter in the underlying decay mechanism, $\xi$, via the equation

$$T_{1/2}^{0\nu}(A, Z)^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)|M^{0\nu}(A, Z)|^2 \xi^2,$$

(1)
for an isotope with mass number $A$ and atomic number $Z$, where $G^{0\nu}$ is the phase space that depends on both $Z$ and the nuclear transition value $Q_{\beta\beta}$, and $M^{0\nu}$ is the nuclear matrix element (NME). Some of the possible underlying $0\nu\beta\beta$ decay mechanisms include the exchange of a massive Majorana neutrino (mass mechanism), the addition of right-handed currents (RHCs) in the weak interaction, and decays involving the emission of majorons ($\chi^0$) [5, 6, 7, 8]. If $0\nu\beta\beta$ decay is mediated by the mass mechanism, then $\xi = m_{\beta\beta}/m_e$ where $m_e$ is the electron mass and $m_{\beta\beta}$ is the effective Majorana neutrino mass. Therefore, measurement of a $0\nu\beta\beta$ decay rate may provide insight into the absolute scale of the neutrino mass. As $0\nu\beta\beta$ decay has not yet been observed, it is unknown which, if any, of the aforementioned mechanisms is responsible for this decay process.

The experimental signature of $\beta\beta$ decay involves the detection of two electrons emitted simultaneously from a common decay vertex. In $2\nu\beta\beta$ decay, the total measured energy of the two electrons, $E_{TOT}$, forms a continuous spectrum up to the $Q_{\beta\beta}$ value of the isotope under investigation. This can be distinguished from $0\nu\beta\beta$ decays mediated by the mass mechanism where $E_{TOT}$ is equal to the $Q_{\beta\beta}$ value with some spread due to energy resolution effects. Decays mediated by RHCs, majoron emission and other $0\nu\beta\beta$ decay mechanisms can also distinguished from $2\nu\beta\beta$ decay and other background events using the $E_{TOT}$ distribution.

The NEMO-3 and SuperNEMO experiments search for $0\nu\beta\beta$ decay using a heterogeneous detector design, where the $\beta\beta$-decay isotopes are separate from the active detector volume. This allows for the measurement of different final state decay topologies and kinematics, which are used for signal and background discrimination. In addition, the correlations between different observables can be used to distinguish between the different underlying mechanisms should $0\nu\beta\beta$ decay be observed [9].

2. The NEMO-3 experiment
The NEMO-3 experiment was conducted between February 2003 and January 2011 in the Modane Underground Laboratory (LSM). There is an overburden of about 4800 m.w.e. at LSM, which provides shielding from cosmic rays. The NEMO-3 detector (Fig 1) is cylindrical and divided into 20 equal sectors. Seven $\beta\beta$-decay isotopes with a total mass of $\sim 10$ kg are distributed around the sectors. The most massive isotope is $^{100}$Mo with 7 kg, which provides the best sensitivity in the search for $0\nu\beta\beta$ decay. The other isotopes include $^{82}$Se, $^{130}$Te, $^{116}$Cd, $^{150}$Nd, $^{96}$Zr, and $^{48}$Ca [10].

The $\beta\beta$-decay sources are produced as thin foils with a width of 63-65 mm, a height of approximately 2.4 m, and a thickness of 30-60 mg/cm$^2$. They are distributed around a fixed radius of about 155 cm. The source foils are surrounded by two wire tracking chambers composed of Geiger cells that provide 3D position measurements of charged particles passing through the detector volume. Surrounding the tracker is the segmented calorimeter, composed of plastic scintillator blocks coupled to low-radioactivity photomultiplier tubes (PMTs), which provides timing and energy measurements. A solenoid surrounding the detector provides a magnetic field of 25 G parallel to the axis of the cylinder to enable charge identification. An extensive passive shielding system composed of iron, wood, borated water and paraffin is used to reduce the external neutron and $\gamma$ ray flux coming from decays of naturally occurring isotopes in the environment surrounding the detector. An anti-radon facility was also installed after the first year of detector operation to reduce the radon activity by a factor of six. More detailed information about the detector can be found in [10]. Using the combined information from the tracker and calorimeter, the NEMO-3 detector is capable of identifying $e^+$, $e^-$, $\alpha$ particles and $\gamma$ rays.

Analysis of the full data set collected with the NEMO-3 detector is ongoing for several isotopes. The most stringent limits on the $0\nu\beta\beta$ decay rate from NEMO-3 are obtained with the isotope $^{100}$Mo [11].
The search for $0\nu\beta\beta$ decay is performed by requiring two reconstructed tracks originating from a common decay vertex in the location of the $^{100}$Mo source foils. Two isolated calorimeter hits, each with an energy deposit greater than 0.2 MeV, must be compatible with the track extrapolation to the calorimeter, both with respect to their impact positions and arrival times under the assumption of simultaneous emission from the source foil. These selection criteria define the $2e$ signal channel, which provides the best sensitivity to search for $\beta\beta$-decay processes.

With an exposure of 34.7 kg·y of $^{100}$Mo, 15 data events are observed in the $0\nu\beta\beta$ decay region of interest, defined as $2.8 < E_{TOT} < 3.2$ MeV as shown in Fig 1. The total number of expected background events is $18.0 \pm 0.6$. The most significant contribution is $8.45 \pm 0.05$ events from the $2\nu\beta\beta$ decay of $^{100}$Mo. This is estimated from the same 2e channel using events with $E_{TOT} < 2.8$ MeV to determine the $2\nu\beta\beta$ decay rate. The expected number of events from the other sources of background are estimated using independent background channels defined by final state toplogies that enhance the efficiency for detecting background decays [11]. No excess of data is observed over the expected background rate. The limits derived for several underlying $0\nu\beta\beta$ decay mechanisms are presented in Table 1. The most stringent limit is associated with the mass mechanism, with a half-life $T_{1/2}^{0\nu} > 1.1 \times 10^{24}$ y at 90%, which translates in to an upper limit on the effective Majorana neutrino mass of $m_{\beta\beta} < 0.33 - 0.62$ eV [11].

As previously mentioned, analysis of the full data set is currently underway for the other isotopes used in the NEMO-3 experiment. Updated results for $2\nu\beta\beta$ decay measurements and $0\nu\beta\beta$ decay searches for several of these isotopes can be expected in the near future.

3. The SuperNEMO experiment

The SuperNEMO experiment builds upon the success and design of NEMO-3. A schematic of one SuperNEMO module is shown in Fig. 2. There will be 20 modules in the full experiment, housing a total of 100 kg of $^{82}$Se produced as thin foils. Each identical module employs the same tracker-calorimeter design as in NEMO-3, with the foils located at the center of a module surrounded by wire tracking chambers and a segmented calorimeter made of PMTs coupled to

1 No neighbouring calorimeter hits contain an energy deposit.
Table 1: The most stringent $T_{1/2}^{0\nu}$ limits from the NEMO-3 experiment for several possible underlying decay mechanisms. Results are obtained using 34.7 kg y of the isotope $^{100}$Mo [11].

| $0\nu\beta\beta$ decay mechanism | $T_{1/2}^{0\nu}$ [$\times10^{24}$ y] (90% CL) | $\xi$ (90% CL) |
|----------------------------------|---------------------------------------------|----------------|
| Mass mechanism                   | $> 1.1$                                     | $m_{\beta\beta} < 0.33 - 0.62$ eV            |
| RHC ($\eta$)                     | $> 1.0$                                     | $\langle \eta \rangle < (0.5 - 0.8) \times10^{-8}$ |
| RHC ($\lambda$)                  | $> 0.7$                                     | $\langle \lambda \rangle < (0.9 - 1.3) \times10^{-6}$ |
| Majoron ($\chi_0^{n=1}$)        | $> 0.05$                                    | $\langle g_{ee} \rangle < 1.6 - 3.0 \times10^{-5}$ |

scintillator blocks.

The increased isotope mass, reduced background levels, and improved tracker and calorimeter performance in SuperNEMO lead to an increase in the expected half-life sensitivity, assuming the mass mechanism, by two orders of magnitude compared to NEMO-3. [9]. With 500 kg y, SuperNEMO aims to reach a sensitivity of $m_{\beta\beta} < 0.04 - 0.1$ eV. Several design specifications for the SuperNEMO experiment are listed in Table 2 and compared to NEMO-3 for reference.

The first of the twenty SuperNEMO modules, referred to as the demonstrator, is currently under construction. The demonstrator module will house approximately 7 kg of $^{82}$Se, and with 2.5 y of running will reach a sensitivity of $m_{\beta\beta} < 0.2 - 0.4$ eV.

One of the primary challenges in the demonstrator construction is the production of the source foils. In particular, there are strict requirements on the allowed activity of the background isotopes internal to the source foil. In order to ensure that these target background levels are met a dedicated detector called BiPo has been developed to measure the internal source foil contamination [12]. The BiPo detector has been commissioned and is operating at its expected sensitivity. All of the source foils intended for use in a SuperNEMO module are measured in BiPo. Approximately 25% of the source foil for the demonstrator has been produced, and radiopurity measurements with BiPo are underway.

The required activity of $^{222}$Rn for SuperNEMO is $< 15$ mBq/m$^3$. To ensure that this target is met, both raw materials and manufactured detector components are cleaned thoroughly following a rigorous procedure, and then screened for radon emanation with specialized measurement chambers. Detector components are also screened for other radioactive impurities using high purity germanium (HPGe) detectors. To reduce the level of $^{222}$Rn coming from the surrounding environment, the SuperNEMO detector will be located inside of an airtight tent that houses an air filtration system. The $^{222}$Rn levels inside of the tracker are monitored using a radon concentration line. Preliminary measurements of the first quarter of the SuperNEMO demonstrator module indicate that the target levels of $^{222}$Rn are within reach.

Approximately 40% of the calorimeter modules required for the demonstrator is complete. Tests of these modules indicate that their energy resolution meets the design specification of 4% (FWHM) at the $Q_{\beta\beta}$ value of $^{82}$Se, which is approximately 3.0 MeV [1].

The first half of the demonstrator’s tracking chamber is also complete. The first quarter has been commissioned using cosmic ray muons. An example of an event display from commissioning can be seen in Fig. 2. The number of dead or problematic channels is $< 2\%$ and expected to improve during the integration phase at LSM.

4. Summary and conclusions
The NEMO-3 and SuperNEMO experiments offer a unique way to search for $0\nu\beta\beta$ decay by reconstructing the full decay topology and kinematics. The analysis of the full data set from
Figure 2: (Left) Exploded view of the SuperNEMO detector and (right) an event display from the commissioning of the SuperNEMO tracker with cosmic ray muons. The black circles indicate Geiger cell hits, and the blue line is a linear fit to the muon track.

Table 2: Comparison of the NEMO-3 experiment to SuperNEMO.

| Feature                        | NEMO-3 [11]          | SuperNEMO       |
|--------------------------------|----------------------|-----------------|
| Main isotope, Mass             | $^{100}$Mo, 7 kg     | $^{82}$Se, 100 kg |
| Radiopurity                    | $A(^{208}$Tl) < 20 µBq/kg | $A(^{208}$Tl) < 2 µBq/kg |
|                                | $A(^{214}$Bi) < 20 µBq/kg | $A(^{214}$Bi) < 10 µBq/kg |
|                                | $A(^{222}$Rn) < 5 mBq/m³ | $A(^{222}$Rn) < 15 mBq/m³ |
| Efficiency                     | 11%                  | 30%             |
| Energy resolution (FWHM at 3 MeV) | 8%                  | 4%              |
| Sensitivity (mass mechanism)   | $T_{1/2}^{0\nu} > 1 \times 10^{24}$ y | $1 \times 10^{26}$ y |
|                                | $m_{\beta\beta} < 0.3 - 0.8$ eV | $m_{\beta\beta} < 0.04 - 0.1$ eV |

NEMO-3 is underway. Stringent $0\nu\beta\beta$ decay limits have been published for the isotope $^{100}$Mo. Results involving the other isotopes investigated will be updated soon. The construction of the SuperNEMO demonstrator is near completion, with many design specifications being met. Commissioning of the demonstrator is expected to begin in late 2016.

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