Radiopurity requirements for the SuperNEMO experiment and the BiPo detector

Guillaume Eurin[1,2], on behalf of the SuperNEMO collaboration

[1] UCL, London WC1E 6BT, United Kingdom
[2] LAL, Univ Paris-Sud, CNRS/IN2P3, F-91405 Orsay, France

E-mail: eurin@lal.in2p3.fr

Abstract. The main goal of the SuperNEMO collaboration is to try to observe neutrinoless double-β decay. This would prove that the neutrino is a Majorana particle ($\nu = \overline{\nu}$). Today the best lower limits on half-lives of this process are set around 10^{24} - 10^{26} years as obtained by the NEMO-3 experiment [1] (for the 2β isotope ^{100}Mo) and other experiments. SuperNEMO is the next generation experiment based on the NEMO-3 tracker-calorimeter detection principle. The targeted contamination levels for the source foils are lower than can be measured through γ spectroscopy. A more sensitive detector has been constructed to measure low contaminations in ^{208}Tl (around few μBq/kg) and ^{214}Bi (few dozen μBq/kg) in thin materials: the BiPo detector. BiPo-3 has been fully operational at the *Laboratorio Subterráneo de Canfranc (LSC)* since January, 2013. The construction, performance and calibration of the BiPo-3 detector will be covered as well as the radiopurity requirements for SuperNEMO.

1. Introduction
Since neutrino oscillations have been clearly established, neutrinos are now known to be massive but their masses are very small compared to all the other Standard Model fermions. The current best experimental technique for proving the Majorana nature of the neutrino is the search for the neutrinoless double-β decay ($0\nu2\beta$).

After the success of the NEMO-3 detector [2], a new generation experiment has been designed. The successor of NEMO-3, SuperNEMO [3], has started with the construction of the first module. This demonstrator aims to prove the required performance for SuperNEMO. Data taking is expected to start at the begining of 2016.

2. Radiopurity requirements for SuperNEMO
The typical available energy in the $0\nu2\beta$ decay is ~ 3 MeV. ^{214}Bi and ^{208}Tl can be found in natural radioactivity chains. They are the main backgrounds for $0\nu2\beta$ from inside the $\beta\beta$ source foil. During their single-β decay they emit high-energy particles: $Q_\beta(^{214}$Bi$) = 3.27$ MeV and $Q_\beta(^{208}$Tl$) = 4.99$ MeV. These isotopes can mimic a double-β decay event via several processes following the single-β decay: Moller scattering of the electron, internal conversion and Compton scattering of the associated γ rays.

The target sensitivity with ^{82}Se is $T_{1/2}(\beta\beta0\nu) > 10^{26}$ years for an exposure of 500 kg.year. To reach this value, the limits on the contamination levels and the energy resolution of the optical modules have been improved. Reducing the value of the energy resolution allows a

Table 1. NEMO-3 parameters and requirements of SuperNEMO.

	NEMO-3	SuperNEMO
Mass	7 kg	100 kg
Isotope	^{100}Mo	^{82}Se (^{150}Nd, ^{48}Ca)
Energy resolution	FWHM = 15% at 1 MeV	FWHM = 8% at 1 MeV
Radon contamination	A(^{222}Rn) = 5 mBq/m^3	A(^{222}Rn) < 0.15 mBq/m^3
^{208}Tl and ^{214}Bi contamination	A(^{208}Tl) = 100 μBq/kg A(^{214}Bi) $\sim$ 300 μBq/kg	A(^{208}Tl) < 2 μBq/kg A(^{214}Bi) < 10 μBq/kg

better discrimination between the $0\nu2\beta$ and the $2\nu2\beta$ decay signals. The half-life sensitivity target of SuperNEMO gives rise to the detector requirements listed in Table 1.

3. The BiPo processes in natural radioactivity chains

SuperNEMO requirements for the contaminations in ^{208}Tl and ^{214}Bi cannot be measured, using non-destructive techniques, with the current performance of High Purity Germanium detectors (HPGe). A new detector has therefore been developed after 5 years of R&D: the BiPo detector which takes advantage of the BiPo cascades that exist in natural radioactivity chains.

A BiPo event consists of a β-decay and a delayed α-decay consistent with the characteristic half-life of the Po nucleus. The energies and delay times for ^{212}BiPo and ^{214}BiPo events are:

- ^{212}Bi : $Q_\beta(^{212}$Bi$) = 2.25$ MeV, $E_\alpha(^{212}$Po$) = 8.78$ MeV and $T_{1/2}(^{212}$Po$) = 299$ ns
- ^{214}Bi : $Q_\beta(^{214}$Bi$) = 3.27$ MeV, $E_\alpha(^{214}$Po$) = 7.69$ MeV and $T_{1/2}(^{214}$Po$) = 164$ μs

4. The BiPo-3 detector

Studies with several prototypes lead to the design of the BiPo-3 detector [4]. BiPo-3 is an ultrapure detector with an effective surface area of 3.6 m^2 capable of measuring 1.4 kg of 2β isotope in a thin source foil (40 mg/cm^2). Each one of the two modules is made of 40 paired light lines (two PMTs + light guides + scintillators).
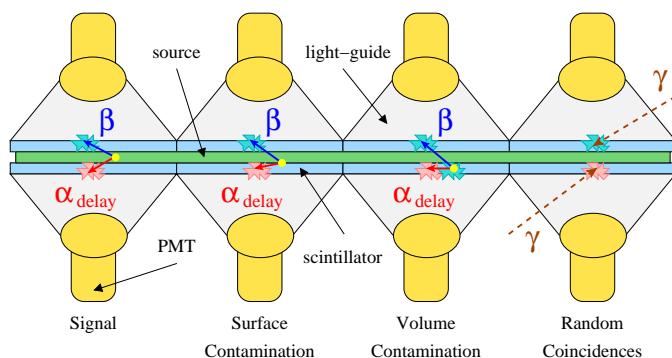

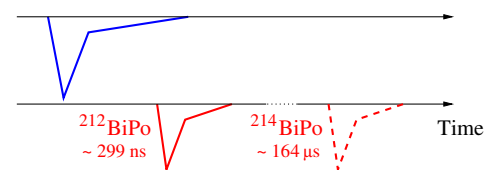**Figure 1.** BiPo & background events topologies.

Figure 2. BiPo events as recorded by the acquisition system.

Thanks to the BiPo event's time signature, few backgrounds remain (see figure 1):

- Surface contamination of the scintillators and radon ($T_{1/2}(^{222}$Rn$) = 3.8$ d allowing it to diffuse into the detector).
- Volume contamination of the scintillators.
- γ-induced random coincidences from the laboratory or detector components.

The electronics digitizes the PMT pulses (see figure 2) at 1 GS/s and the delay time between events is studied up to 1 ms for the ^{214}BiPo study. The energy deposited by the particles in the scintillator is proportional to the integral of the pulse (charge).

5. Construction and calibration of the BiPo-3 detector

The detector has been installed at the LSC, a deep underground laboratory. It has been assembled in a clean room. The two modules are hosted in a gas tight tank flushed with nitrogen and shielded by iron and lead. The full detector has been running since January 2013.

All the BiPo optical modules have been qualified (PMT gain and energy resolution) before the installation using α (^{241}Am) and β (1 MeV conversion e$^-$ from ^{207}Bi) sources. Regular γ calibrations of the detector are also performed before each measurement. For the BiPo analysis, the energy resolution (FWHM) and the charge-to-energy calibration constant must be determined for each block using statistical tests comparing data and simulations. A time calibration between two opposite optical modules is also performed with crossing electron events, signified by two almost simultaneous energy deposits.

Several corrections were applied to the simulations such as alpha quenching, energy resolution and non-uniformity of the light collection of the scintillator to match the data and the corrected simulations. This was done comparing the electron and α energy spectra.

An aluminium foil has been introduced in the detector as part of the calibration procedure. This foil has a known contamination in both ^{214}Bi and ^{208}Tl (measured in the prototypes and HPGe). An agreement with the expected value of 299 ns on the delay times for the ^{212}BiPo events was observed. For ^{214}BiPo events the value is also compatible with 164 μs. The measured activities agreed with HPGe measurements of the foil.

6. Expected sensitivities

The sensitivities of the BiPo detector for the measurement of the SuperNEMO source foils have been estimated using background measurements (see figures 3 & 4). Dedicated runs were performed to determine the background level of the detector. The required activities have to be reached within $\sim$ 6 months. Some improvements of the analysis are still ongoing, such as a source surface contamination rejection method. However the current sensitivities are at the levels of the requirements of the SuperNEMO demonstrator.
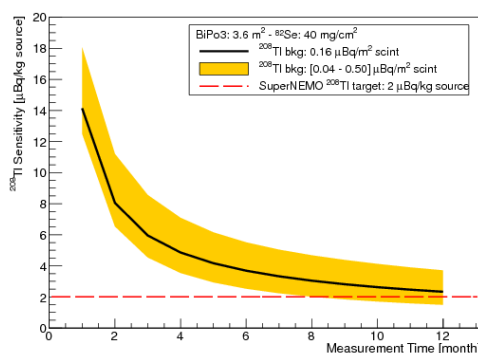

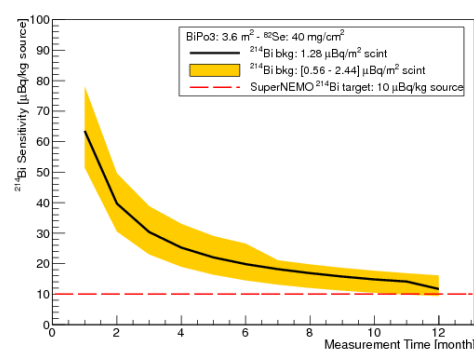**Figure 3.** Expected sensitivity in ^{208}Tl.

Figure 4. Expected sensitivity in ^{214}Bi.

References

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