The SuperNemo $\beta\beta 0\nu$ enriched $^{82}$Se source foils and their radiopurity measurement with the BiPo-3 detector

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Abstract. The SuperNemo collaboration is currently building the SuperNemo demonstrator at the Modane Underground Laboratory, as the proof of concept for the full SuperNemo program. The enriched $\beta\beta 0\nu$ source consisting of thin foils containing 7 kg of $^{82}$Se is enclosed by the gas tracker and the plastic scintillator calorimeter. The full reconstruction of the $\beta\beta 0\nu$ event topology ensures an excellent background rejection and points at a true zero-background search. One of the most critical sources of background is a contamination in the source foils. The required radiopurity is $^{208}$Tl $< 2 \mu$Bq/kg and $^{214}$Bi $< 10 \mu$Bq/kg to achieve the sensitivity $T_{1/2}(\beta\beta 0\nu) > 10^{26}$ years. The collaboration has developed a dedicated detector to measure the ultra high natural radiopurities requested, the BiPo-3 detector, installed in the Canfranc Underground Laboratory. The experimental design and performances of BiPo-3 are presented. Dedicated background measurements have been performed. After an exposure of about 2 years.m$^2$ the surface activities of the scintillators of $A(^{208}$Tl) = 1.0 ± 0.2 µBq/m$^2$ and $A(^{214}$Bi) = 1.0 ± 0.3 µBq/m$^2$ are measured. Results of the $^{208}$Tl and $^{214}$Bi activity measurements of the first enriched $^{82}$Se foils of SuperNemo are also presented.

1. Introduction
The BiPo-3 detector, running in the Canfranc Underground Laboratory, Spain, since 2013, has been initially developed to measure ultra low natural contaminations of $^{212}$Bi and $^{214}$Bi in the SuperNemo source foils. The goal of the SuperNemo experiment is to search for the neutrinoless $\beta\beta$ decay, $\beta\beta 0\nu$ [1] as an experimental proof that the neutrino is a Majorana particle, i.e. identical to its own antiparticle, with a sensitivity of $T_{1/2}(\beta\beta 0\nu) > 10^{26}$ years. The baseline isotope is $^{82}$Se ($Q_{\beta\beta} = 2.998$ MeV).

2. $\beta\beta 0\nu$ enriched $^{82}$Se source foils
The SuperNemo foils are in the form of strips, 270 cm long and 13.5 cm wide. To produce the foils thin and chemically purified $^{82}$Se powder is mixed with 10% Polyvinyl alcohol (PVA) glue and then deposited between Mylar sheets. One of the main sources of background for SuperNemo is a possible contamination of $^{208}$Tl and $^{214}$Bi inside the source foils. The required radiopurities are $A(^{208}$Tl) $< 2 \mu$Bq/kg and $A(^{214}$Bi) $< 10 \mu$Bq/kg in order to achieve the targeted SuperNEMO sensitivity [1]. To measure such low levels the collaboration has developed the BiPo-3 detector.
3. The BiPo-3 detector

In order to measure $^{208}$Tl and $^{214}$Bi contaminations, the underlying concept of the BiPo-3 detector is to detect the so-called BiPo process, which corresponds to the detection of an electron followed by a delayed $\alpha$ particle. The $^{214}$Bi isotope is a $\left(\beta, \gamma\right)$ emitter decaying to $^{214}$Po, which is an $\alpha$ emitter with a half-life of 164 $\mu$s. The $^{208}$Tl isotope is measured by detecting its parent, $^{212}$Bi. Here $^{212}$Bi decays with a branching ratio of 64% via a $\beta$ emission to $^{212}$Po which is a pure $\alpha$ emitter with a short half-life of 300 ns. The BiPo-3 experimental technique consists in installing the foil of interest between two thin ultra radiopure organic plastic scintillators, as illustrated in Figure 1.

![Figure 1. Schematic view of the BiPo detection technique with the source foil inserted between two plastic scintillators (left). The dot represents the contamination, the cross and open circle represent energy depositions in the scintillators. The prompt $\beta$ signal and the delayed $\alpha$ signal observed by the top and bottom scintillators respectively are schematically illustrated (right).](image)

A complete description of the BiPo-3 detector can be found in [2].

4. The BiPo-3 backgrounds

The sources of background as illustrated in Fig. 2 are: (a) Random coincidences due to the $\gamma$ flux, (b) $^{212}$Bi or $^{214}$Bi contamination on the surface of the scintillators and (c) $^{212}$Bi or $^{214}$Bi contamination in the volume of the scintillators.

![Figure 2. Illustration of the possible sources of background: (a) random coincidences due to the $\gamma$-rays, (b) $^{212}$Bi or $^{214}$Bi contamination on the surface of the scintillators, (c) $^{212}$Bi or $^{214}$Bi contamination in the volume of the scintillators. The dots correspond to the contamination, the black stars to the prompt signal and the open stars to the delayed signal.](image)

In the case of a $^{212}$Bi or $^{214}$Bi bulk contamination inside the scintillator volume, the delayed $\alpha$ particle deposits also all its energy inside the scintillator. But the prompt electron first triggers this scintillator block before escaping and entering the opposite one, as illustrated in Figure 2 (c). Therefore two prompt signals are detected in coincidence in the two opposite scintillators, allowing the rejection of this class of background events. Thus the background can be defined by two components: the random coincidences and the surface background.

Dedicated background measurements have been performed, obtained by closing the detector without any sample between the scintillators. The results are presented in Table 1.

5. Measurement of the first SuperNemo $\beta\beta0\nu$ $^{82}$Se source foils

Four first SuperNEMO $^{82}$Se strips with thickness $\sim 40$ mg/cm$^2$, have been measured from August 2014 to June 2015. The total duration of this measurement is 262.0 days for the $^{212}$BiPo
Table 1. Results of the $^{212}$BiPo and $^{214}$BiPo background measurements: separate and combined results of the dedicated background measurements in the two BiPo-3 Modules. We report the number of surface background events and random coincidences calculated by the fit of the delayed energy spectrum and the random coincidences calculated with the single rate measurement.

|                   | $^{212}$BiPo |               | $^{214}$BiPo |               |
|-------------------|--------------|---------------|--------------|---------------|
|                   | Module 1     | Module 2      | Comb.        | Module 1     | Module 2      | Comb.        |
|                   | Temp. shield | Final shield  | shielding    | Temp. shield | Final shield  | shielding    |
| Duration (d)      | 73.5         | 51.2          | 75.7         | 290.4        | 36.2          | 75.7         | 111.9        |
| Scint. surf. (m²) | 2.7          | 3.06          | 3.42         | 3.10         | 3.06          | 3.42         | 3.24         |
| Data events       | 9            | 8             | 12           | 29           | 18            | 30           | 48           |
| Surf. Bkg (fit)   | 7.4          | 8.0           | 12.0         | 27.7         | 2.5           | 6.9          | 9.4          |
| Coinc. (fit)      | 1.6          | 0.0           | 0.0          | 1.3          | 15.5          | 23.1         | 38.5         |
| Coinc. (singles)  | 0.20         | 0.10          | 0.14         | 0.44         | 14.3          | 25.0         | 39.3         |
| $A(^{208}$Tl) μBq/m² | 0.8 ± 0.3    | 1.0 ± 0.4     | 1.0 ± 0.3    | 0.9 ± 0.2    |                |              |
| $A(^{214}$Bi) μBq/m² |                |                |              | 1.0 ± 0.6    | 1.0 ± 0.4     | 1.0 ± 0.3    |

We search for an excess of BiPo events in data above the background expectation in the delayed energy spectrum. The components of background are the random coincidences and the $^{212}$Bi or $^{214}$Bi contamination on the surface of the scintillators. For the measurement of the $^{82}$Se foils, the contamination inside the Mylar is added as an extra component of background. The delayed energy spectra of the background components are simultaneously fitted to the observed data. The energy spectra of each component are calculated by Monte Carlo, except for the random coincidence background for which the energy spectrum is measured using the single counting events.

For the $^{212}$BiPo measurement, with a delayed energy lower than 700 keV, 9 $^{212}$BiPo events are observed and 2.2 background events are expected. The excess of observed events above the fitted background is in agreement with a $^{212}$Bi contamination inside the $^{82}$Se+PVA mixture. Taking into account the detection efficiency of 2.65% (calculated by simulating $^{212}$BiPo events emitted uniformly inside the $^{82}$Se+PVA mixture), this corresponds to a 90% C.L. interval for the $^{208}$Tl activity of the $^{82}$Se+PVA mixture (using the statistical analysis approach described in [3]) of:

$$A(^{208}$Tl) = [6.3 − 34.2] μBq/kg (90% C.L.)

For the $^{214}$BiPo measurement, with a delayed energy lower than 600 keV, 44 $^{214}$BiPo events are observed and 35.9 background events are expected. Considering it as a background fluctuation, and taking into account the detection efficiency of 0.66% an upper limit at 90% C.L. is set to the $^{214}$Bi contamination of the $^{82}$Se+PVA mixture:

$$A(^{214}$Bi) < 300 μBq/kg (90% C.L.)

References
[1] Arnold R. et al. 2010 J Eur. Phys. J. C 70 927
[2] Barabash A. et al. to be submitted to JINST
[3] Feldman G. J. and Cousins R. D. 1998 Phys. Rev. D 57 3873