The BiPo detector

Measure the purity in $^{208}$Tl and $^{214}$Bi of the SuperNEMO $\beta\beta$ source foils

Required sensitivity:

$^{208}$Tl < 2 $\mu$Bq/kg and $^{214}$Bi < 10 $\mu$Bq/kg

Best limits for NEMO-3 foils measurement with HPGe:

$A(^{208}$Tl) < 100 $\mu$Bq/kg
Detect the BiPo decay cascade: beta + delay alpha

\[ \begin{align*}
  ^{238}\text{U} & \rightarrow ^{214}\text{Bi} & (19.9 \text{ mn}) \\
  ^{214}\text{Bi} & \rightarrow ^{214}\text{Po} & (164 \mu\text{s}) \\
  ^{214}\text{Po} & \rightarrow ^{210}\text{Pb} & (22.3 \text{ y}) \\
  ^{232}\text{Th} & \rightarrow ^{212}\text{Bi} & (60.5 \text{ mn}) \\
  ^{212}\text{Bi} & \rightarrow ^{212}\text{Po} & (300 \text{ ns}) \\
  ^{212}\text{Po} & \rightarrow ^{208}\text{Pb} & (3.1 \text{ mn}) \\
  ^{210}\text{Bi} & \rightarrow ^{210}\text{Tl} & (1.3 \text{ mn}) \\
  ^{210}\text{Tl} & \rightarrow ^{208}\text{Tl} & \text{(stable)}
\end{align*} \]

Time topology signature: 1 hit + 1 delay hit (and no coincidence)

Sandwich of two low radioactive thin polystyrene plastic scintillators
Sources of background

Random coincidence
(e⁻ Compton from ext. γ)

- Low counting rate
  \( \tau \times S \lesssim 1 \text{ mHz.m}^2 \)
- Low background detector and shield in Canfranc Underground Lab (Spain)
- Discrimination e⁻/α

Bulk contamination
Scintillator

- Low energy threshold to reject coincidence
  10 keV \( \approx 100 \text{ µm} \)
- Radiopure scintillator
  \( A^{(232}\text{Th}) \lesssim 1 \text{ µBq/kg} \)

Surface contamination
\(^{238}\text{U}\) and \(^{232}\text{Th}\)

- Ultra high surf. radiopurity
  (~100 µm deep)
  \( A^{(232}\text{Th}) \lesssim 1 \text{µBq/m}^2 \)
- No Radon and Thoron
  \( A(\text{Radon}) \lesssim 10 \text{ mBq/m}^3 \)
  (if gap = 200µm)
R&D Program

2007-2009: R&D program, funded by ANR

Development of 3 prototypes using different designs

✓ BiPo-1 prototype

✓ BiPo-2 prototype

✓ BiPo-1 phoswich (IFIC Valencia)
BiPo-1 prototype

20 modules of 20×20×0.3 cm³ scintillators
Total surface = 0.8 m² running in LSM Modane

✓ Polystyrene based scintillators produced in JINR Dubna
✓ Surface machining in LAL
✓ Ultrapure aluminium sputtering in IPN Orsay
✓ Low radioactive 5” Hamamatsu PMTs

Mathieu Bongrand’s thesis
Results published in *N.IM. A 622 (2010) 120-128*
Validation of the detection efficiency

Measurement of a calibrated aluminium foil

Activity measured with **HPGe γ spectroscopy**: $A(^{212}\text{Bi} \rightarrow ^{212}\text{Po}) = 0.19 \pm 0.04 \text{ Bq/kg}$

- After 160 days of data, 1306 BiPo events detected
- Activity measured with **BiPo**: $A(^{212}\text{Bi} \rightarrow ^{212}\text{Po}) = 0.16 \pm 0.01\text{(stat)} \pm 0.03\text{(syst.) Bq/kg}$
- Delay distribution between the prompt $\beta$ signal and the delay $\alpha$ signal: $T_{1/2} = 276 \pm 12 \text{ ns}$

\[\begin{align*}
\Delta t &= 240 \text{ ns} \\
\beta &\quad \alpha
\end{align*}\]
e$^-$/$\alpha$ pulse shape discrimination

- High dE/dx for $\alpha$ enhances the slow component of the scintillation decay curve
- Already known in liquid scintillator
- Observed here also in plastic scintillator

Measurements with (prompt e$^-$, delayed $\alpha$) sample from aluminium foil

Discrimination factor: $\chi = \frac{Q_{\text{slow}}}{Q_{\text{tot}}}$

Condition $\chi > 0.2$ applied for the delayed signal
- Rejects 85% of random coincidence events
- Keep 90% of true BiPo events
Background measurement

**Channel $^{212}\text{Bi} \rightarrow ^{212}\text{Po}$ for $^{208}\text{Tl} (^{232}\text{Th})$ measurement**

Background has been measured during 488 days in Modane (Dec. 2007 – Jul. 2009)

12 BiPo-1 modules $\equiv$ detector surface area of 0.48 m$^2$

30 $^{212}\text{Bi}^{212}\text{Po}$ events observed

Surface bkg (per scint. surface unit)

$A(^{208}\text{Tl}) = 1.5 \pm 0.3 \ (\text{stat}) \pm 0.3 \ (\text{syst}) \ \mu\text{Bq/m}^2$

**Requirements:**

$A(^{208}\text{Tl}) \leq 1 \ \mu\text{Bq/m}^2$

**Channel $^{214}\text{Bi} \rightarrow ^{214}\text{Po}$ for $^{214}\text{Bi} (^{238}\text{U})$ measurement**

Radon contamination observed in BiPo-1

$A(\text{Radon}) \sim $ few tens of mBq/m$^3$

Origins: emanation of PMTs, Radon purity of the gas…

$\Rightarrow$ Will require a dedicated Radon tightness design for BiPo-3

Part of $^{212}\text{Bi} \rightarrow ^{212}\text{Po}$ bkg events may be due to Radon bkg. I hope so !...
BiPo-3 detector
(Canfranc Underground Laboratory)

✓ **Total active area** = 3.6 m²
✓ Detector composed of **2 modules**
✓ Each module is an array of **40 optical sub-modules**
  Optical sub-modules = thin aluminized scintillators coupled via PMMA optical guides to 5" low-radioactive PMT
  ⇒ **Total of 80 PMTs + Optical guide + scintillators**
✓ **Scintillators:**
  ✓ Polystyren based, size: 300×300×2 mm³
  ✓ Produced by JINR Dubna and machined in France under N₂ flush
  ✓ entrance active face **aluminized** with 200nm of ultra pure Aluminium
BiPo-3 sensitivity

Assuming: $^{82}$Se foil 40 mg/cm$^2$
Total surface BiPo-3 = 3.6 m$^2$
Energy threshold = 100 keV for prompt and delay signals ($\epsilon$ ~ 5%)

The main systematic in BiPo is the correct knowledge of the “surface” background
⇒ Long background measurement
⇒ Avoid surface contamination when the Se foil is introduced inside the detector

Number of expected $^{212}$BiPo bkg event in BiPo-3 (assuming surface bkg as in BiPo-1)
~ 4.5 events/month with $^{82}$Se foil (~14 events w/o foil)
Random coincidence background
– measure the single counting rate with different $\gamma$ shields
– choice of the scintillator thickness

Tl and Bi surface background
– validation of the new aluminium evaporation chamber
– validation of the new scintillator surface machining

Radon background

Radon strongly suppressed
$A(\text{Radon}) < 1\text{mBq/m}^3$
when pure N2 is flushed with flux ~ 1 vol/hour
(~ 200 l/h for total BiPo3 detector)
Assembly and test of the 80 optical sub-modules

Calibration on test bench in LAL

- Good light yield collected and good reproducibility
- ~ 250 photoelectrons / MeV
Assembly of the 1st BiPo-3 module in LAL Orsay
Assembly of the 1st BiPo-3 module in LAL Orsay

1. Implementation of light boxes and connexion gas PMT
2. Set of EVOH film
3. Implementation of down light lines
   And implementation of:
   - cables,
   - optical fibers
   - connexion gas
4. Adjustment of plan of scintillator with down support
5. Implementation of up light lines
6. Set of EVOH film
7. Setting of 20 light boxes
   Implementation of:
   - cables
   - optical fibers
8. Setting up of frame with monorail
   Set up of supports and connexion gas
Design of the shield

- Lead 50 mm
- Lead 100 mm
- Pure iron 20 mm
- Lead 50 mm
- Water 300 mm
- Iron 178 mm
- Pure iron 2 mm
- Pure iron 4 mm
- Iron 178 mm
- Lead bricks (11.3 kg) of 200 x 100 x 50 mm
- Lead: 50 mm
- 10 plates iron of 1780 x 980 x 178 mm
Operation in Canfranc Underground Lab.
• **1st July 2012**: installation of the 1st BiPo-3 module in Canfranc

• **Summer 2012**: start measuring the bkg of the 1st module

• **Oct. 2012**: installation of the 2nd BiPo-3 module in Canfranc

• **Fall 2012**: background measurement of the two modules

• **Year 2013**: measurement of SuperNEMO $^{82}$Se foils

Possibility later to measure other thin materials like polyethylene film (used to screen copper surfaces) or reflecting films (used in scintillating bolometers)

⇒ could reach a sensitivity of ~10 μBq/kg in $^{208}$Tl
BACKUP
Initial design of the shield
Welded mechanical structure (radiopure iron)
built in LAL Workshop

Inner volume closed by EVOH+ polyethylene film
flushed by LSC N$_2$
to suppress Radon background

Shield: low active Pb
Inside stainless steel tank (tightness)
PMT’s readout and acquisition

- **PMT signals sampled with MATACQ VME digitizer boards (LAL & IRFU)**
  - 4 channels, 2.5ms time window
  - 1 GS/s high sampling rate
  - 12-bit amplitude resolution
  - 1 Volt amplitude dynamic range
  - Electronic noise ~ 250 µV (r.m.s.)

- **Trigger (LAL)**
  - MATACQ sampling of the PMT signal during 1.5 µs
  - Dead time during 10 µs ⇒ avoid false trigger on PMT delay noise
  - Start watch dog
  - MATACQ sampling of the PMT signal during 1 ms in case of a 2nd trigger
  - IQR generated after 1 ms

- **Acquisition developed by LPC Caen**
BiPo-2 prototype

- Two scintillators plates (molding production, Bicron BC-408) ⇒ $S = 75\times75\times1 \text{ cm}^3 \ (0.56 \text{ m}^2)$
- Scint. light collected by total internal reflectivity
- Read out on two opposite lateral sides of each plate with 3" radiopure PMT's ⇒ 20 PMT's

Possible advantages:
- Molded plate: no treatment of the entrance surface of the scintillators plates
- Same-side BiPo events could be used
- Random coincidence can be reduced if good resolution for the location of the event
Detection efficiency measured with aluminium foil in Modane

Efficiency BiPo-2 ~ BiPo-1 for back-to-back events
Efficiency can be increased if we use same-side events

BUT:

✓ Modest energy threshold ~ 100 keV
✓ Optical cross-talk ~ few 10 keV
✓ Spatial resolution : 90% of delayed $\alpha$ reconstructed with distance < 10 cm from prompt $e^-$

⇒ Poor identification of coincidence background

⇒ random coincidence ~ 4 times higher than BiPo-3

✓ No $e^-/\alpha$ discrimination (due to a relatively too low light collection)

It has been decided to extrapolate the BiPo-1 design for the large BiPo-3 detector