Radio assay for nEXO

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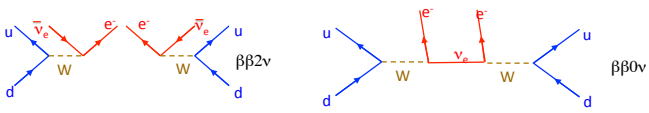
Neutrinoless double beta decay (0νββ)

- Double beta decay is a second order weak interaction where two neutrons turn into two protons
- Only observable for nuclei where beta decay is energetically forbidden or highly suppressed
- Two neutrino double beta decay (2νββ) is allowed in the Standard Model and has been found for a handful of isotopes
  - There are two neutrinos in the final state
- Neutrinoless double beta decay (0νββ)is only allowed[1]
  - Neutrinos are massive Majorana particles
  - And lepton number is not conserved (ΔL=2)

[1] J. Schechter and J .W. F. Valle, Phys. Rev. D 11, 2951 (1982)



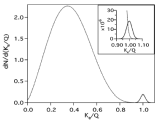
Finding the neutrino mass from 0νββ decay

- For 2νββ the halflife of the decay is unrelated to the neutrino mass
- For 0νββ the halflife of the decay is related to the Majorana mass of the neutrino

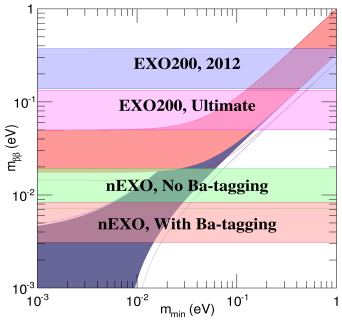
$$\left(T_{1/2}^{2\nu}\right)^{-1} = G^{2\nu} \mid M^{2\nu} \mid^2$$

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \cdot \left|M^{0\nu}\right|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

$G^{0\nu}$ phase space factor
$M^{0\nu}$ nuclear matrix element (NME)
$\langle m_{\beta\beta} \rangle^2 = |\Sigma_i U_{ei}^2 * m_{vi}|^2$



$$T_{1/2} > \frac{\ln 2 \cdot N_{136Xe} \cdot \varepsilon \cdot t}{n \cdot \sqrt{B \cdot t \cdot m \cdot 4 \cdot \sigma_E}}$$



For EXO-200:
N_{136Xe}=2.26·10²⁶
ε=0.84
t=1.3 yr
n= 1.6 for 90% CL
B=1.7 cnts/(yr·t·keV)
m=0.1 t
σ_E=37 keV
(1.53% resolution)

To achieve the sensitivity needed (reduce backgrounds):

1. Natural radioactivity
2. Man-made radioactivity
3. Cosmogenic radioactivity
4. Neutrons

Impact can be minimized by appropriate materials selection.

Backgrounds

•EXO-200 has one of the lowest backgrounds in our field
•The nEXO Majorana neutrino mass sensitivity (above) is based mainly on materials measurements performed for EXO-200. → We know a "low background" solution exists for these choices.
•Deviate from EXO-200 materials whenever needed to accommodate the larger detector size (cryostat), un-availability of EXO-200 components (APDs), or address technical imperfections (large amounts of internal Teflon). → The nEXO materials R&D programme currently focuses on these issues.

Philosophy

•To reduce the risk of finding an unacceptably high background nEXO will adopt the same general strategy as in EXO-200:
•There will be no component allowed into the detector for which we don't have a quantitative background impact estimate.
•Low energy radioactivity such as ^{40}K and ^{60}Co will be traced as well to maintain the capability to measure 2νββ-decay with a signal to background ratio similar to that of EXO-200. This is a convenient two electron data set that can serve as an in situ calibration tool.

How to minimise the background

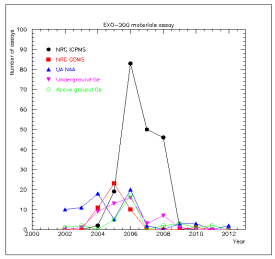
1. Use the Monte Carlo model to determine a hit efficiency for each technical component.
2. Define a percent allowance for major and minor components. This, together with the component mass, defines the tolerable radioactivity content of a component (we specify these in ppb of K and ppt of Th/U).
3. Choose an analysis tool adequate for the material and the desired sensitivity, perform a measurement, and arrive at a yes/no decision.
4. Work with the manufacturer to improve the material properties, find an alternative vendor, or change the design amount

What methods were used for EXO-200

1. ICPMS: K 50 ppb Th/U ppt sensitivity, fast turn around (~1 week per sample), interpretation of data requires chain equilibrium assumption. Suited for metals or substances soluble in acids, small sample size order 1 g.
2. GDMS: K 5 ppb, Th/U 10 ppt sensitivity, fast turn around (~1 week per sample), relies on equilibrium assumption, suited for metals with good conductivity, small sample size order 1 g.
3. NAA: K 1 pb, Th/U 1 to sub ppt sensitivity, slow turn around (~1 month per three to four samples), requires equilibrium assumption, suited for non-metals or those metals with low neutron capture cross section of short half lives, small sample size (order 1 g) destructive.
4. Underground Ge counting: K 150 ppb, Th/U 50 ppt sensitivity, slow turn around (~1 month per sample and per screening detector available), no equilibrium assumption needed, suited for all materials, non-destructive, for good sensitivity needs large sample of order hundreds of g to kg.
5. Above ground Ge: K 1 ppm, Th/U 1 ppb sensitivity. Faster turn around of ~2 weeks per sample and detector.
6. Radon release counting: 5 ^{222}Rn atoms/day sensitivity, no equilibrium assumptions needed, not very fast, needs large samples.

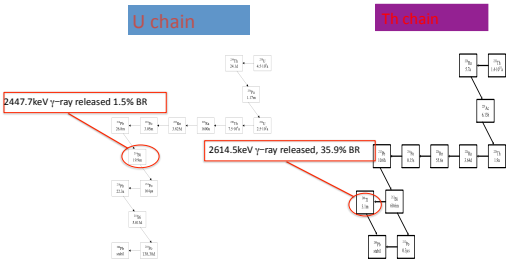
Relative loads for different methods:

ICPMS:	49%
GDMS:	11%
NAA:	19%
UG Ge:	9%
AG Ge:	8%
Other:	4%



What methods will be used for nEXO

- Direct Ge detector based counting, above and underground Th/U:
  50 ppt (U Bern) — All materials, most direct test, requires large samples, up to a month per sample.
  250 ppt (UA) (future Duke)
- ICPMS at Seoul and possible INMS (future IHEP) Th/U:
  1 ppt — Mainly metals (needs to dissolve in acid), small samples ~1 g, fast (optimally 1 week per sample).
- GDMS commercially done at INMS Th/U:
  10 ppt — Metals only, small samples ~1 g, fast (1 week per sample).
- NAA at UA (future Duke). Th/U:
  0.3 ppt instrumental NAA
  0.02 ppt with pre-concentration
  0.009 ppt (for KamLAND)[2] with post irradiation radio-chemistry.
  Mainly non-metals or those metals that don't activate. Small sample size ~1 g, takes about 1 month per sample because of long ^{233}Pa half live.



$$n + {}^{41}K \rightarrow {}^{42}\underset{12.36h}{K} \xrightarrow{\beta^-} {}^{42}Ca, \quad \sigma_{th} = 1.2\,b\,(1.2\,b)$$

$$n + {}^{232}Th \rightarrow {}^{233}Th \xrightarrow[22.3m]{\beta^-} {}^{233}Pa \xrightarrow[27.0d]{\beta^-} {}^{233}U, \quad \sigma_{th} = 6.1\,b\,(7.8\,b)$$

$$n + {}^{238}U \rightarrow {}^{239}U \xrightarrow[23.5m]{\beta^-} {}^{239}Np \xrightarrow[2.36d]{\beta^-} {}^{239}Pu, \quad \sigma_{th} = 2.3\,b\,(7.9\,b)$$

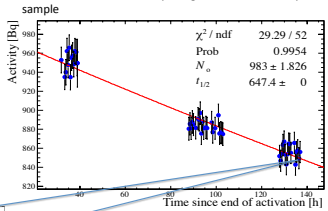
Counting:

•Use one of the three Ge detectors at UA
•The counting is split up in to different time periods to find the time development of the peaks
•Use the gdfit[3] programme to fit peaks
- Simultaneously fits for all peaks and corrects for BR
  - This allows for local fluctuations to be countered
- Corrects for efficiency of detector for different geometries and energies
  - Efficiency was found using a liquid calibration source now use GEANT4 MC

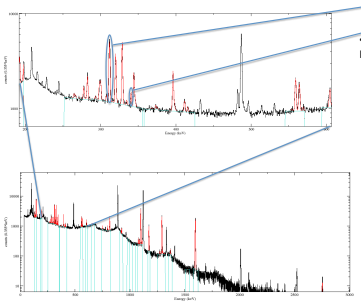
•Fit the found activity for each nuclei to the known half-life
•Correct for the neutron flux found by the fly ash to find the original parent concentrations

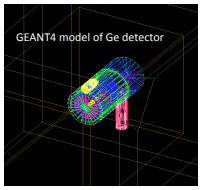
Neutron Activation Analysis:

• In the ^{238}U decay chain ^{214}Bi can decay with a γ-ray that is close to the ^{136}Xe Q-value
•In the ^{232}Th decay chain ^{208}Tl decays with a γ-ray that is above the ^{136}Xe Q-value so can scatter with an energy that is within the ROI
•^{40}K important background for the 2νββ decay
•U/Th have long half-lives, so may not show up in the 2-3 weeks of counting in a small Ge detector
  - Use ^{41}K activation to estimate how much ^{40}K in sample
• However using the MIT reactor as a neutron source we can change these nuclei into daughter nuclei that are shorter lived (but long enough for delayed counting)
•The reactor flux is found by using a NIST calibrated fly ash sample



• Fit of points generated by gdfit that were associated with Pa233 fitted to the Pa233 half-life





2) hep-ex/0210038 Nuclear Instruments and Methods in Physics Research A 507 (2003) 680
3) D. L. et al, "Systematic study of trace radioactive impurities in candidate construction materials for EXO-200," NIM A, vol. 591, no. 3, pp. 490 – 509, 2008