Radon daughter plateout background in nEXO – a simulation study

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on behalf of

nEXO

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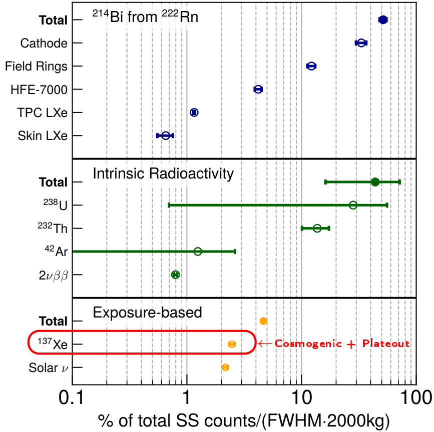
nEXO backgrounds

- nEXO searches for $0\nu\beta\beta$ of ^{136}Xe in a LXeTPC.
- Background sources:
  - Radon outgassing
  - Intrinsic radioactivity
  - Exposure-based background
    - Cosmogenics
    - Dust
    - **Radon daughter plateout**
- Not a major background, but still on our radar.

nEXO Background

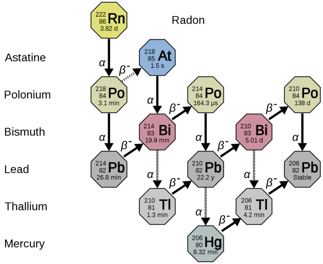


nEXO Collaboration, J. Phys. G: Nucl. Part. Phys. 49, 015104 (2022)

Rn daughter plateout mechanism

Creation of ^{210}Po:

- Rn daughters plate out on surfaces
- Decay to ^{210}Pb during assembly
- ^{210}Pb decays to ^{210}Bi then ^{210}Po during operation



Background due to ^{210}Po:

- Emission of 5.304 MeV α by ^{210}Po
- (α, n) reaction in low-Z materials ($Z \leq 14$).
- Neutron capture on ^{136}Xe and scattering $\implies$ background (smaller)
- ^{137}Xe β decays ($Q = 4.173$ MeV, $\tau_{1/2} = 3.8$ mins) $\implies$ background

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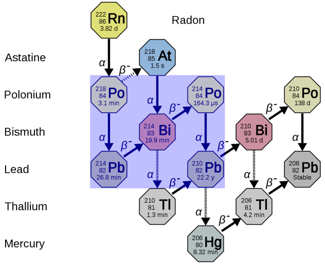

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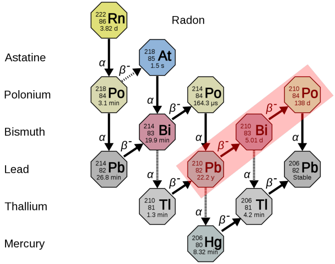

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Background rate calculation

The background rate due to ^{210}Po, B_{210Po}, can be calculated as:

$$B_{210Po} = A_{210Po} \cdot Y_n \cdot \varepsilon_n \cdot \varepsilon_{distrib.}$$

where

- A_{210Po}: ^{210}Po activity
- Y_n: Neutron yield
- ε_n: Hit efficiency for neutrons
- $\varepsilon_{distrib.}$: 1 if in bulk matter, $\frac{1}{2}$ for surfaces.

Focus of the talk:

- Determination of Y_n and ε_n.
- Allowed amounts of ^{210}Po for nEXO.

Determining the neutron yields Y_n

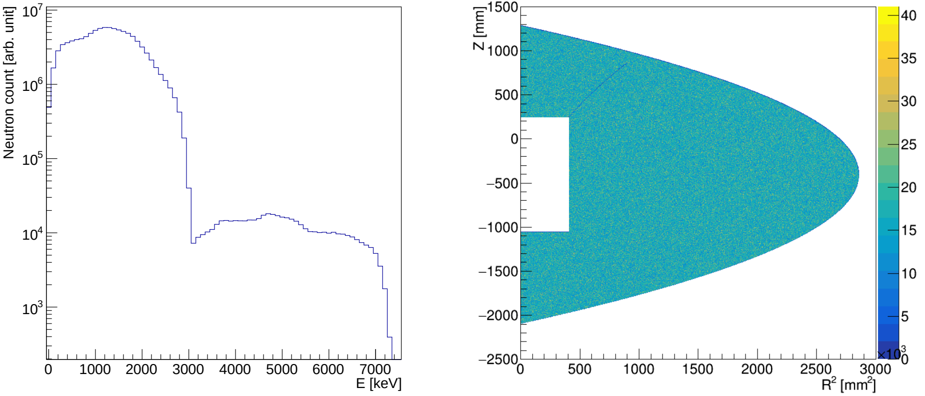
- SOURCES-4C with some modifications:
  - Newer (α, n) cross-section data from JENDL-2005/AN and TENDL 2009.
  - Energy range extended from 6.5 MeV to 15 MeV to accommodate higher-energy α's from ^{218}Po and ^{214}Po.
- Verified with numerical calculation using stopping power from the NIST ASTAR online database.

Comparison of neutron yield and mean energy between original and modified SOURCES-4C.

Nuclide	$\frac{Y_n^{mod}}{Y_n^{orig}}$	$\frac{\langle E_n^{mod} \rangle}{\langle E_n^{orig} \rangle}$
^{13}C	1.05	1.01
^{17}O	0.98	1.002
^{18}O	1.01	1.001
^{19}F	0.97	0.99
^{27}Al	1.23	1.007
^{29}Si	0.63	0.935
^{30}Si	0.58	1.32

Simulation result

Distributions of neutrons from (α, n) in HFE* in which the TPC is submerged.



*HFE-7000, a cryogen by 3M with chemical formula $C_3F_7OCH_3$.

Calculated neutron yields

Plateout location		(α, n) target		Y_n
Component	Material	Component	Nuclides	$[10^{-8}]$
TPC vessel	Cu	HFE	^{13}C, ^{17}O, ^{18}O, ^{19}F	511
HFE	HFE	itself	^{13}C, ^{17}O, ^{18}O, ^{19}F	511
Inner vessel liner	Ti	HFE	^{13}C, ^{17}O, ^{18}O, ^{19}F	511
Field cage spacers	Sapphire	itself	^{17}O, ^{18}O, ^{27}Al	33.2
SiPM	Si	itself	^{29}Si, ^{30}Si	7.3
Charge tile backing	Quartz	itself	^{17}O, ^{18}O, ^{29}Si, ^{30}Si	6.7
Interposer	Quartz	itself	^{17}O, ^{18}O, ^{29}Si, ^{30}Si	6.7

- The neutron energy spectrum and their location of creation are used for the next step – the calculation of ε_n.

Determining the hit efficiencies of neutrons ε_n

- GEANT4-based `nEXO_MC` with modifications:
  - "Shielding" physics list for high-precision low-energy hadronic interactions.
  - Disabled radioactive decays in order to separate backgrounds due to ^{137}Xe decays from everything that happens before, such as inelastic scattering of neutrons.
- Neutron hit efficiency can be split into two terms:

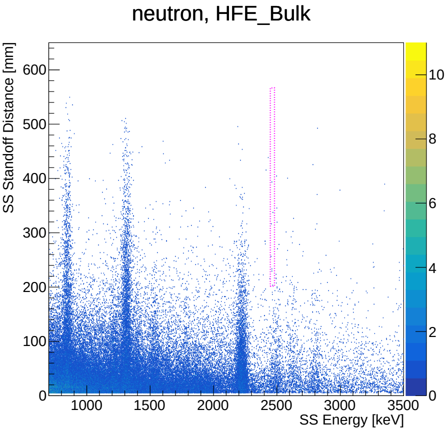
$$\varepsilon_n = \varepsilon_{prompt} + \varepsilon_{n \rightarrow 137Xe} \cdot \varepsilon_{137Xe}$$

where

- ε_{prompt}: Hit efficiency for prompt effects of neutrons
- $\varepsilon_{n \rightarrow 137Xe}$: Probability for neutron capture anywhere in the active volume.
- ε_{137Xe}: Hit efficiency for β decay of ^{137}Xe

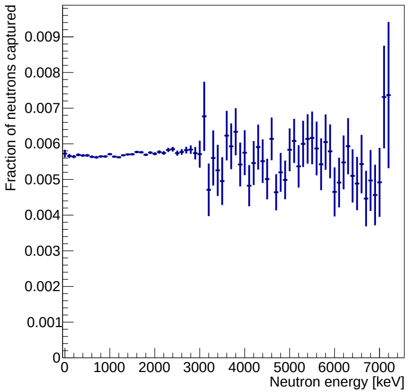
Neutron prompt effects

- "Prompt effects" include:
  - Neutron inelastic scattering on Xe, e.g. $^{136}Xe(n,n'\gamma)^{136}Xe$, $^{134}Xe(n,n'\gamma)^{134}Xe$.
  - Prompt gammas from neutron captures on nuclides, such as 2.2 MeV γ's from ^{1}H.
- Small background impact compared to ^{137}Xe.

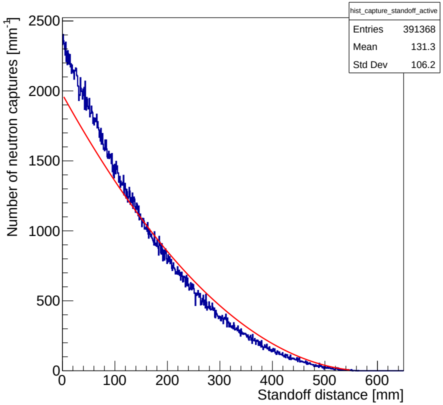


Captures on ^{136}Xe of neutrons created in HFE

Neutron capture probability



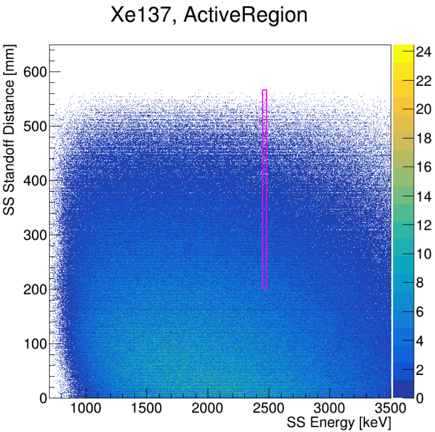
Uniformity of neutron captures



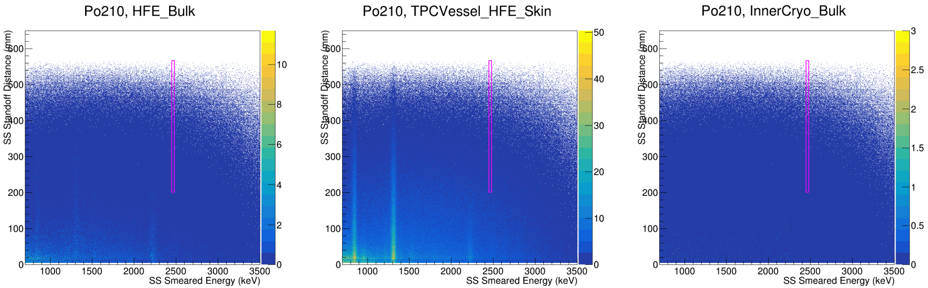
The red line shows a uniform standoff distribution.

Hit efficiency of ^{137}Xe β decays

- Since ^{137}Xe decays are localized, the positional distribution of ^{137}Xe decays should follow that of the neutron captures.
- Therefore, the distribution of ^{137}Xe β decays is assumed to be uniform.
    - The hit efficiency of ^{137}Xe depends very weakly on position for decays within the field cage.
    - Outside the field cage, the hit efficiency of ^{137}Xe decays is substantially lower.
- The bias introduced by this assumption is expected to be small.



Results



Component	Y_n $[10^{-8}]$	ε_n $[10^{-4}]$	Area/Mass $[m^2]$	Bkg. impact $[(c/y)/(Bq/m^2)]$	Allowed ^{210}Po activity† $[Bq/m^2]$
TPC Vessel	511	1.9	7.84	0.12	0.0047
SiPMs	7.3	2.1	11.43	2.8×10^{-3}	0.20
Interposer	6.7	2.0	11.43	2.4×10^{-3}	0.22
Field cage spacers	33.2	2.1	0.5	5.5×10^{-4}	1.0
Charge tile backing	6.7	1.7	2.54	4.6×10^{-4}	1.1
IV liner	511	7.2×10^{-4}	40.72	2.4×10^{-4}	2.4
	$[10^{-8}]$	$[10^{-4}]$	$[kg]$	$[(c/y)/(Bq/kg)]$	$[\mu Bq/kg]$
HFE	511	0.2	31814	103	58

†HFE is allocated 6.25×10^{-3} of the total background, the rest 6.25×10^{-4} each.

Conclusion

Summary

- We have estimated the background impact of radon daughter plateout to nEXO.
- Based on the estimates, we have allocated background budgets to the components that are more susceptible to this background.
- While it is not expected to be a major background source, we need to devise ways to measure ^{210}Po contamination on surfaces and in bulk volumes.

More presentations related to this topic:

- Dmitry Chernyak, Radon daughter plate-out as a background source in nEXO experiment.
- Isaac Arnquist, Exploration of Methods to Remove Implanted Pb-210 and Po-210 Contamination from Silicon Surfaces

Talks and posters by nEXO collaborators

- Dmitry Chernyak, Radon daughter plate-out as a background source in nEXO experiment
- Isaac Arnquist, Exploration of Methods to Remove Implanted Pb-210 and Po-210 Contamination from Silicon Surfaces
- Venkatesh Veeraraghavan, ^{42}Ar background in nEXO
- Brian Mong, Improving nEXO Sensitivity with Radon Distillation
- Khadouja Harouaka, Sample preparation strategies for ultra-trace assay of actinides in difficult samples matrices
- Amanda French, Use of QQQ-ICP-MS for Ultra Low Background Measurements
- Andreas Piepke, The nEXO Background Control Program
- Douglas Leonard, Facilities and Recent Developments for Radioactivity Assay at CUP
- Richard Saldanha, Ultra-low background flexible cables
- Eric Hoppe, Update on Electroforming Plans and Facilities

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Backups

SOURCE-4C checks

Neutron yield:

$$Y_n(E_\alpha) = \frac{N_A}{M_T} \cdot \int_0^{E_\alpha} \frac{\sigma(E)}{P_m(E)}\, dE$$

where E_α is the initial alpha energy, N_A is the Avogadro's number, M_T is the molar mass of the target material, $\sigma(E)$ is the (α, n) cross-section, and $P_m(E)$ is the stopping power per unit density.

Comparison between original and modified SOURCES-4C with numerical calculation.

Target material	Y_n for ^{210}Po α's [10^{-6}]		
	Orig.	Mod.	Num.
HFE‡	5.3	5.1	4.3
Sapphire	0.28	0.33	0.31
SiPM	0.12	0.073	0.074