Neutron Background Simulations for the SuperNEMO Experiment

GDR Deep Underground Physics Plenary Meeting

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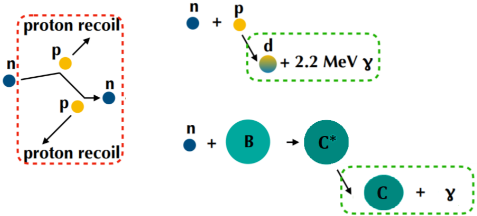
Introduction

Motivation: background induced by neutrons in underground laboratories is dangerous for all experiments searching for rare events (dark matter, $0\nu\beta\beta$, ...)



Calculations of the neutron yield and neutron energy spectrum:

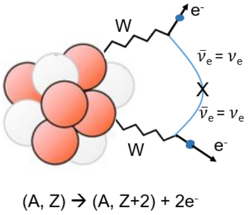
→ yield indicates the number of neutrons that enter or are produced in the target

→ E spectrum determines the total background events in the region of interest (ROI)

Neutrinoless Double Beta Decay

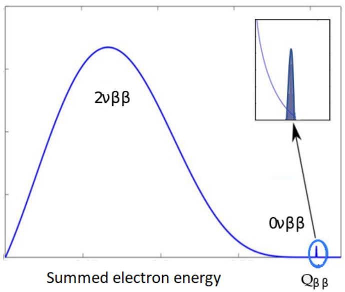
$2\nu\beta\beta$: allowed and observed 2^{nd} order weak process
- ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{150}Nd, ...

$0\nu\beta\beta$: requires massive Majorana neutrinos



- Forbidden in SM - total lepton number violation
- $T_{1/2} > (10^{24} - 10^{26})$ years

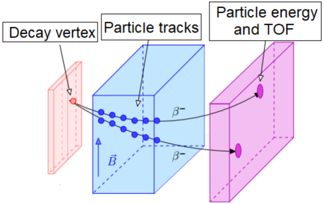
Experimental signal: 2 electrons carry away all of the decay energy

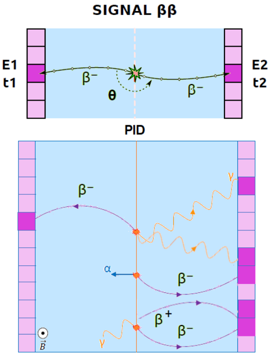


Source of background: any activity that deposits energy near or above the Q-value of the reaction

SuperNEMO Experiment

Super Neutrino Ettore Majorana Observatory



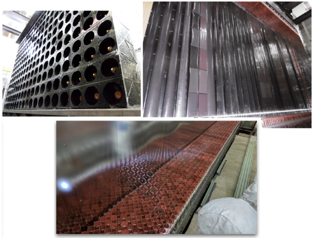


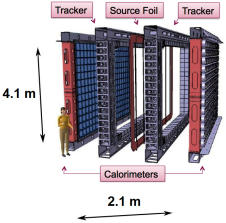
Tracker-calorimeter approach:

- ✓ Choice of $\beta\beta$ isotope
- ✓ Kinematics of decay: $E_{e1}, E_{e2}, cos\theta, \Delta t$
- ✓ Particle identification (β^-/β^+, γ, α)
- ✓ Background rejection (^{208}Tl, ^{214}Bi : 1eNγ N>0, ^{214}Bi : 1e1α)
- ✓ Measure all $\beta\beta$ ($2\nu\beta\beta$, $0\nu\beta\beta$ (probe mass mechanism), $\beta\beta^*$)

Demonstrator Design

Super **N**eutrino **E**ttore **M**ajorana **O**bservatory





Detector property	Demonstrator	Full scale
Isotope	^{82}Se	^{82}Se / ^{150}Nd / ^{48}Ca.
Source mass	6.2 kg	100 kg
Energy resolution	8% (FWHM) @ 1 MeV, 4% @ 3 MeV	
Total background	$\lesssim$ 1/year in ROI (2.8-3.2 MeV)	
$T_{1/2}^{\beta\beta0\nu}$ sensitivity	$\sim 5.7\times 10^{24}$ years	$> 10^{26}$ years
$\langle m_{\beta\beta}\rangle$ sensitivity	0.2 - 0.4 eV	0.05 - 0.1 eV

Source foil - 286 μm thin foils of enriched ^{82}Se, $Q_{\beta\beta} = 2.995$ MeV

Tracker - particle trajectories and identification, 2034 Geiger cells + 25G magnetic field

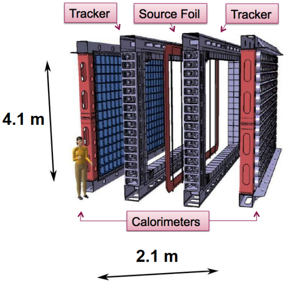
Calorimeter - TOF and energy measurements, 712 optical modules (scintillator + 8"/5" PMT)

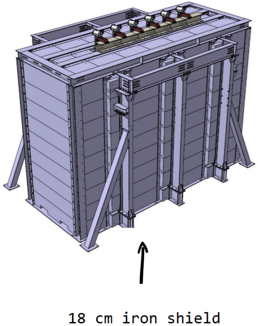
Demonstrator Design

γ shielding materials: high density and atomic number Z

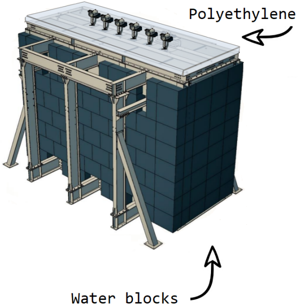
n shielding materials: low atomic number elements (Hydrogen + Boron)

Shielding design: 18 cm of iron + 20 cm PE (top/bottom) and 50 cm water (sides)





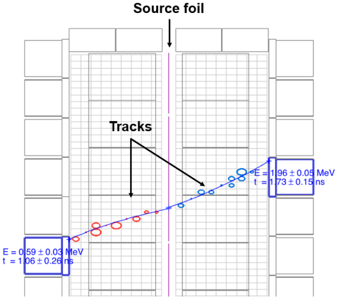
Gamma shield



Neutron shield

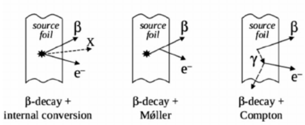
Background of the SuperNEMO Experiment

$\rightarrow$ all events that mimic the topology of **two electrons** emitted from a **common vertex in the source foil** with: $\sum E = Q_{\beta\beta}$ of ^{82}Se = 2995 keV

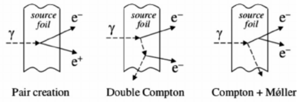


Simulated 0νββ event

Internal background - 2 electrons produced by *internal contamination* inside the $\beta\beta$ source foil



External background - 2 electrons produced by an *external* γ

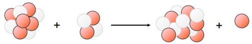


Neutron Background Sources

Origin of neutrons

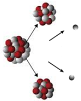
- **Cosmogenic**
  - → muon-induced

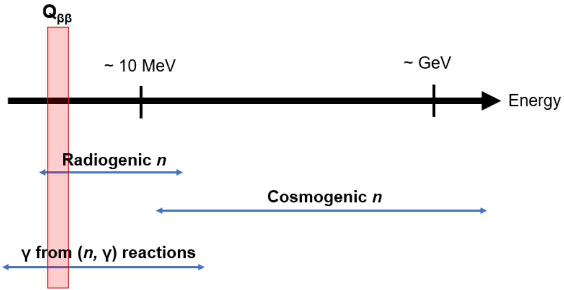
- **Radiogenic**
  - → (α, n) reactions



$${}^{A}_{Z}X + {}^{4}_{2}He \longrightarrow {}^{A+3}_{Z+2}Y + {}^{1}_{0}n$$

  - → spontaneous fission





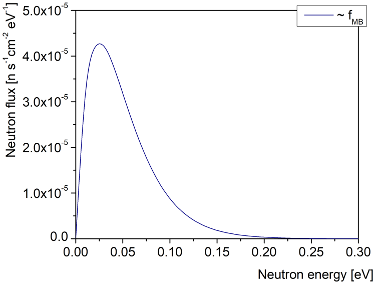
Origin with respect to the detector:

- External - radiation coming from rocks and laboratory
- Internal to the detector - contamination of materials

Ambient neutron fluxes in LSM

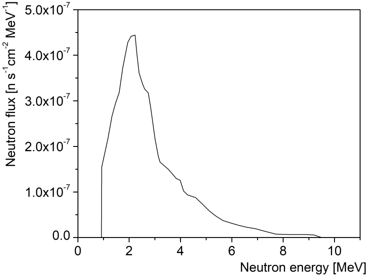
Measured spectra and fluxes from available literature

Thermal neutrons
(Rozov et al. (2010))



$\Phi_{n,thermal} = (2.9 \pm 0.4) \times 10^{-6} ns^{-1} cm^{-2}$

Fast neutrons
(Chazal et al. (1998))

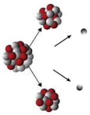


$\Phi_{n,fast} = (4.0 \pm 1.0) \times 10^{-6} ns^{-1} cm^{-2}$

- Highly dependent on the location, materials placed near the detectors and contamination
- Point-to-point variation in measured fluxes

  → They do not represent ideal unaffected ambient fluxes

Spontaneous Fission



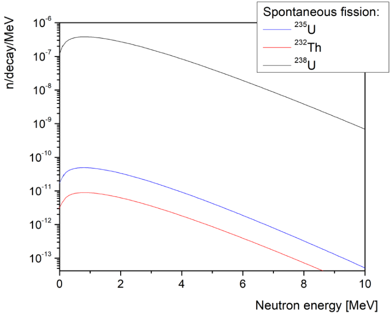
Spontaneous fission of naturally occurring primordial radionuclides ^{232}Th, ^{235}U and ^{238}U.

Watt spectrum: $p(E) \approx e^{-E/a} sinh(\sqrt{bE})$

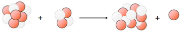
$$\textbf{Neutron yield} = \nu_k(SF)\frac{T_{1/2}}{T_{1/2}(SF)}$$

	^{232}Th	^{235}U	^{238}U
Average multiplicity ν_k	2.14	1.86	2.01
Branching ratio	1.17×10^{-11}	7.18×10^{-11}	5.45×10^{-7}
Neutron yield [n/decay]	2.50×10^{-11}	1.34×10^{-10}	1.09×10^{-6}

→ highest contribution is due to **SF of ^{238}U**



(α,n) Reactions



$^{A}_{Z}X + ^{4}_{2}He \longrightarrow ^{A+3}_{Z+2}Y + ^{1}_{0}n$

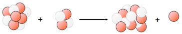
Reactions of α particles from radionuclides in ^{238}U and ^{232}Th decay chains with light nuclei.

Neutron yield of (α,n) reaction depends on material properties and activity of the α-decaying isotopes

$$Y_n \approx \int_0^{E_\alpha} \frac{\sigma_{(\alpha,Xn)}(E)}{\varepsilon(E)} dE$$

α **particle's energy** **Cross-section of the reaction** α **energy loss in a given material**

(α,n) Reactions



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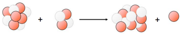
α particle's energy
- Energies of α emitters in ^{238}U and ^{232}Th decay chains + BR

Cross-section of the reaction

α energy loss in a given material

(α,n) Reactions



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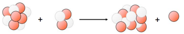
Cross-section of the reaction
a) Nuclear models - TALYS
b) Evaluated Nuclear Data Files - JENDL, TENDL

α energy loss in a given material

$(\alpha$,n) Reactions



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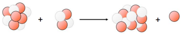
α energy loss in a given material
- Can be calculated independently with MC codes (e.g. SRIM, ASTAR)

(α,n) Reactions



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α particle's energy
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Cross-section of the reaction
a) Nuclear models - TALYS
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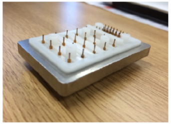
α energy loss in a given material
- Can be calculated independently with MC codes (e.g. SRIM, ASTAR)

MC transport code - Geant4 - capable of calculating Y_n in (α,Xn) reactions and neutron energies
Advantage: production of γ decays in the same nuclear process - **(α,nγ) reactions**

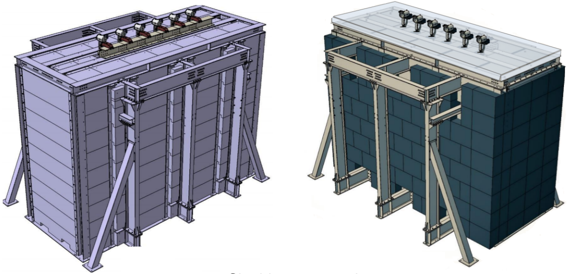
Neutron Contributions for SuperNEMO

Contaminated materials - large mass and high *U* and *Th* activities.

PMT glass bulbs



Feedthroughs



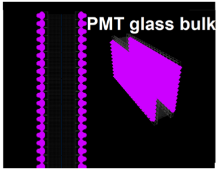
Shielding materials

Neutron Contributions for SuperNEMO

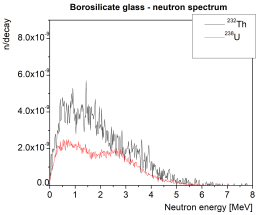
Contaminated materials - large mass and high *U* and *Th* activities.

Component	Mass [kg]	^{232}Th activity [Bq]	^{238}U activity [Bq]
PMT glass bulbs	**286**	**112**	**246**
Feedthrough CuBe pins		-	
Iron shield			
PE brick			
PE(B) brick			

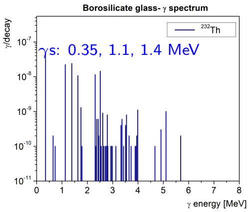
Composition - borosilicate glass (SiO_2, Al_2O_3, B_2O_3, ...)

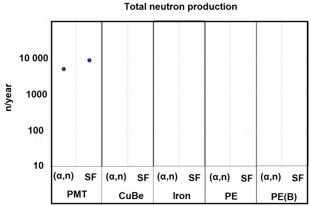


$(\alpha, n) \rightarrow$ neutron spectrum



$(\alpha, n\gamma) \rightarrow \gamma$ spectrum





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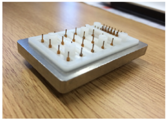
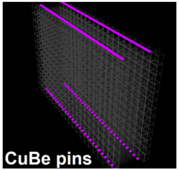
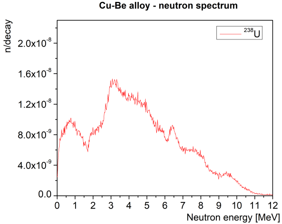
Feedthrough CuBe pins	**1.36**	-	**18.4**
Iron shield			
PE brick			
PE(B) brick			

Composition - Copper-Beryllium alloy

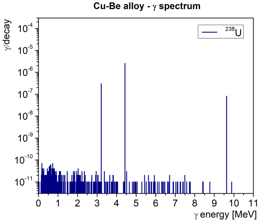


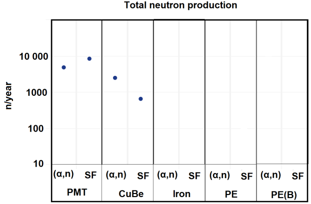


$(\alpha, n) \rightarrow$ neutron spectrum



$(\alpha, n\gamma) \rightarrow \gamma$ spectrum





Contaminated materials - large mass and high *U* and *Th* activities.

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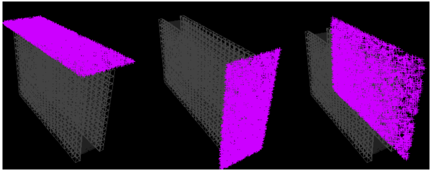
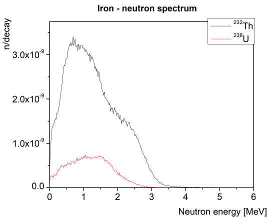
Iron shield	**230 000**	**<115**	**<230**
PE bricks	**4100**	**<6.2**	**<9.3**
PE(B) bricks	**4100**	**49**	**847**

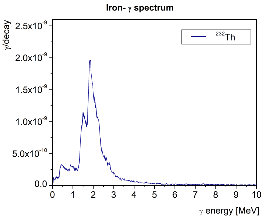
Composition - Fe (^{54}Fe, ^{56}Fe, ^{57}Fe,^{58}Fe)

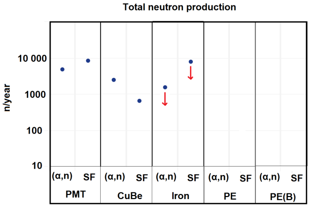


$(\alpha, n) \rightarrow$ **neutron spectrum**



$(\alpha, n\gamma) \rightarrow \gamma$ **spectrum**





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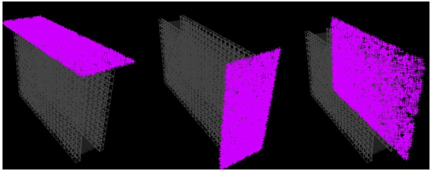
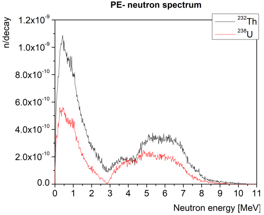
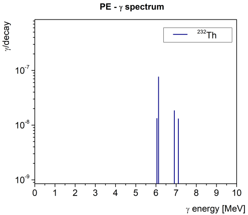
Composition - PE, PE(B): $(CH_2)_n + B$

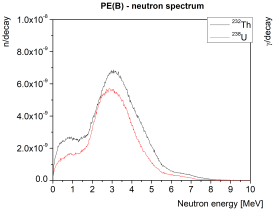


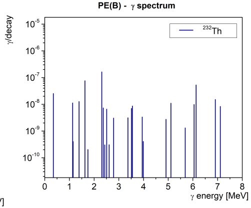
$(\alpha, n) \rightarrow$ neutron spectrum



$(\alpha, n\gamma) \rightarrow \gamma$ spectrum







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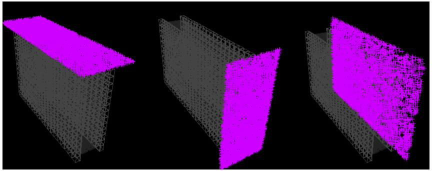
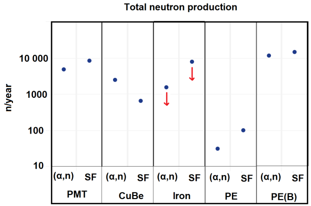
Pure PE $\rightarrow$ low n yield, low mass, low activity

PE(B) $\rightarrow$ the n yield for PE(B) is $\sim 9 \times$ higher
$+$ high activity of PE(B) bricks

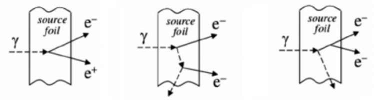
Composition - PE, PE(B): $(CH_2)_n + B$





Neutron Capture Gamma Cascades

$$n \rightarrow {}^{A}_{Z}X \rightarrow {}^{A+1}_{Z}X^{*} \rightarrow {}^{A+1}_{Z}X + \gamma \quad \ldots$$



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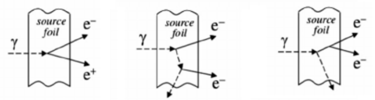

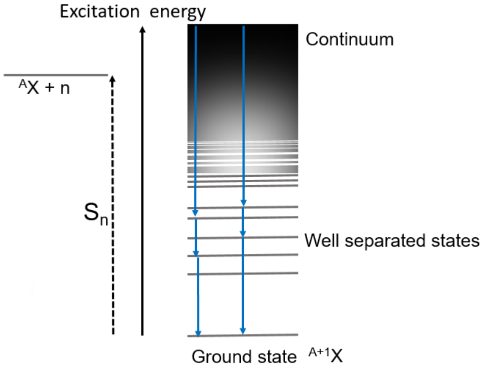

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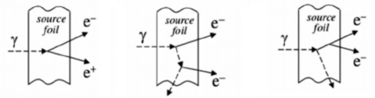

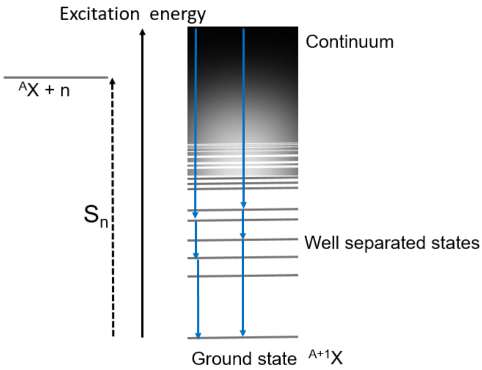

- Fe and Cu - gamma energies from neutron capture extend to high values + large mass of iron and copper in the detector

Isotope	Abundance [%]	S_n of CN [MeV]
^{54}Fe	5.85	9.298
^{56}Fe	91.75	7.646
^{63}Cu	69.17	7.916
^{65}Cu	30.83	7.066

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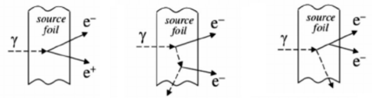

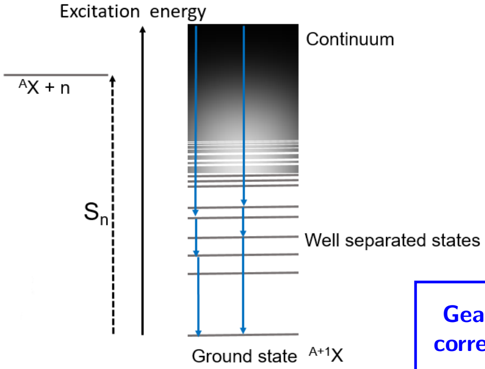

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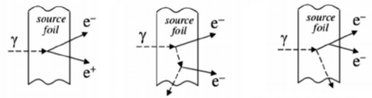
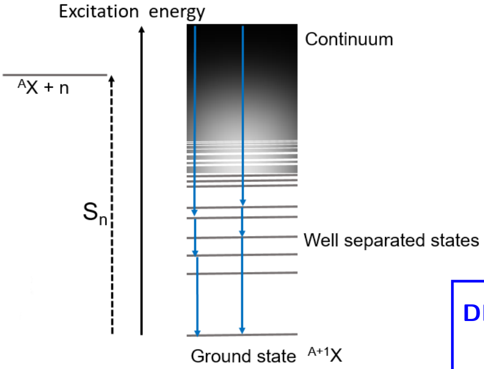
Geant4 is not able to reproduce (n,γ) reactions well: correlations between γs are not taken into account correctly

Neutron Capture Gamma Cascades

$$n \to {}^{A}_{Z}X \to {}^{A+1}_{Z}X^{*} \to {}^{A+1}_{Z}X + \gamma \quad \dots$$





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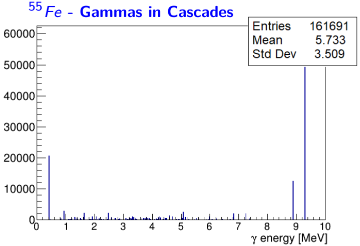
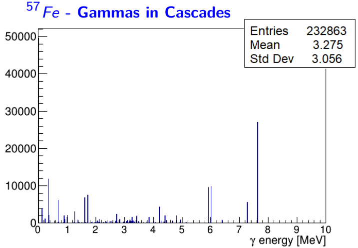
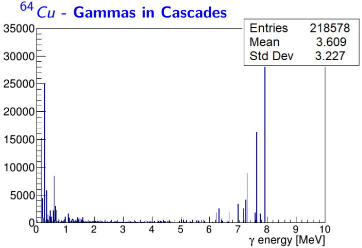
DICEBOX γ decay simulation tool - LD and PSFs as input quantities that characterize the cascade γ emission
https://www-nds.iaea.org/dicebox/

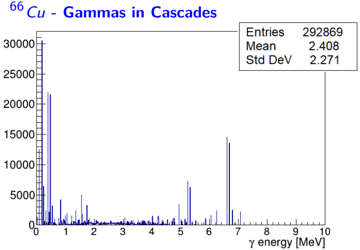
Individual Gammas in Cascades

100 000 thermal neutron captures simulated in DICEBOX



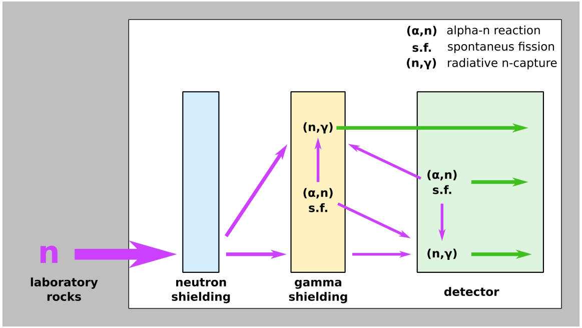






Neutron Induced Background

Goal: Analyze detector's response to neutron radiation

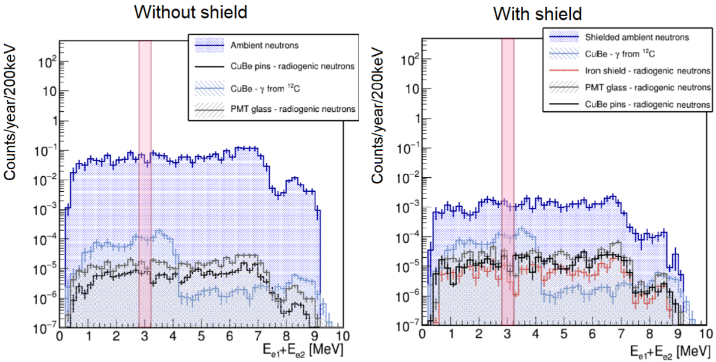


Falaise: SuperNEMO simulation software (Geant4 based)

1. Generate *n* from their source positions according to their E spectra
2. Store *n* capture positions on Fe and Cu isotopes and number of captures
3. Generate γ cascades from stored positions
4. Get expected number of background events

Neutron Induced Background

Results



→ $0.2 \pm 0.03/\text{year}$

→ $0.003 \pm 0.001/\text{year}$

Total external neutron induced background in the $2e^-$ channel

→ ROI - (2.8,3.2) MeV

→ ambient neutron fluxes are the dominant source

→ γs from *n*-captures in the iron shield are simultaneously attenuated

✓ the contribution from radiogenic *n* is negligible

Summary and Conclusions

The aim of this work was to estimate the background contributions from neutrons in the SuperNEMO experiment.

Evaluation of different background sources:

- ✓ SF - fission libraries + Watt spectrum
- ✓ (α,n) and (α,γn) reactions - Geant4 simulations using evaluated nuclear data libraries
- ✓ γ production from cascades from thermal neutron capture in Geant4 - γ decay software DICEBOX

✓ **Negligible external background rate from investigated sources!**