CANDLES

@Kamioka Observatory

Low Background Techniques in CANDLES

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for the CANDLES Collaboration

Low Radioactivity Techniques 2015
Mar.20, 2015, Seattle, Washington Univ.

CANDLES

CAlcium fluoride for the study of **N**eutrinos and **D**ark matters by **L**ow **E**nergy **S**pectrometer

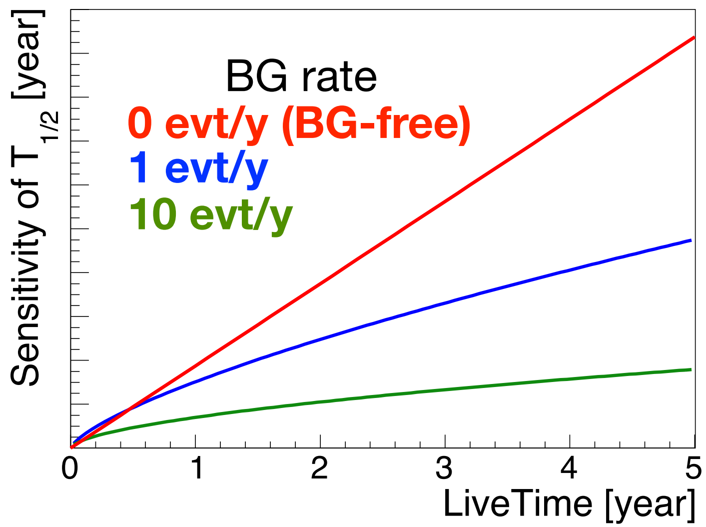
- **CANDLES**: Double beta decay experiment with ^{48}Ca
  - **Advantage**: Highest Q-value (4.27 MeV)
    - cf. Next highest: ^{150}Nd (3.37 MeV)
  - **Disadvantage**: Low natural abundance, 0.187%
    - Enrichment technique is under development.

Possibility of BG-free Measurement

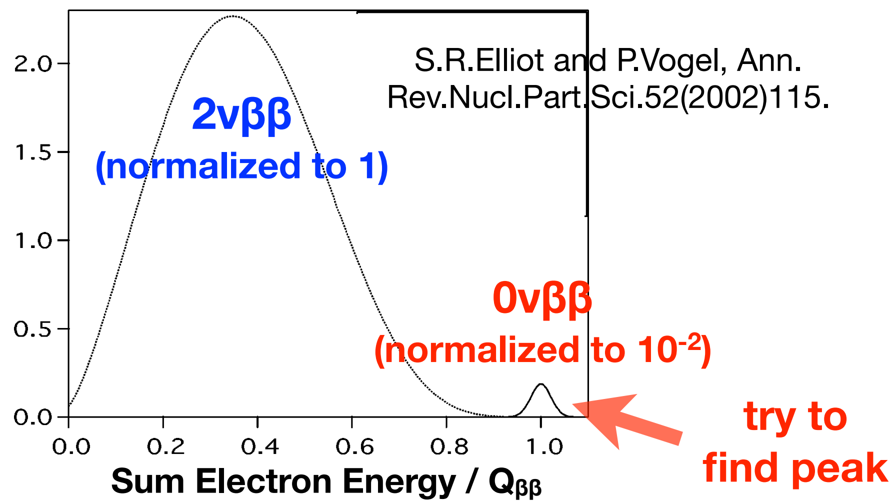
BG-free: $T_{1/2} \propto (M_{target} \cdot T_{live})$

BG-limited: $T_{1/2} \propto (M_{target} \cdot T_{live})^{1/2}$

Sensitivity vs Live time



Electron Spectrum with Resolution



✓ **Very low signal rate ($T_{1/2} > 10^{25}$ y)**

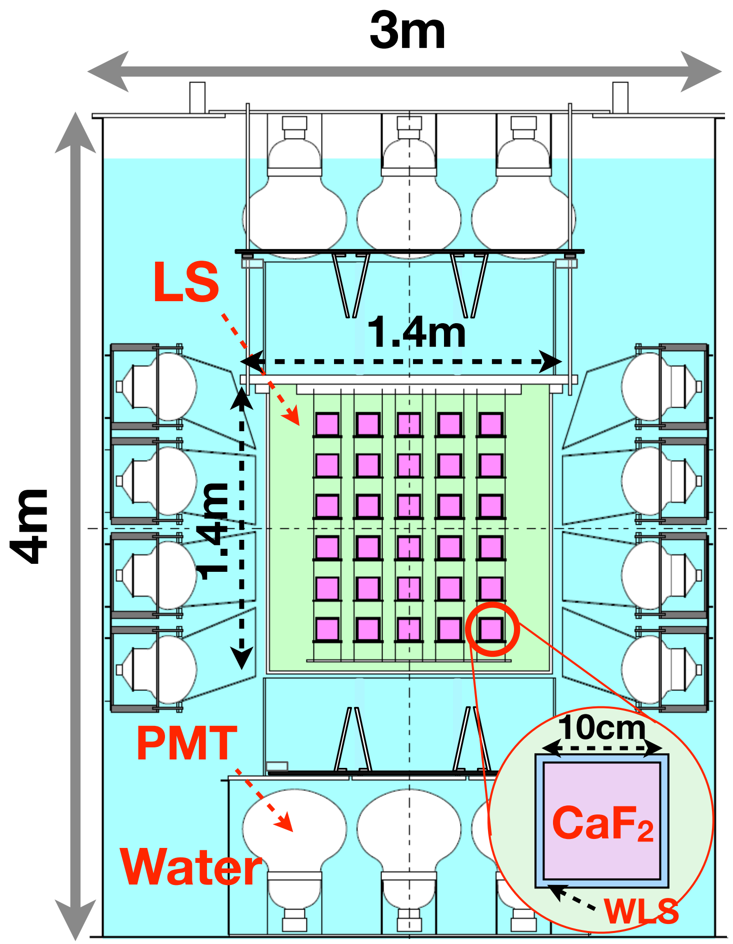
- **Good energy resolution**
- **Low BG measurement**

CANDLES III (U.G.) Detector

Under Ground

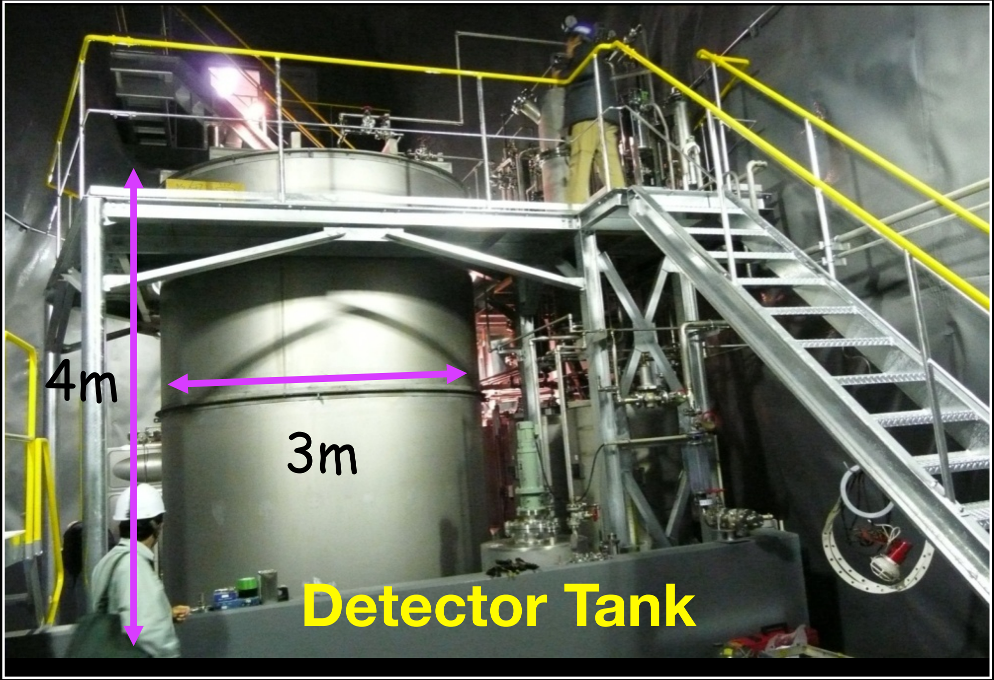
CANDLES Detector

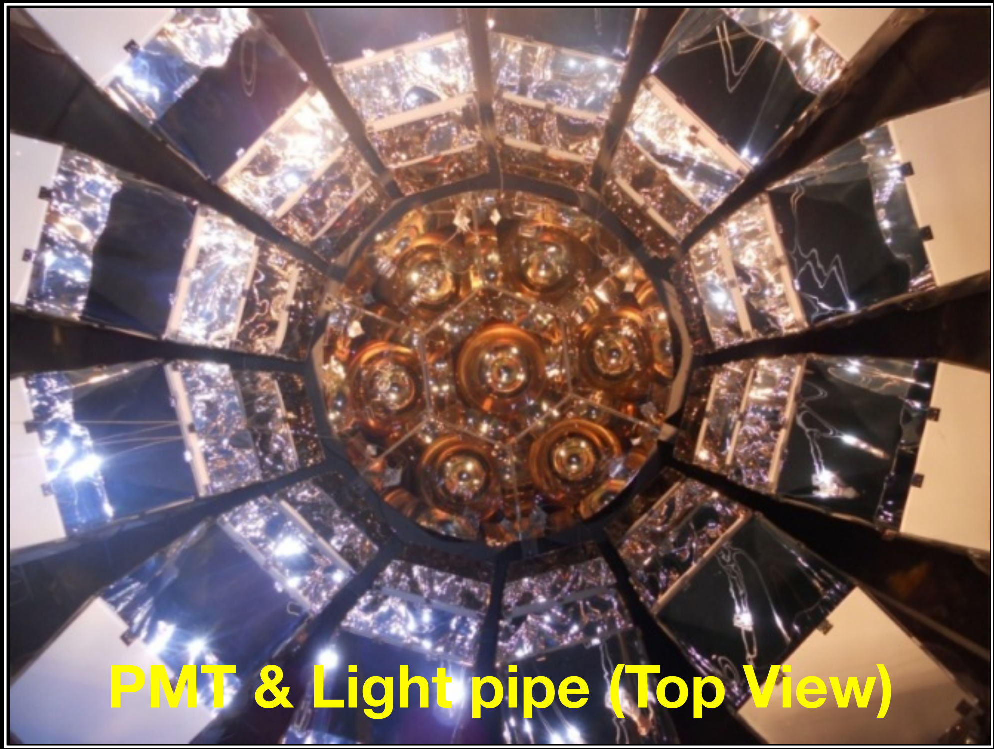
@ Kamioka (2700 m.w.e.)

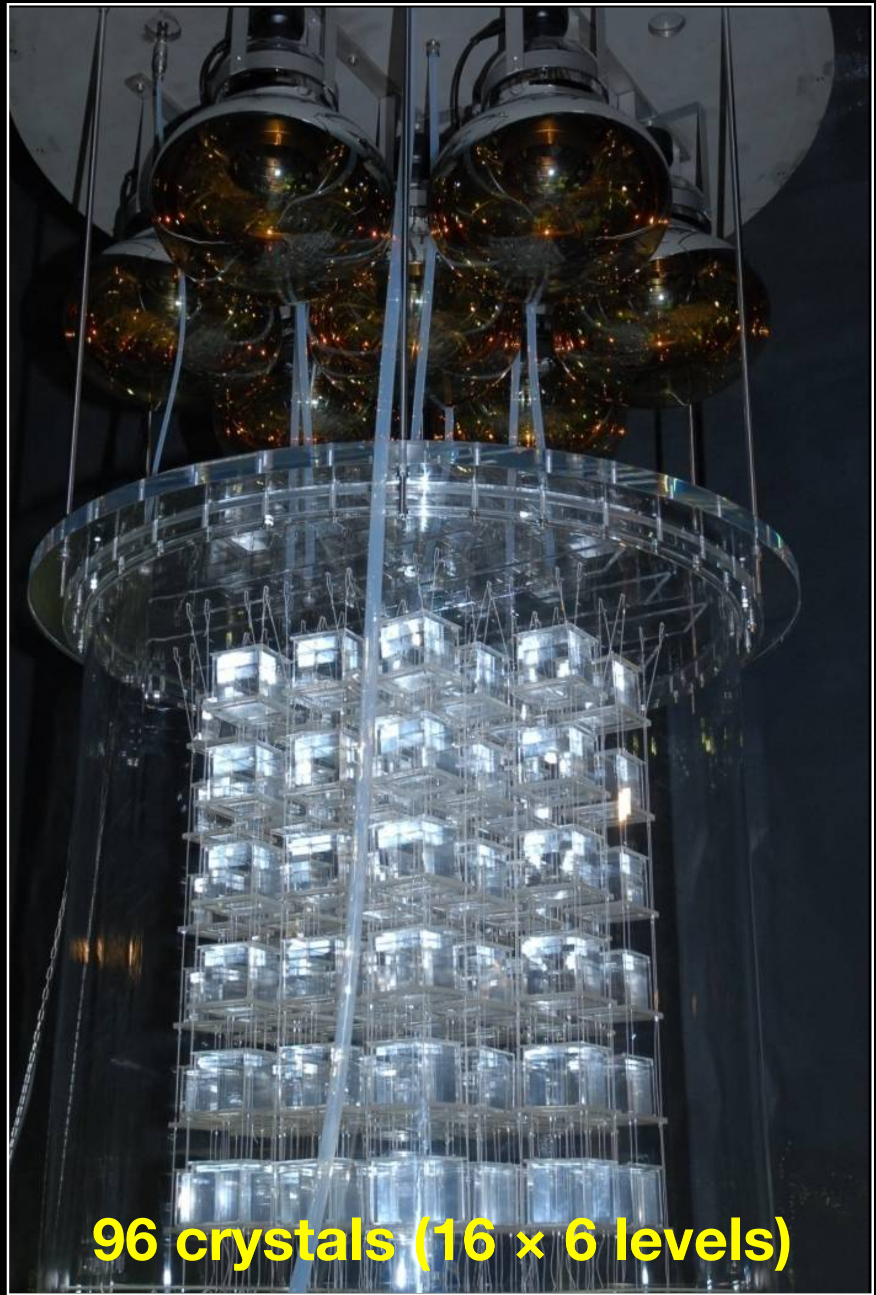


Detector components (from inside)

- **CaF_2 module**
  - $10\times10\times10$ cm^3 × 96 crystals (305 kg)
    - ^{48}Ca ~350 g (0.187% nat.)
  - Wave length shifter (WLS)
    - 280 (CaF_2) → 420 nm (PMT-sensitive)
- **Liquid scintillator (LS)**
  - Active veto (for internal/external γ-rays)
  - ϕ1.4m × H1.4m (Acrylic tank), V~2 m^3
- **Pure water**
  - Passive shield (for external γ-ray, neutron)
  - ϕ3m × H4m (Stainless steel tank), V~30 m^3
- **62 PMTs**
  - 13 inch PMT × 48, Side
  - 20 inch PMT × 14, Top/Bottom
  - Light pipe: reflection ~ 93% @ 420 nm


4m
3m
Detector Tank


PMT & Light pipe (Top View)

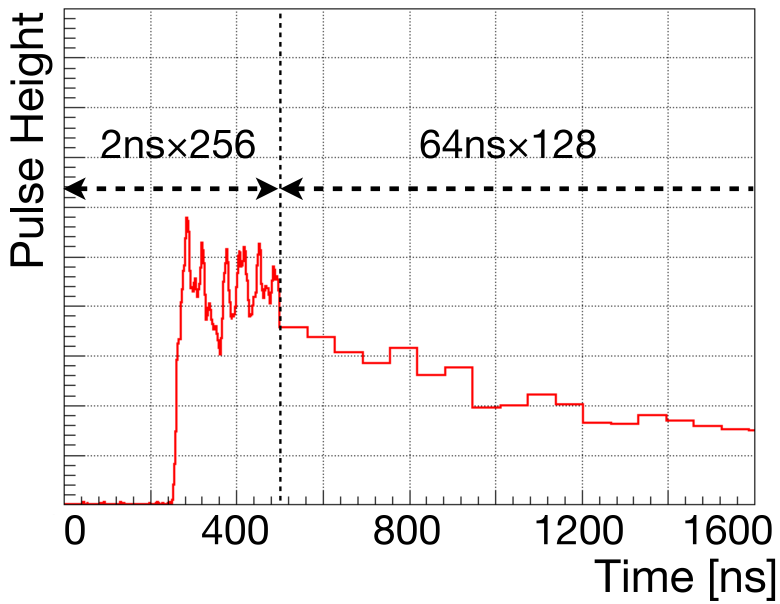

96 crystals (16 × 6 levels)

LS Active Veto

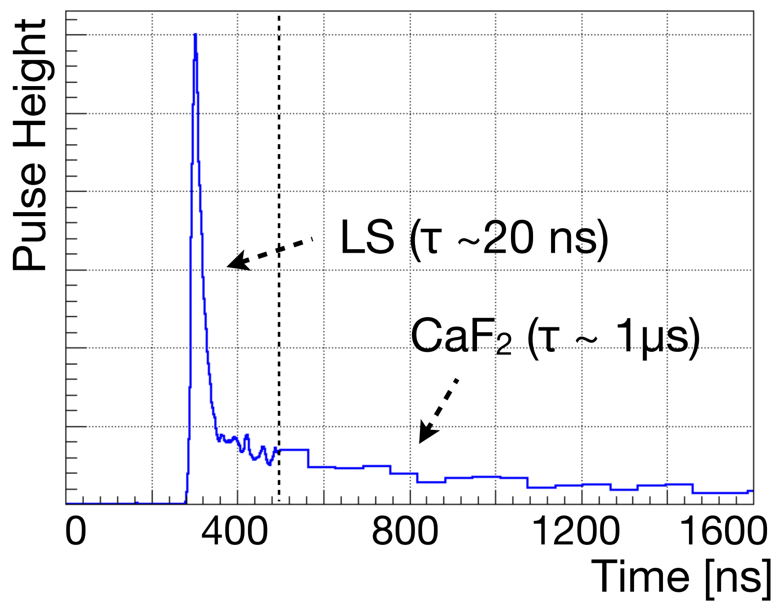
- Time constant of CaF_2 and LS pulse shape is different.
  - **CaF_2: ~1 μs, LS: ~20 ns**
    - Remove LS-only signals by triggers
    - Remove "CaF_2 + LS" events by pulse shape discrimination
- Sampling period of pulse shape
  - 2 ns × (First 256 points), 64 ns × (Later 128 points) = **8.7 μs**

Sum Pulse of 62 PMTs

CaF_2 only



CaF_2+LS



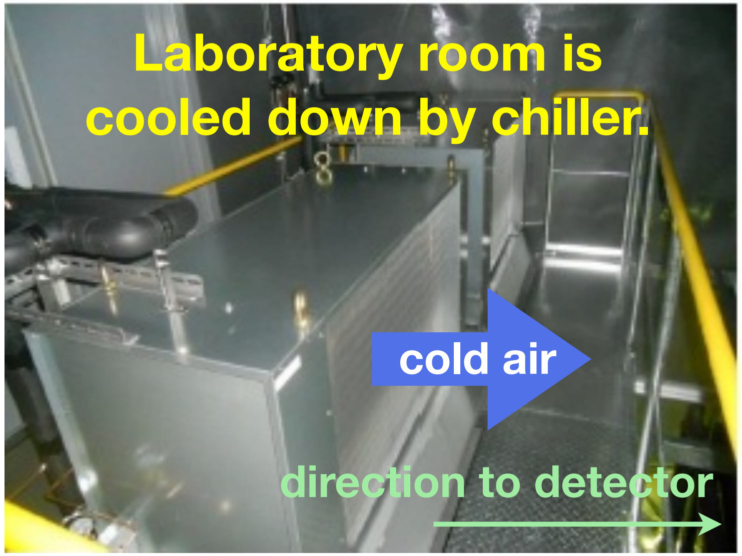
☑ **LS active veto: E_{LS}/E_{total} < a few % → Find CaF_2-only β signals!**

Measurement Status

Current status: Study with prototype detector (CANDLES III) for the high sensitive measurement in the future
→ Understanding of BG, detector improvement

2012	2013	2014
Data taking	Data taking	Data taking
• **Light pipe installation**	• **DAQ Update**	• **Magnetic cancellation coil** • **Cooling system**

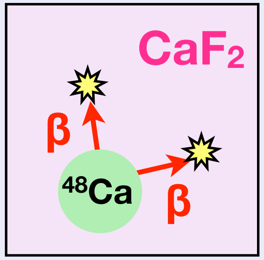
- **Light pipe installation**
  - Light yield × 1.8
- **DAQ Update**: Improve data transfer speed
  - Live time: ~80% → 98%
- **Magnetic cancellation coil**
  - Light yield × 1.3 (light collection efficiency)
- **Cooling system**: Temperature ~20°C → ~4°C
  - Light yield × 1.3



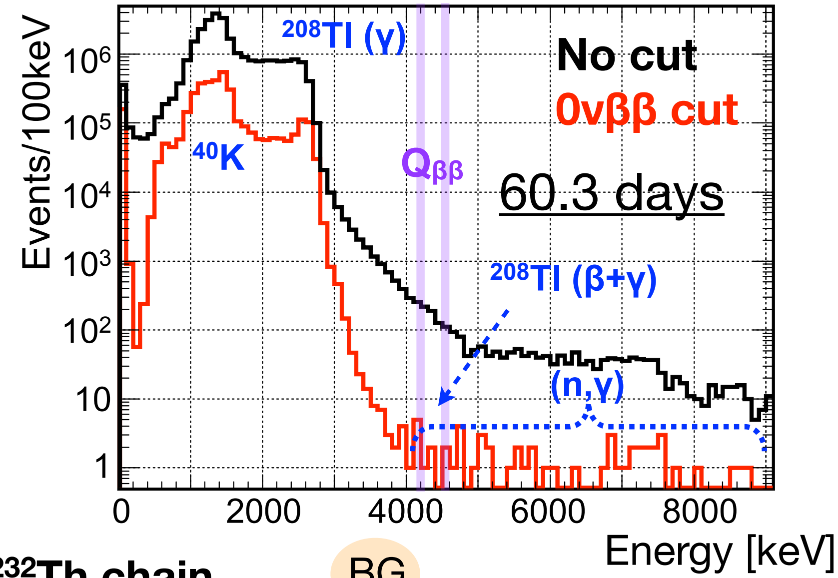
☑ **Current light yield: ~1000 p.e./MeV**

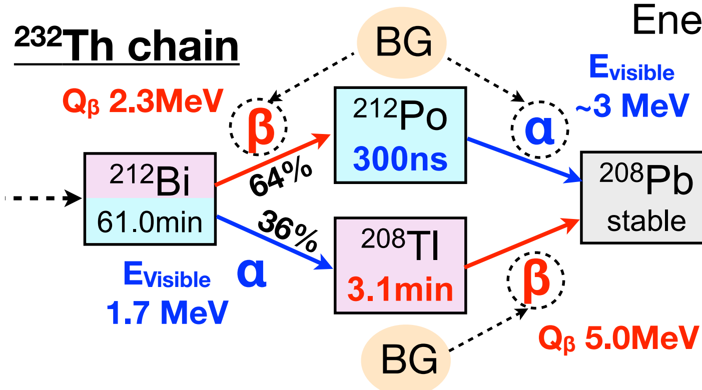
Background in $Q_{\beta\beta}$ (4.3 MeV)

1. 2νββ



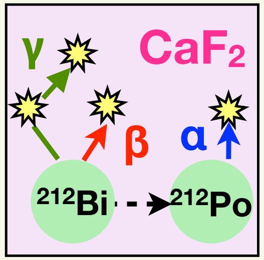
- Improve energy resolution
  - ‣ -1°C → +2% light yield
- Not serious in the current sensitivity





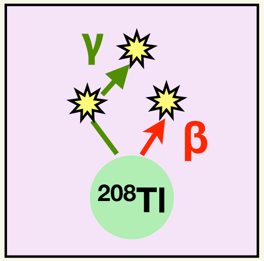
Radioactive impurities in CaF_2

2. ^{212}Bi-^{212}Po (^{232}Th chain)



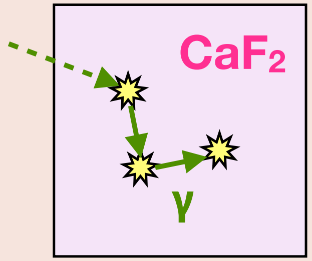
- Double pulse ($T_{1/2}$~300ns)
- – Max $E_{visible}$ ~5.3 MeV
- – Double pulse & PSD cut

3. ^{208}Tl (^{232}Th chain)



- Q_β = 5.0 MeV, $T_{1/2}$~3 min
- – Tag $^{212}Bi(\alpha)$ and veto for 12 min

4. External γ-ray ((n,γ) reaction)



- Recently identified
- Remain even after LS active veto

Pulse Shape Discrimination (PSD)

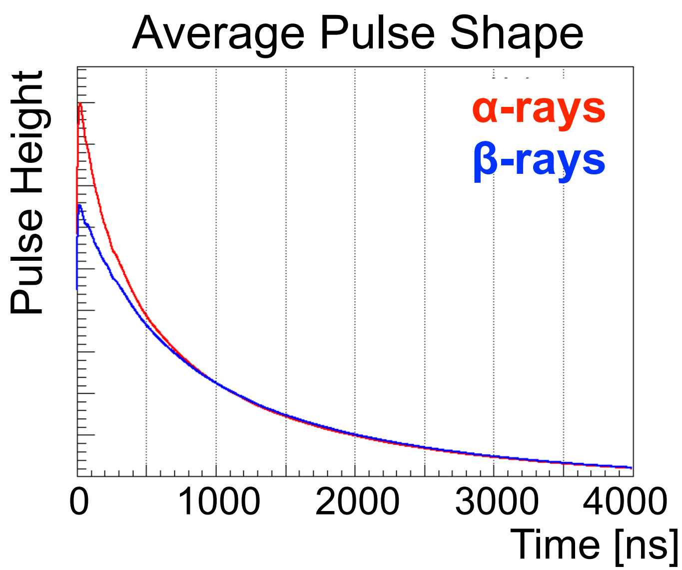
PSD is a key for BG reduction in CANDLES.

PSD

1. CaF_2 selection (0νββ is β-ray signal only in CaF_2)
- Separate "CaF_2" signal from "CaF_2+LS" signal

2. Background rejection
- Find α-rays from β-rays to tag ^{212}Bi (parent nuclei of ^{208}Tl)
  → Apply veto time (**^{208}Tl rejection**, **$\varepsilon_{rejection}$ ~ 60%**)
- Double pulse rejection (**^{212}Bi-^{212}Po rejection**, **ε > 99%**)

PSD Methods
- Make reference pulses for α-ray, β-ray, LS (> 1,000 events)
- Fit pulse shape event by event with reference pulse
  → Obtain PSD parameters; χ^2_α, χ^2_β, $\chi^2_{\beta+LS}$



Radioactive Impurities in CaF_2

- **CANDLES developed low contaminated CaF_2 by powder selection.**
- Radioactivities in CaF_2 crystals can be measured by delayed coincidence assuming radioactive equilibrium.

- **^{238}U: ~36 μBq/kg** (= 9.9 decays/day/crystal)

$^{238}U \dashrightarrow {}^{214}Bi \xrightarrow[\text{3.27MeV}]{\beta\text{ decay}} {}^{214}Po$ (**164μs**) $\xrightarrow[\text{7.83MeV}]{\alpha\text{ decay}} {}^{210}Pb$

- **^{232}Th: ~21 μBq/kg** (= 5.8 decays/day/crystal) BG

$^{232}Th \dashrightarrow {}^{220}Rn \xrightarrow[\text{6.41MeV}]{\alpha\text{ decay}} {}^{216}Po$ (**145ms**) $\xrightarrow[\text{6.91MeV}]{\alpha\text{ decay}} {}^{212}Pb$

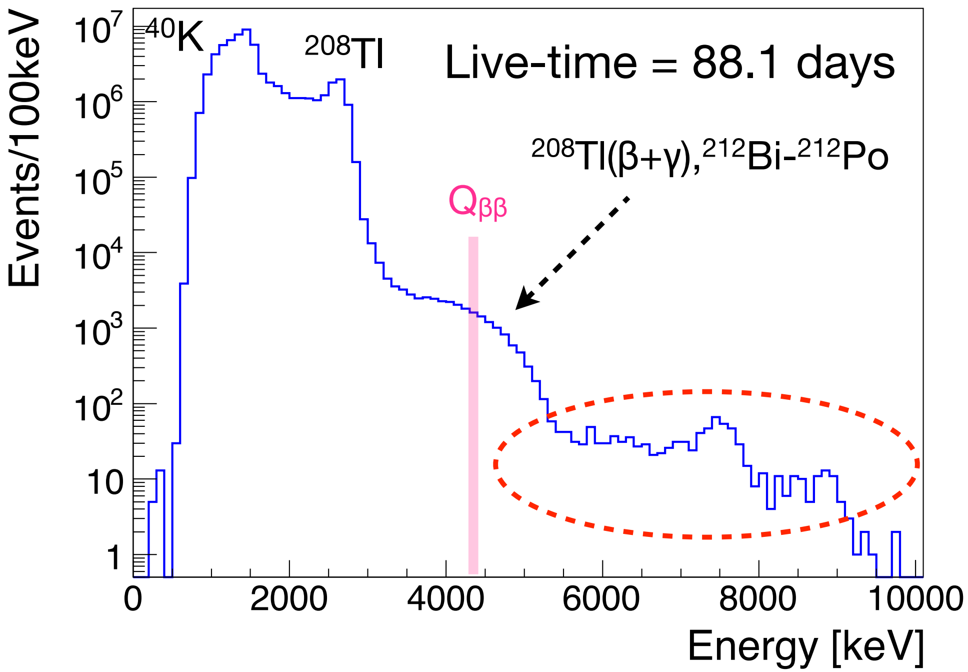
- **^{235}U: ~16 μBq/kg** (= 4.4 decays/day/crystal)

$^{235}U \dashrightarrow {}^{219}Rn \xrightarrow[\text{6.95MeV}]{\alpha\text{ decay}} {}^{256}Po$ (**1.78ms**) $\xrightarrow[\text{7.53MeV}]{\alpha\text{ decay}} {}^{211}Pb$

- These α-rays can be used for energy and PSD studies.
- α-ray peaks are observed around 1.5~3 MeV due to quench.

(n,γ) Reaction

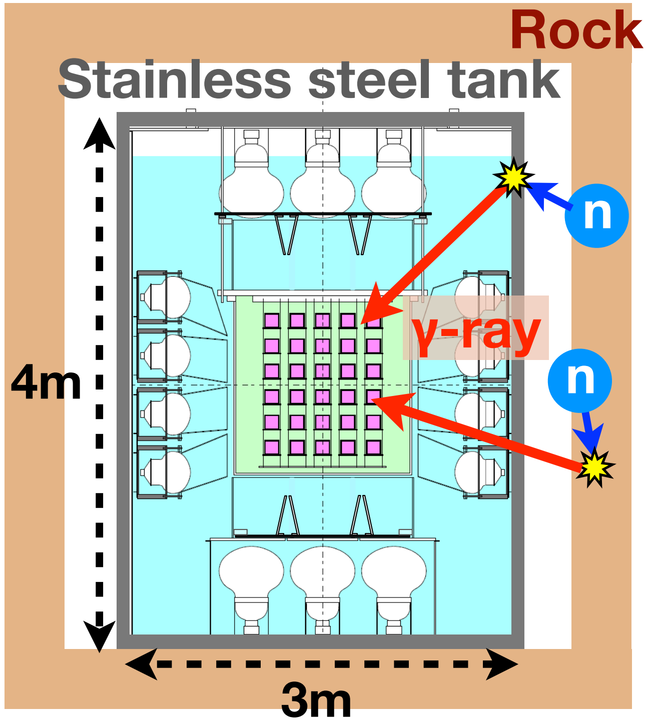
Energy Spectrum
(applied loose cut to get high statistics)



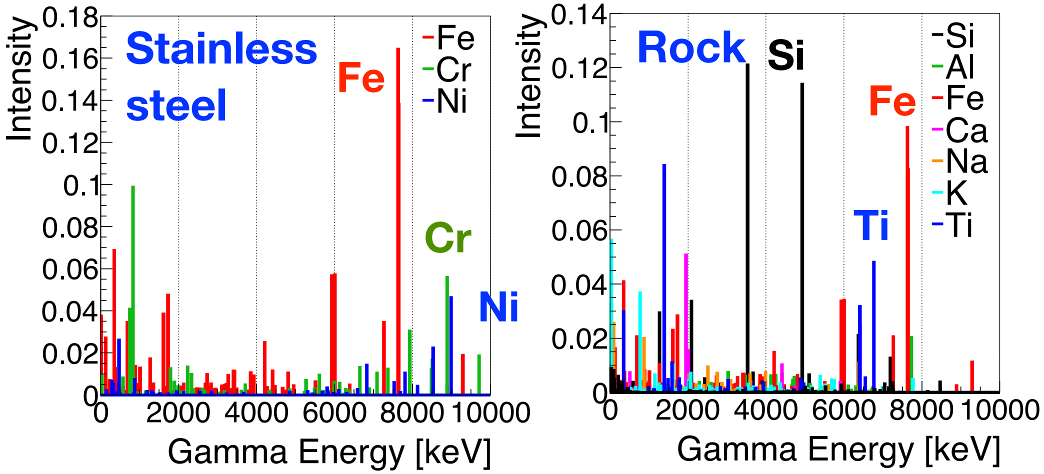
- High energy events were identified as **(n,γ) reaction** by two methods.

1. **Neutron source (^{252}Cf) set out of detector**
2. **(n,γ) simulation by Geant4**

Schematic View of (n,γ) Reaction



γ-ray spectrum by (n,γ) reaction



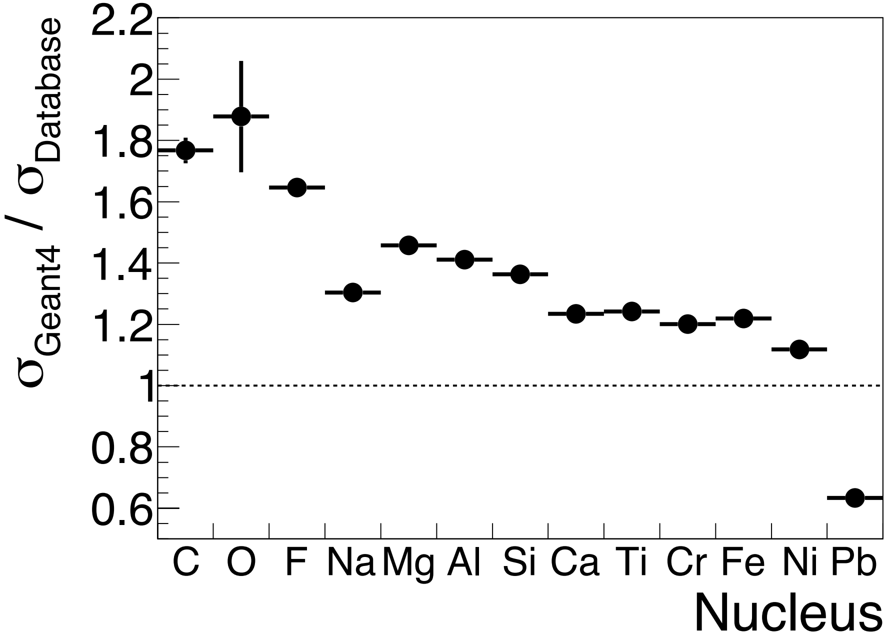
☑ (n,γ) on rock and tank is dominant

IAEA database: https://www-nds.iaea.org/pgaa/

Problems in (n,γ) Simulation

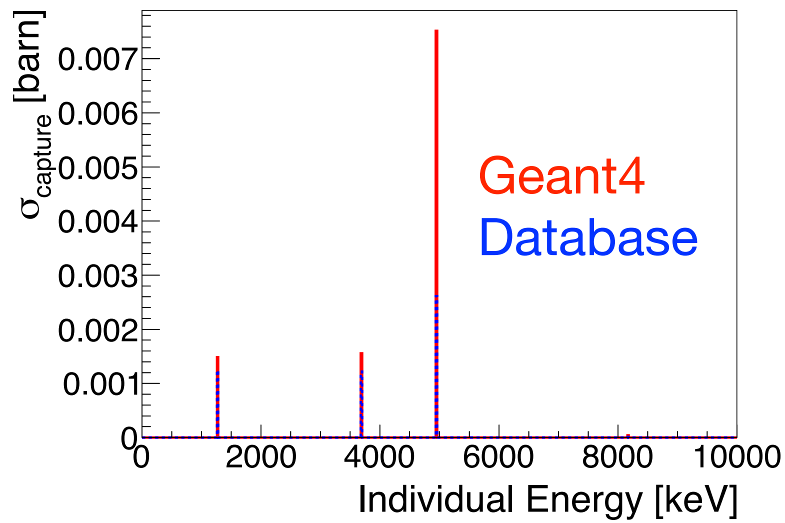
- As a validity check of (n,γ) MC, check following items
  - Geant4 version: 4.10.00.p01 (Physics list: QGSP_BERT_HP)
- ☑ Compare neutron capture cross section between database and MC
  - Difference: Rock < 1.4, Stainless < 1.2 → **a few tens % error**
- ☑ γ-ray intensity by (n,γ) reaction: Incorrect except H
  - **→ Generate γ-rays based on database**

Difference of neutron capture cross section between Geant4 and database



✓ Capture cross section diff. < 2

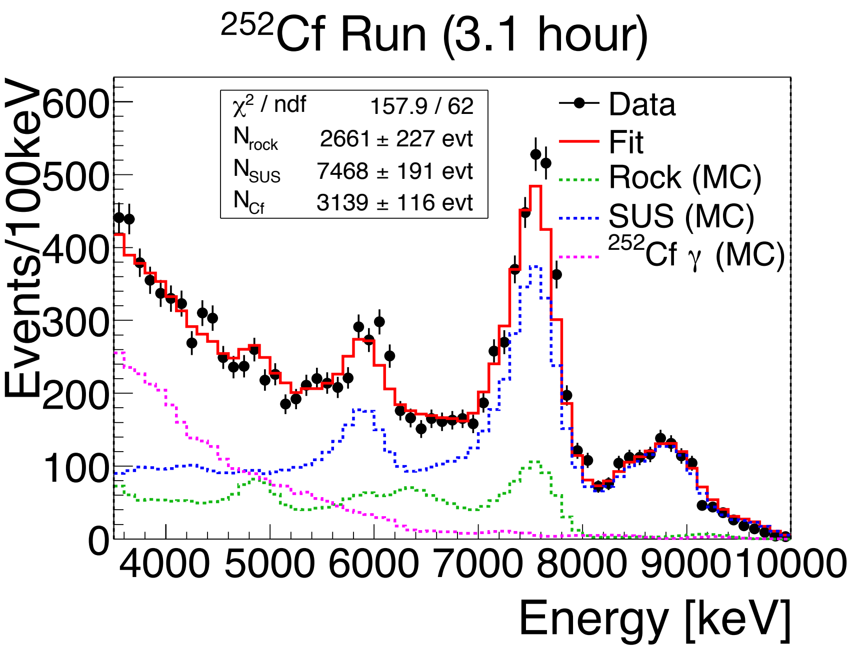
e.g. (n,γ) Intensity of $_6$C "in barn"

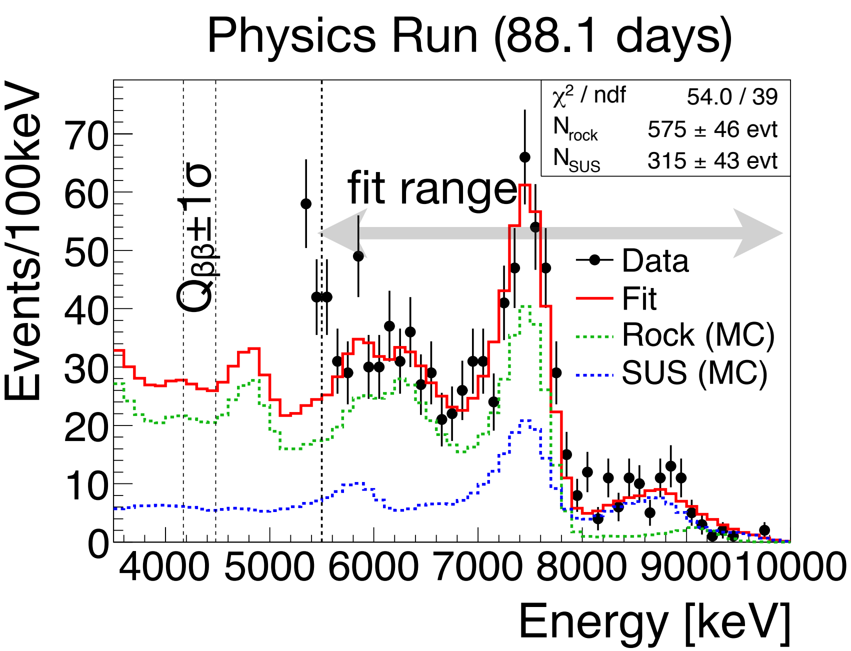


✓ γ-ray spectrum should be based on database.

Comparison of Data and MC for (n,γ)

- Detector simulation of (n,γ)
  - Generate γ-rays uniformly in rock or tank based on γ-ray spectrum on (n,γ) reaction



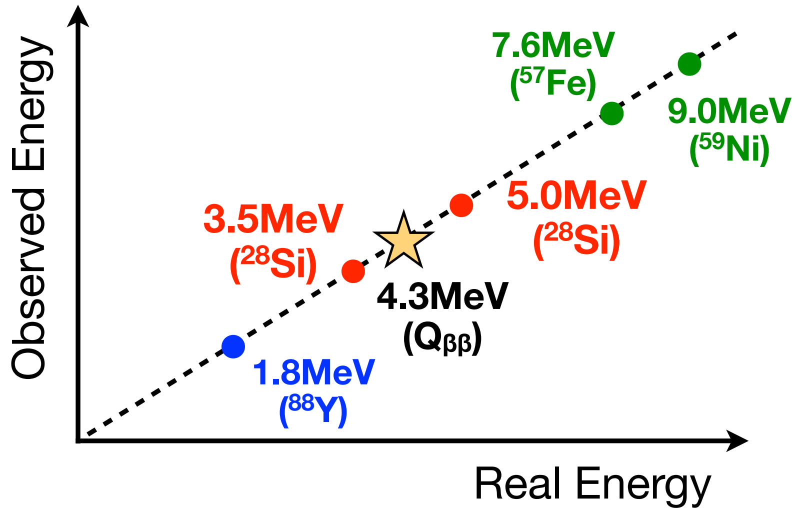


☑ **Observed spectra are well reproduced by MC simulations.**

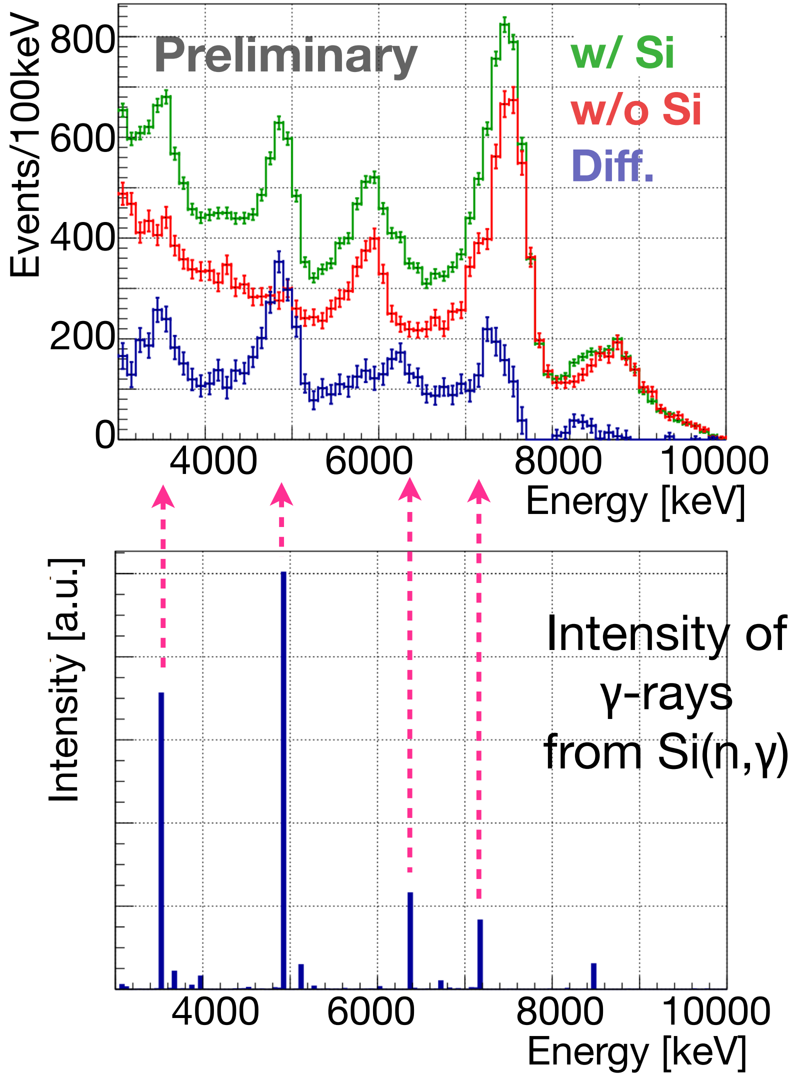
- (n,γ) BG in Q value is evaluated from MC.
  - ✓ **Number of (n,γ) BG: Rock/tank = 3.6±0.7 in $Q_{\beta\beta}\pm 1\sigma$**
  - ✓ **(n,γ) BG: 76±9(stat.) events/year/96crystals**

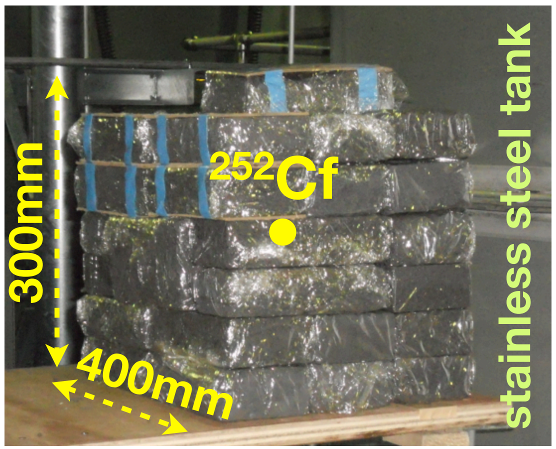
Application of (n,γ) Reaction

- Calibration source: ^{88}Y (1.836 MeV)
- cf. $Q_{\beta\beta}$ = 4.3 MeV
  → **Use (n,γ) as calibration source**



Observed Spectrum (~1day)





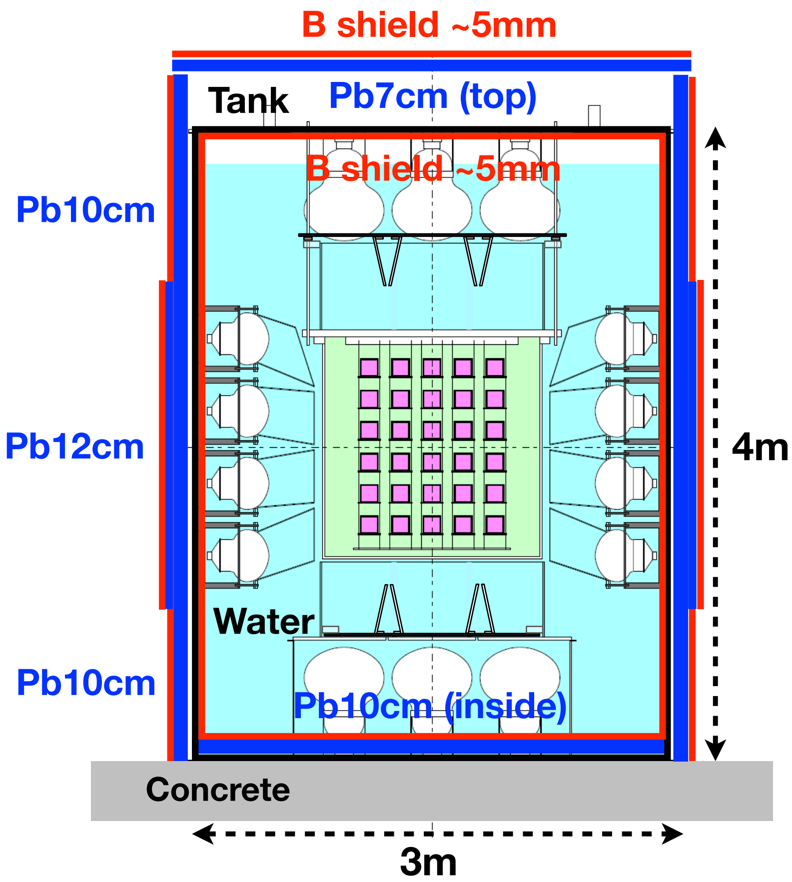
Si block surrounding ^{252}Cf
(Si:PE:Bond=3:1:1)

Ni ball
(NiO:PE=1:2)

✓ **Energy scale can be checked up to ~10 MeV.**

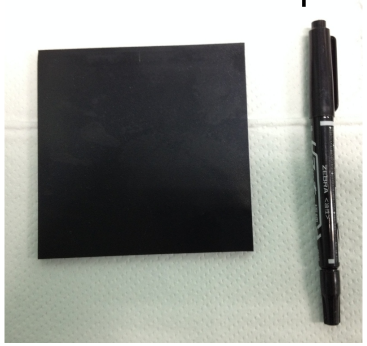
Toward BG Free: Detector Shielding

- **Reduce (n,γ) events by additional shielding**
  - ▸ **Goal: ~1 events/year/96crystals (~1/80 level)**
- Optimize shield design by Geant4 simulation
  - Rock: Pb shield for γ-rays
  - Tank: Si rubber sheet including B for thermal neutron



<u>(n,γ) BG Estimation (MC)</u>
- **Total: ~0.7 (±50%) evt/y**
  - ▸ **Rock γ: 0.34±0.14 evt/y**
  - ▸ **Tank γ: 0.4±0.2 evt/y**

B Sheet Sample

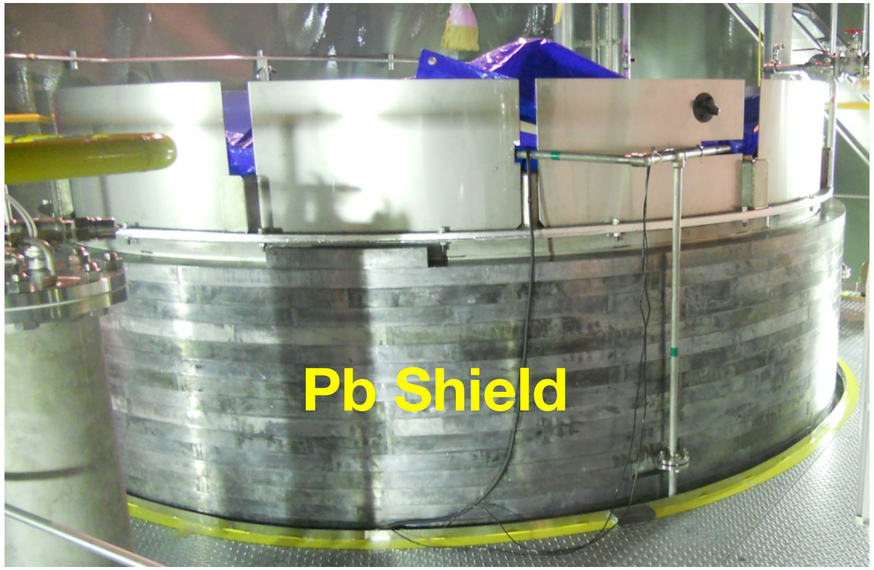


- **Schedule to install around this autumn**

Status of Pb Shield Construction

Side of stainless steel tank (Mar.17)

Top of tank (Mar.19)



- Side shield will be constructed by this March
- Other parts will be installed by the end of this summer
- **Next data taking around autumn!**

Summary

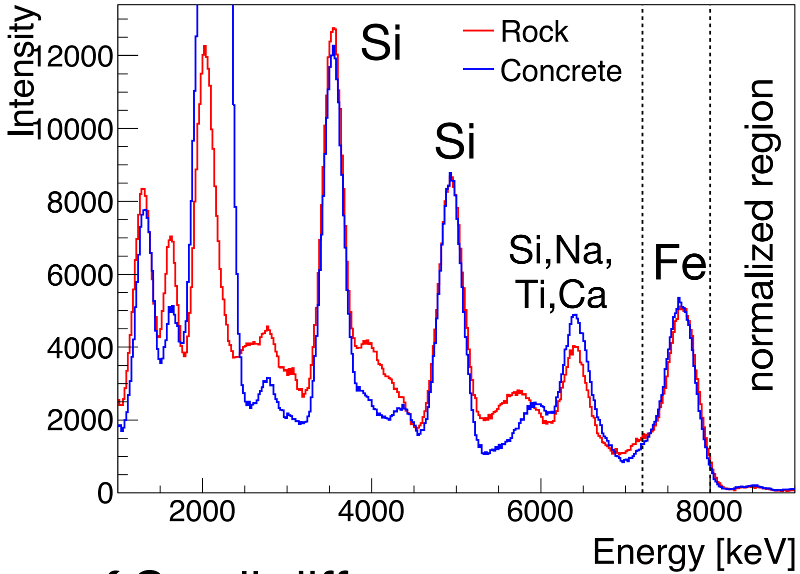
- CANDLES is a double beta decay experiment with ^{48}Ca.
- LS active veto and PSD analysis are the key for BG reduction.
- Backgrounds in CANDLES
  - ^{232}Th series → Low radioactive CaF_2 & analytical reduction
  - (n,γ) BG → Additional detector shielding
- (n,γ) reaction can be used as energy calibration.
  - Si block, Ni ball
- Next data taking will start around autumn.

BackUp

Discussion about Rock Components

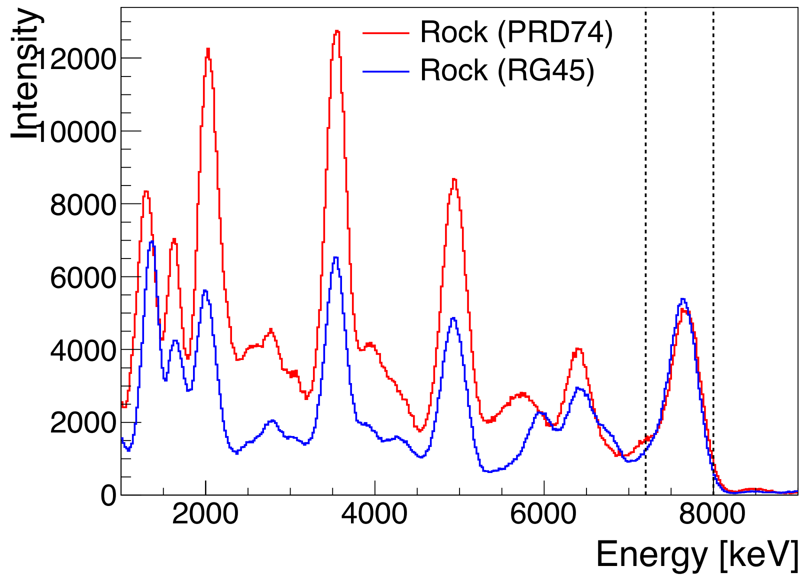
- (n,γ) spectrum is checked for two rock models and concrete.
  - Rock1: Component of Ikenoyama rock (PRD74, 053007 (2006))
  - Rock2: Component in Mozumi mine, more than 10 samples (Resource geology 45, 25-40, 1995, written in Japanese)
  - Concrete: Use typical component

Rock1 vs Concrete (6%/√E[MeV])



✓ Small difference
→ Ignore concrete

Rock1 vs Rock2 (6%/√E[MeV])



✓ Large difference due to double FeO
→ Fit spectrum with each model

☑ Fit quality is almost same for two rock models
☑ Confirmed small effect to BG rate at Q value