Search for Neutrino-less Double Beta Decay of ^{48}Ca - CANDLES -

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CANDLES Collaboration

Candles

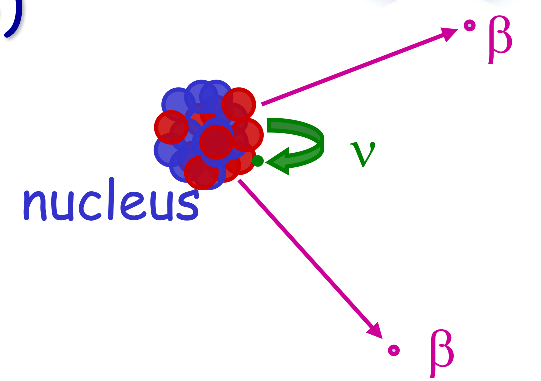
Outline

- Double beta decay
  - Double beta decay of ^{48}Ca
- CANDLES System

  = CaF_2(pure) scintillators + Liquid scintillator
  - CANDLES III system at Kamioka underground lab.
    - Expected backgrounds
    - Shielding system for background reduction
- Further improvement
- Summary

Double beta decays

- Neutrino-less double beta decay($0\nu\beta\beta$)
  - Process beyond the Standard Model
    - Non-zero neutrino mass
    - Lepton number violation
  - Predicted lifetime : $T_{1/2} > 10^{25}$years



- Why ^{48}Ca?
  - Higher $Q_{\beta\beta}$-value(4.27MeV) . . .

    →Low background

    because $Q_{\beta\beta}$-value is higher than BG

    E_{max}=2.6MeV(^{208}Tl, γ-ray), 3.3MeV(^{214}Bi,β-ray)

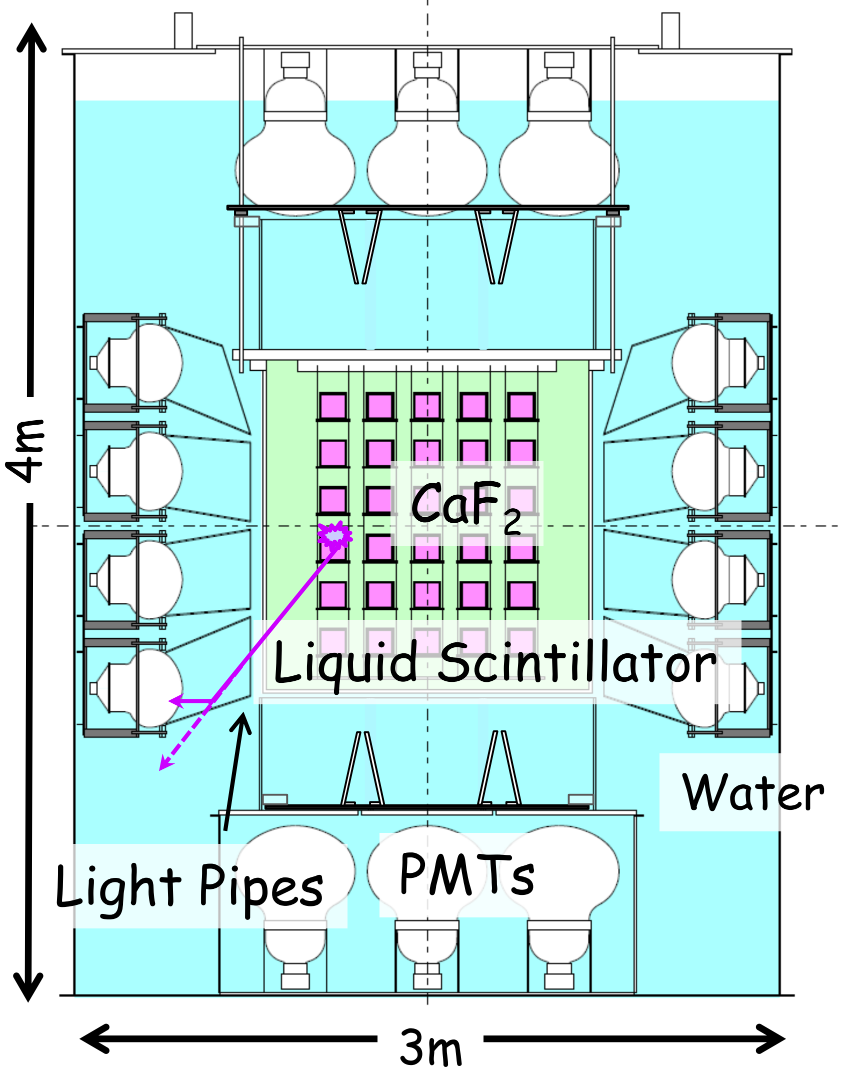
Double beta decay of ^{48}Ca by using CaF_2 scintillators

→We installed the CANDLES III system at Kamioka Lab.

CANDLES III

CANDLES at Kamioka underground laboratory

CANDLES III



- CaF_2 scintillator (CaF_2(pure))
  305 kg (96 modules × 3.2kg)
  τ ~ 1μsec
- Liquid scintillator (LS)
  4 π active shield
  Volume:2m^3
  τ ~ a few ten nsec
- Large photomultiplier tube
  13inch PMT × 48
  20inch PMT × 14
- Light pipe system
  Guide scintillation light to PMTs
  Light collection effi. : ×1.8

Active Shielding Technique by FADC

Different time constants
CaF_2(pure) : ~1μsec
Liquid scintillator : a few 10 nsec

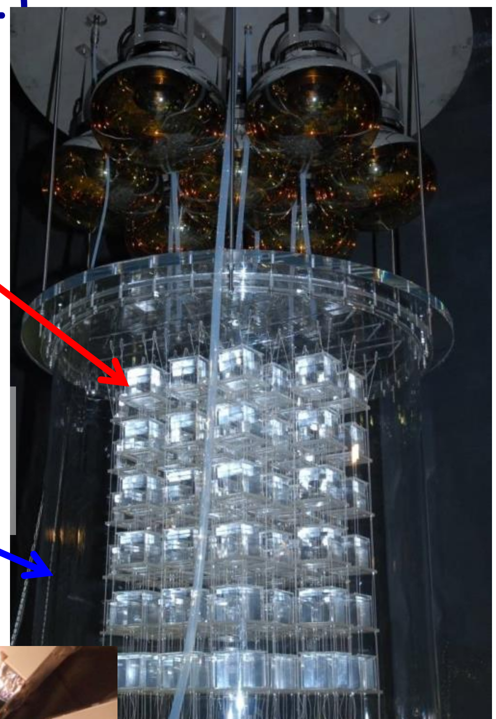
CANDLES III

CANDLES at Kamioka underground laboratory

CANDLES III

Main detector
CaF_2 Scintillators
(305kg)

Liquid Scintillator
Tank(2m^3)



13inch and 20inch
PMTs with light pipes

- <u>CaF_2 scintillator</u> (CaF_2(pure))
  305 kg (96 modules $\times$ 3.2kg)
  τ ~ 1μsec
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  4 π active shield
  Volume:2m^3
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Active Shielding Technique by FADC

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Backgrounds in CANDLES

$2\nu\beta\beta$ Events : negligible for CANDLES III

Possible to reduce by good energy resolution (~4% at 4.27MeV)

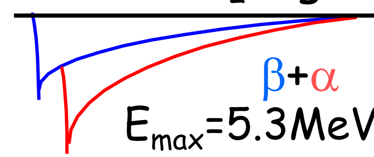
Radioactive Contaminations in CaF_2 Crystals

Pile-up Events

Th-Chain

^{232}Th ● ● ^{212}Bi $\xrightarrow[64\%]{\beta}$ ^{212}Po ($T_{1/2}$ = 0.3μsec) $\xrightarrow{\alpha}$ ^{208}Pb stable

Pile-up because of τ of CaF_2 signal = 1μsec



E_{max}=5.3MeV(Th-chain)
5.9MeV(U-chain)

^{208}Tl Event

Th-Chain

^{232}Th ● ● ^{212}Bi $\xrightarrow[36\%]{\alpha}$ ^{208}Tl ($T_{1/2}$ = 3.0min, Q_β = 5.0MeV) $\xrightarrow[+\gamma]{\beta}$ ^{208}Pb stable

E_{max}=5.0MeV

^{212}Bi and ^{208}Tl($T_{1/2}$=3min) . . .
rejection by tagging of ^{212}Bi
(α−γ particle identification)

γ-rays from neutron capture

high energy γ-rays from neutron capture on Fe, Ni, Si
within stainless steel (main tank), rock in the mine.

To reject these BG events;
Pile-up event : identification of the "pile-up" shape
particle identification between α and γ rays
^{208}Tl event : identification of prompt ^{212}Bi (by α-γ rays PI)
High energy γ-ray : the shileding system

Rejection of pile-up events

$^{212}Bi \rightarrow {}^{212}Po$ decay

Th-Chain

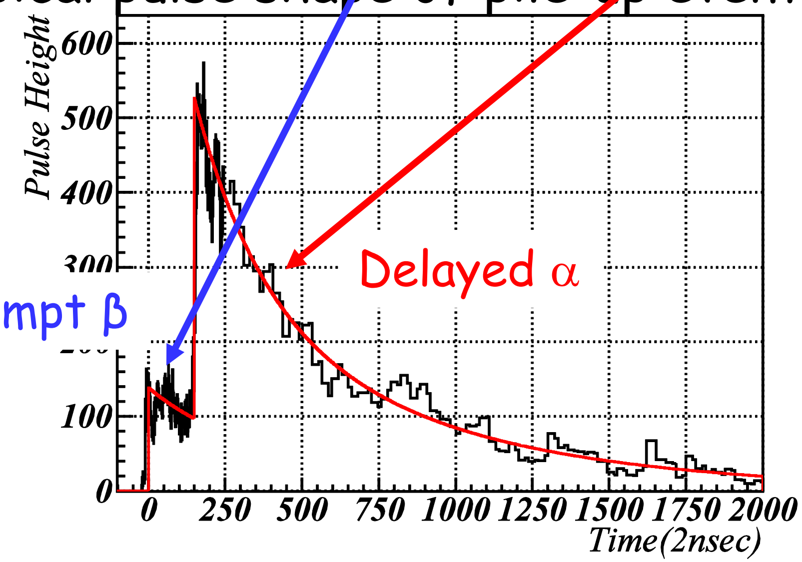
^{232}Th $T_{1/2}$ = 1.1 x 10^{10}year

Pile-up $T_{1/2}$ = 0.3μsec

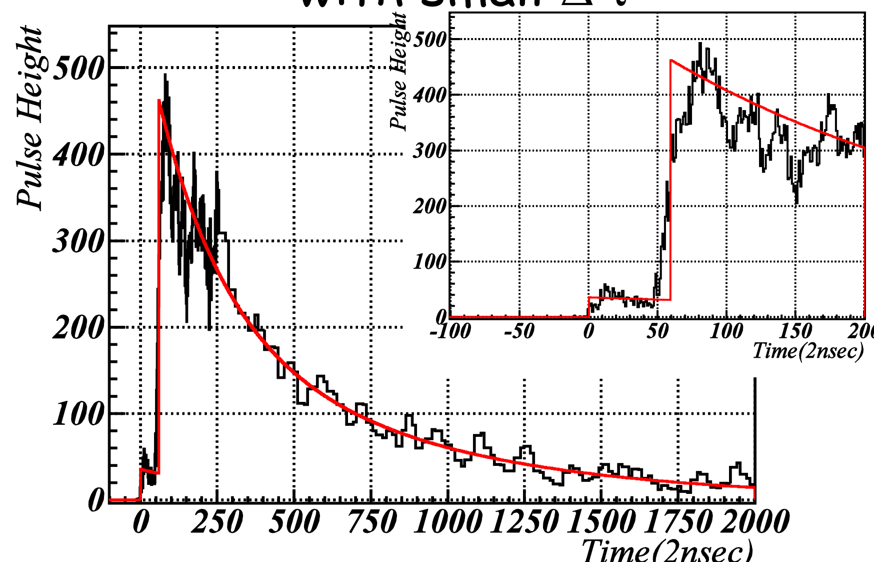
^{212}Bi Q_β=2.2MeV prompt $\xrightarrow{\beta\ 64\%}$ ^{212}Po Q_α=7.8MeV delayed $\xrightarrow{\alpha}$

Decay Constant of CaF_2(pure) :1μsec

Typical pulse shape of pile-up events



with small Δ τ



Sum-up signal of 62 PMT

We can identify the pile-up events.
current rejection efficiency > 95%

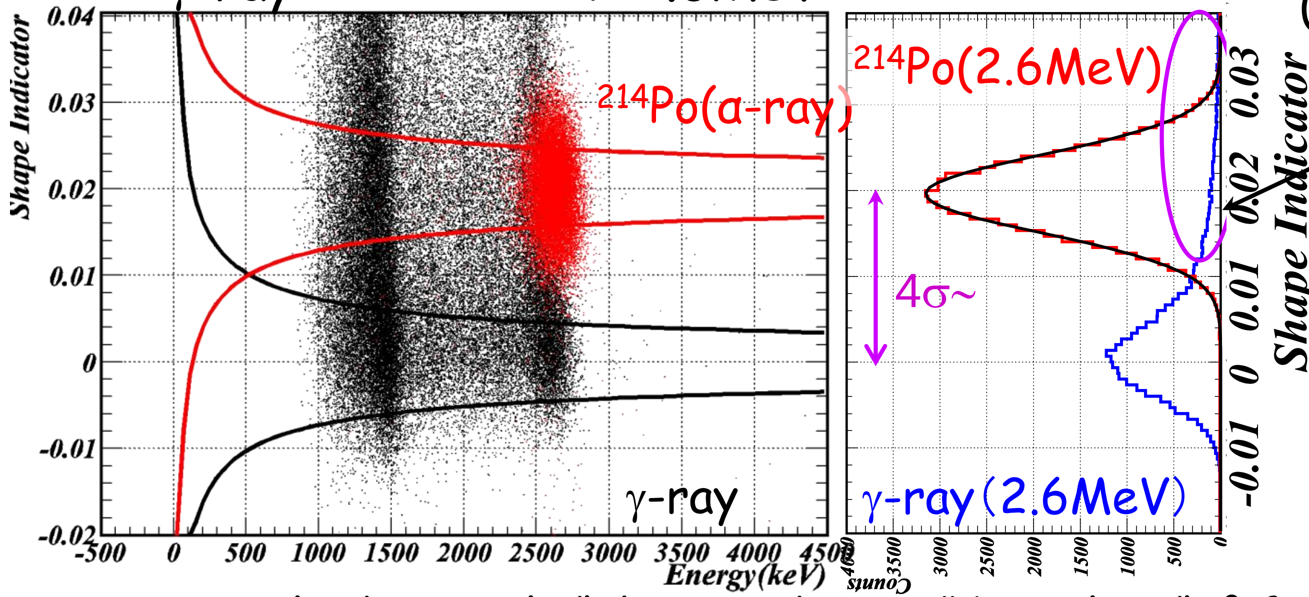
Pulse Shape discrimination between α and γ-rays

Particle identification between α and γ rays

Event distribution by using "shape indicator"

α-ray : ^{214}Po 7.6MeV(E_e=2.6MeV)
γ-ray : ^{208}Tl 2.6MeV

ref : Shape Indicator (PRC67(2003) 014310)



CaF$_2$ γ +small LS signal

mean :0.0000(γ-ray)
:0.0196(α-ray)
σ :0.0046(α-ray)

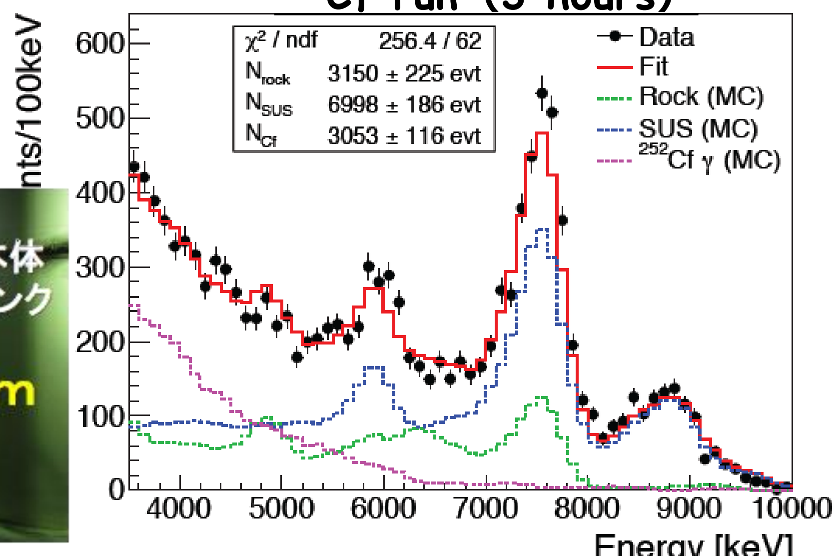
We applied not only "shape indicator" but also "χ^2 fitting" for PI.

97 % rejection efficiency at 2.6MeV (γ ray:3%)
→97% (β+α) at 4.27MeV (γ:3%)
- for rejection of β–α pile-up events
- for identification of proceeding ^{212}Bi event

Background from neutron capture

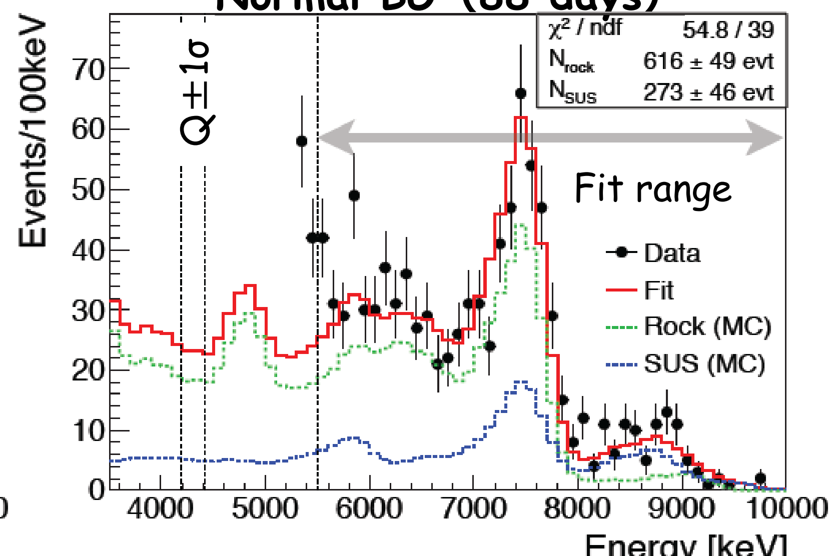
- Neutron source run (^{252}Cf)
  - 1 hour of source run = 1 year of physics run
  - Energy spectrum : well reproduced by MC of neutron capture γ-ray.
- (n,γ) BG in 0νββ window is evaluated from MC spectrum.
  - (n,γ) BG: 3.4±0.4(stat.) evt/26crystals/60days (Run data, 3±1 evt)
  - Currently, most serious background component in CANDLES

^{252}Cf run (3 hours)



Loose event selection cut !

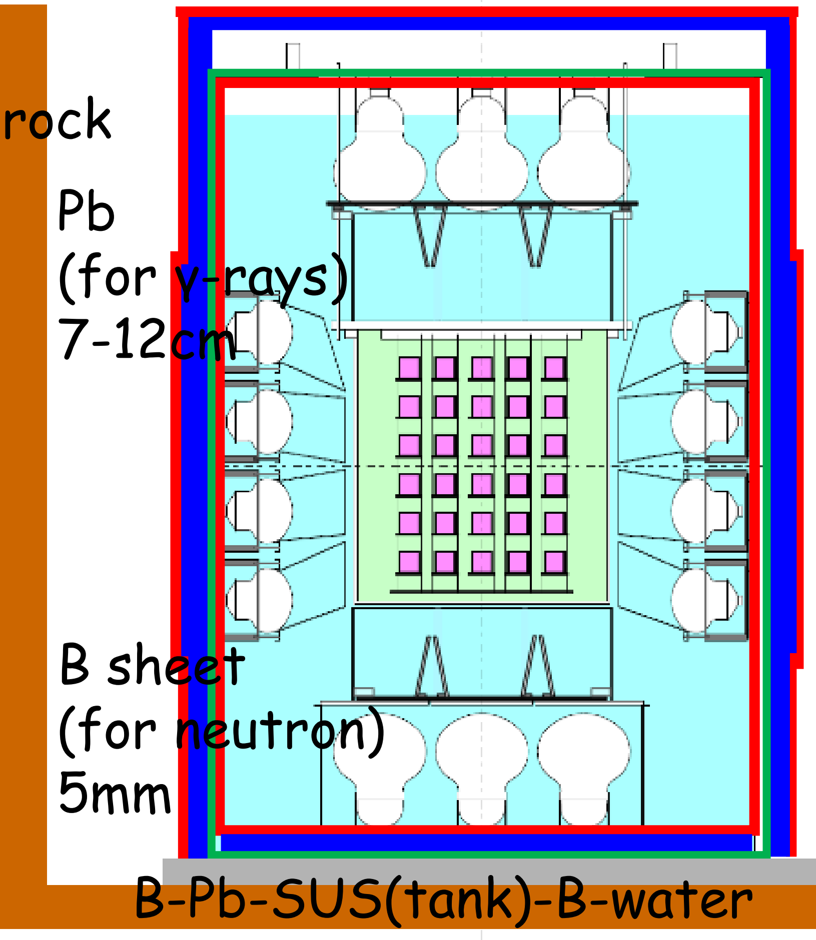
Normal BG (88 days)



Shielding system

Toward "Background Free Measurement"

Schematic view of the shielding system



Shielding system : BG ~1/100

Pb bricks

- 7 ~ 12cm in thickness
- Reduce (n,γ) BG from rock.
- BG γ-rays from rock decrease by factor of ~1/120

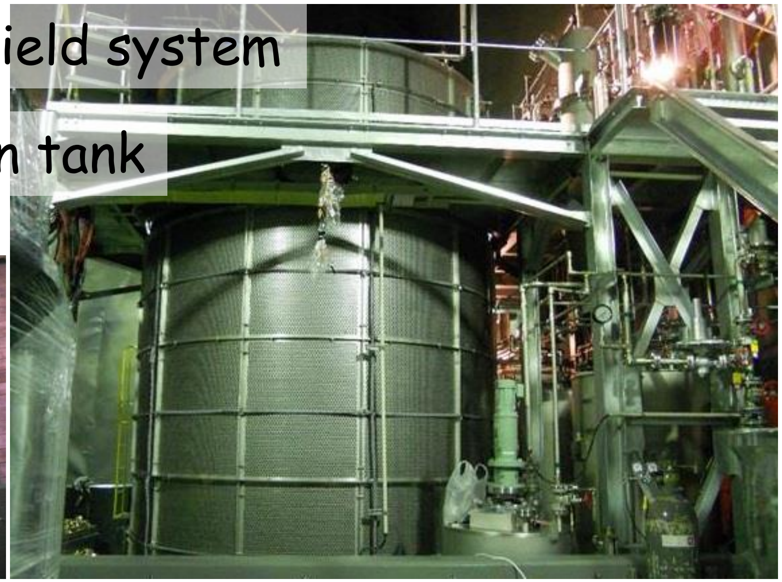
B sheet

- B_4C loaded silicone rubber sheet ~ 5 mm in thickness
- Reduce thermal neutron
- N-capture events decrease by factor of ~1/30

Construction of the shielding system
Shieldings inside/outside the tank
BG rate : ~1/100

CANDLES shield system

Construction was finished in February 2016

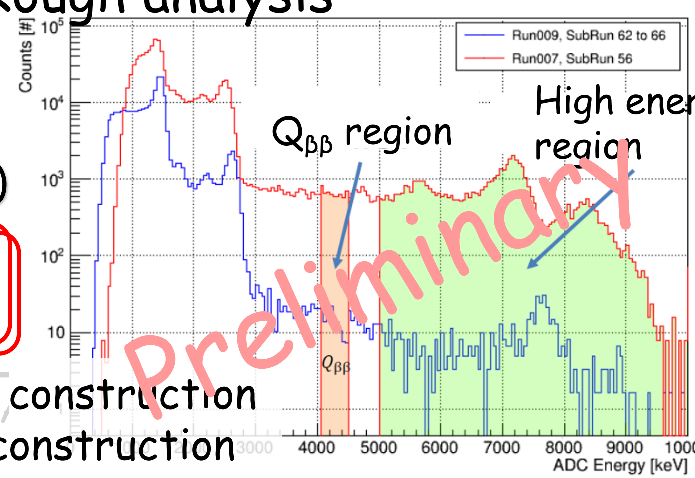


BG Reduction factor

- ^{252}Cf Run : reduction test of fast neutron
  - Source position : near the rock
  - Correction of live time, ^{252}Cf activity($T_{1/2}$=2.7year)

Reduction factor
: ~ 2 order of magnitude(near the rock)

Rough analysis



Before shield construction
After shield construction

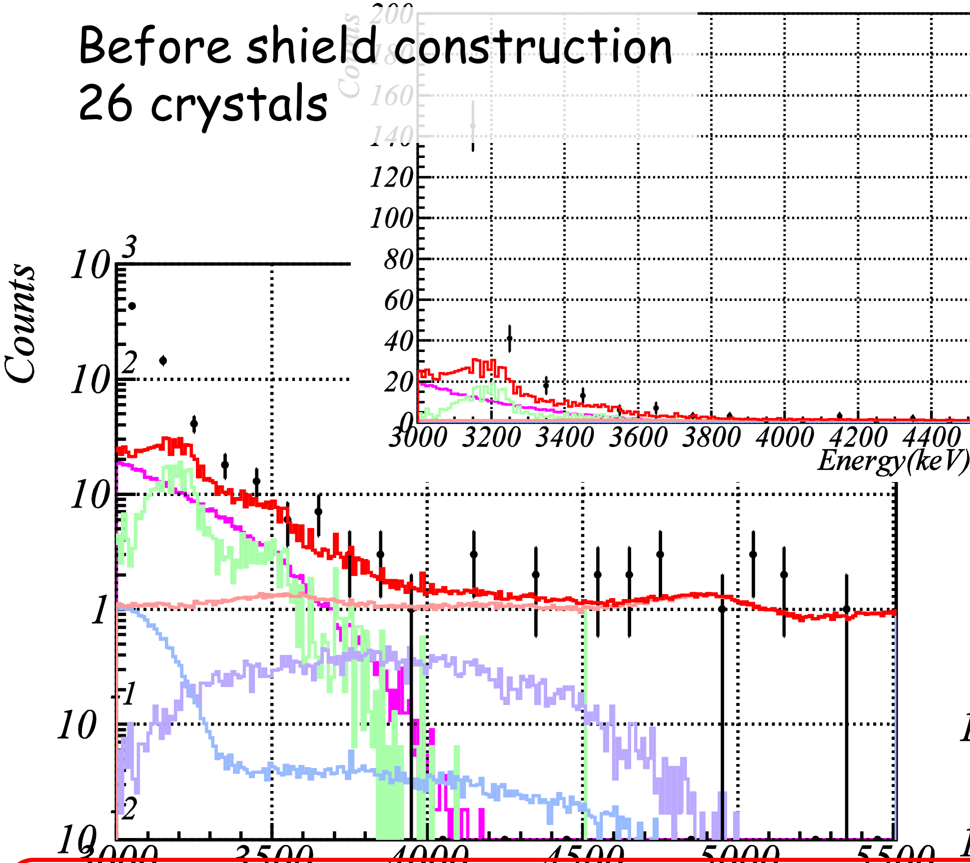
Preliminary

Energy spectra

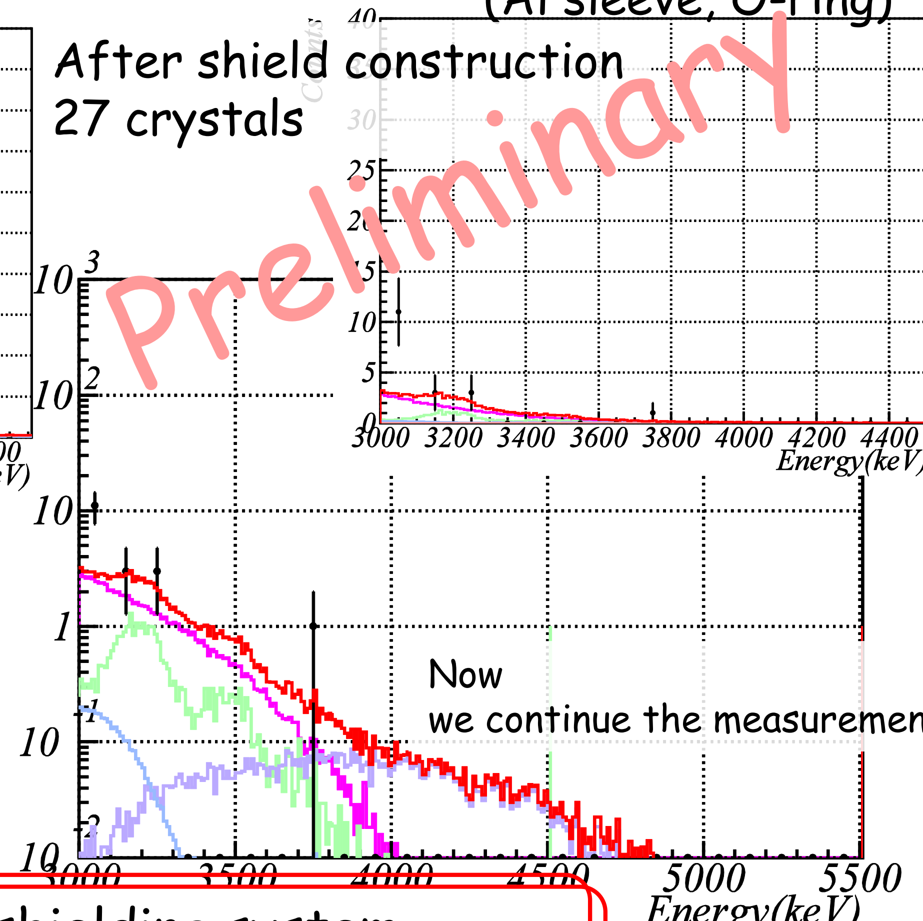
BG spectra and simulation : before(60days), after(8.6days) data

- data
- total(simulation)
- γBG from n capture
- ^{208}Tl
- 2νββ
- surrounding materials (Al sleeve, O-ring)

Before shield construction
26 crystals



After shield construction
27 crystals



Now
we continue the measurement.

γ-ray background : reduced by the shielding system
*^{208}Tl events will be reduced by improved analyses.

Further improvement

- CANDLES III upgrade
  - Shielding system : installation in 2016
  - Cooling system : Already installed and operation started
    - CaF_2 light output increases with low temperature(~-20℃)
- Sensitivity and R&D

	CANDLES III	Next CANDLES	Next CANDLES
Crystal	3.2kg×96 (305kg)	2% ^{48}Ca (2 ton)	50% ^{48}Ca (6 ton)
Energy Resolution	(4.0%)	2.8%(Req.)	0.5%(Req.)
Expected BG	0.27/year	<0.7 /3year	<0.2 /9year
$\langle m_\nu \rangle$	0.5 eV	0.08	0.009
	Current system	with cooling system	bolometer

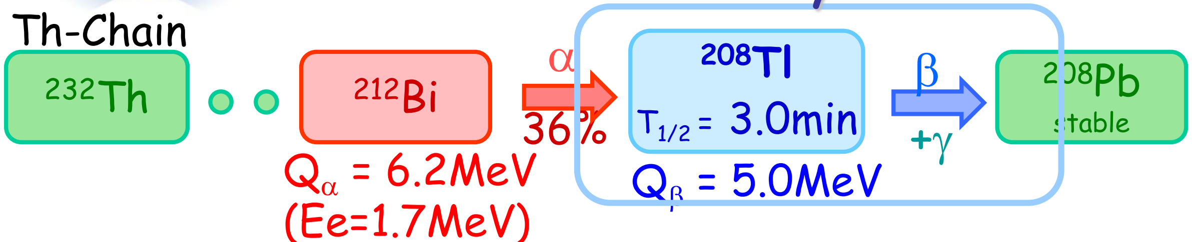
  - Enrichment : now on stage of mass production
  - Good energy resolution by bolometer
    - CaF_2(Eu) is OK. ref: NIMA386(1997)453 by Milano group
    - Now we have developed at sea level laboratory

Summary

- Double beta decay measurement
- R&D for CANDLES system
  - Analysis for background rejection : pile-up events
- CANDLES III at Kamioka Lab.
  - We installed the shielding system for detector sensitivity of 0.5 eV.
    - BG rate will be reduced by ~1/100.
- R&D for next CANDLES
  - Scintillating bolometer by using CaF_2(pure)
  - Enriched $^{48}CaF_2$(pure) scintillators
    - Now: on stage of "cost effective" mass production of ^{48}Ca

^{208}Tl rejection

^{212}Bi→^{208}Tl →^{208}Pb decay

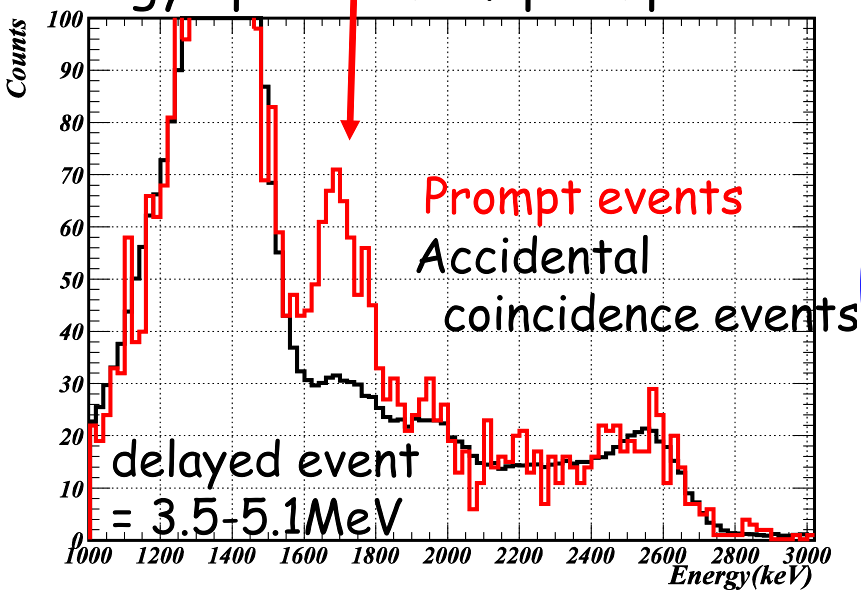


E_{max}=5.0MeV

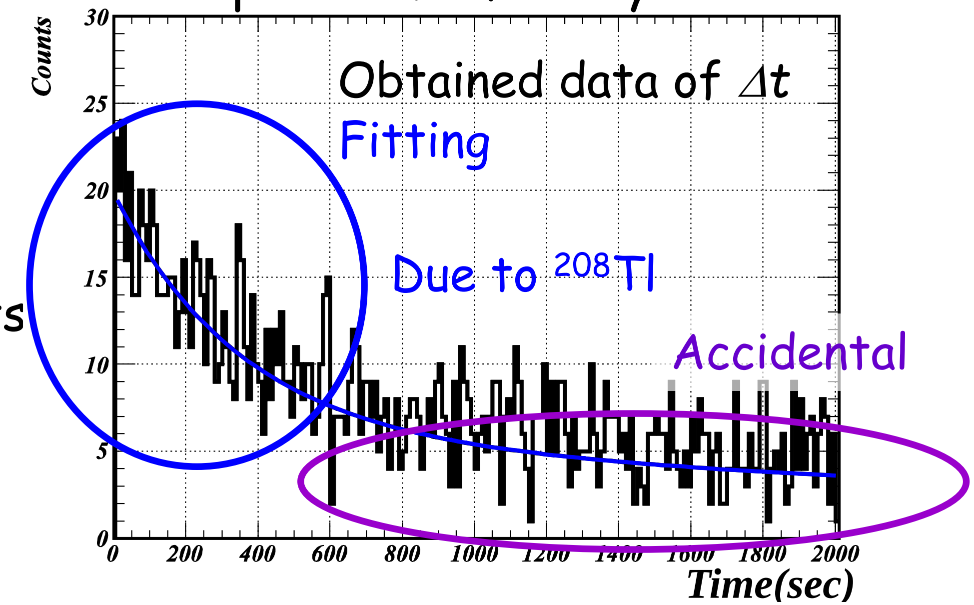
^{212}Bi and ^{208}Tl($T_{1/2}$=3min) . . .

Space-Time Correlation Cut

Energy spectrum of prompt ^{212}Bi



Δt spectrum of delayed ^{208}Tl



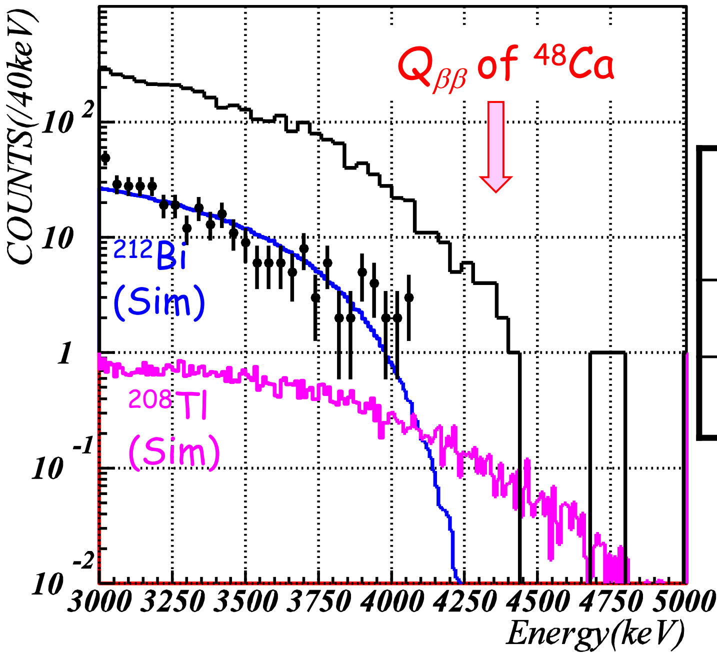
- We can identify the prompt ^{212}Bi
- We improved these efficiencies by DAQ upgrade etc.

Obtained half-life = 241±46sec

Result of ELEGANT VI

Obtained Result

Energy Spectra



Run summary (Measurement for 4 years)

Run	Number of Event	Expected BG (^{212}Bi, ^{214}Bi, ^{208}Tl)	Live Time kg・day
First Run	0	1.30	1553
Second Run	0	0.27	3394

No events in 0νββ Energy Window

0νββ Half-Life of ^{48}Ca : > 5.8 × 10^{22} year (90% C.L.)

$\langle m_\nu \rangle$ < (3.5-22) eV

・4π active shield is effective for background free measurement.

・Expected backgrounds are ^{212}Bi and ^{208}Tl

For higher sensitivity, we need a large amount of ^{48}Ca.