Neutrino-less double beta decay of ^{48}Ca studied by CaF_2(pure) scintillators --CANDLES--

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CANDLES Collaboration

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
  - Low background measurement
- Summary

Double beta decay of ^{48}Ca

- Double beta decay nuclei
  - ^{48}Ca : low background → large scale detector
    - 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)

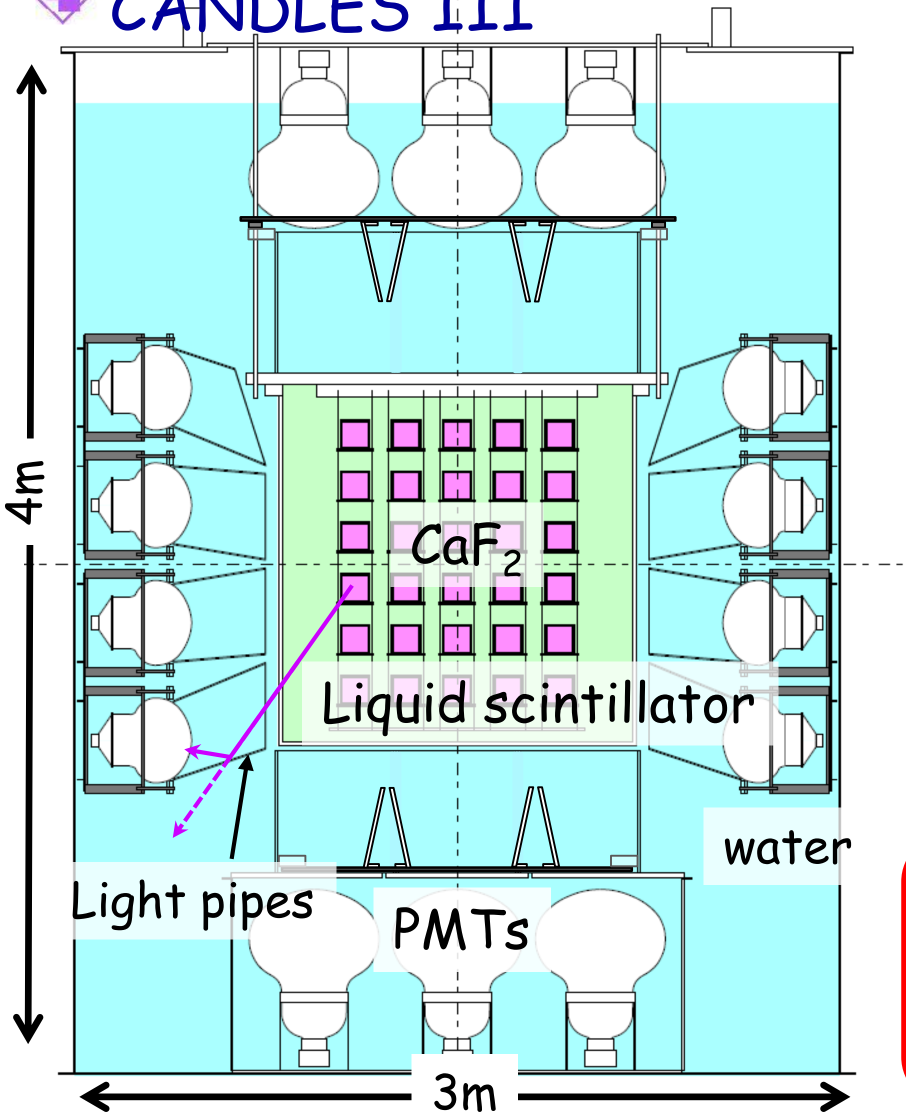
      3.3MeV(^{214}Bi,β-ray)
- Double beta decay of ^{48}Ca by using CaF_2 scintillators
  - ELEGANT VI : CaF_2(Eu) scintillator

    ↓ →realized low background condition
  - CANDLES system: for large scale detector
    - CANDLES III : current system

CANDLES III

CANDLES at Kamioka underground laboratory

CANDLES III



- CaF_2 scintillator (CaF_2(pure))
  - 305 kg (96modules × 3.2kg)
  - ^{48}Ca : 350g
  - time constant τ~ 1μsec
- Liquid scintillator (LS)
  - 4π active shield
  - volume :$2m^3$
  - time constant τ ~ a few ten nsec
- Large photomultiplier tube
  - 13inch PMT × 36
  - 20inch PMT × 14
  - 10inch PMT × 12
- Light pipe system
  - guide scintillation light to PMTs

Pulse shape difference between CaF_2 and liquid scintillators
(4μsec) (a few 10nsec)
→background rejection

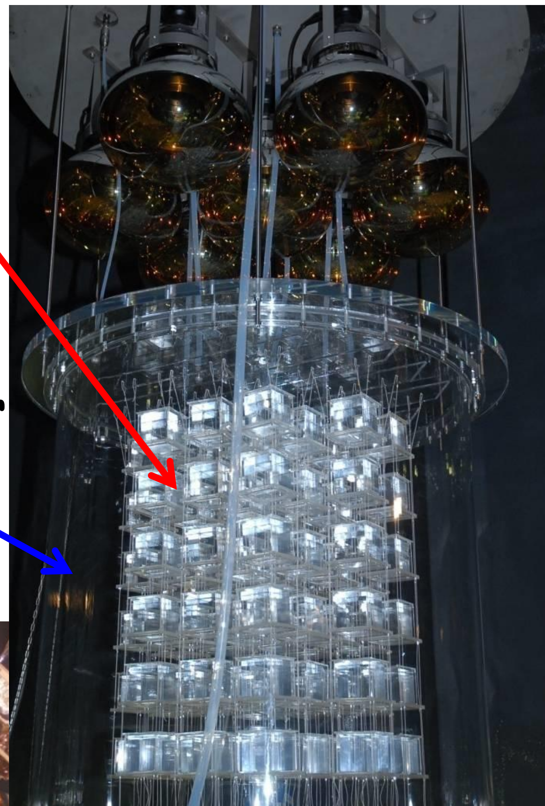
CANDLES III

CANDLES at Kamioka underground laboratory

CANDLES III

Main detector
CaF_2 scintillators
(305kg)

Liquid scintillator
tank ($2m^3$)



PMTs and
Light pipes

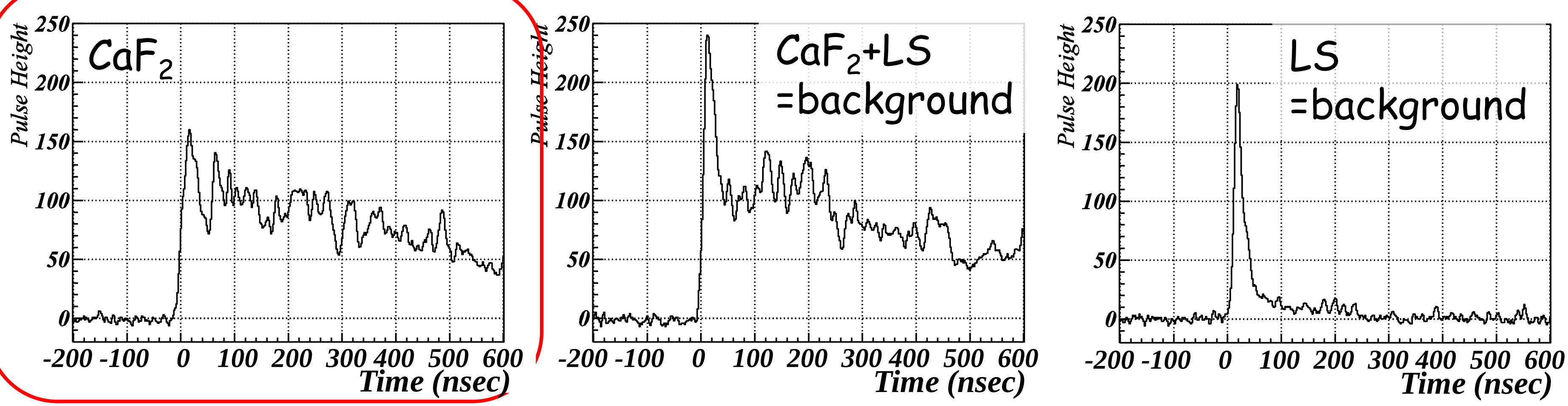
- **CaF_2 scintillator (CaF_2(pure))**
  305 kg (96modules × 3.2kg)
  ^{48}Ca : 350g
  time constant τ~ 1μsec
- **Liquid scintillator (LS)**
  4π active shield
  volume :$2m^3$
  time constant τ ~ a few ten nsec
- **Large photomultiplier tube**
  13inch PMT × 36
  20inch PMT × 14
  10inch PMT × 12
- **Light pipe system**
  guide scintillation light to PMTs

Pulse shape difference between
CaF_2 and liquid scintillators
(4μsec) (a few 10nsec)
→background rejection

Background rejection by liquid scintillator

- Rejection of external γ-ray backgrounds by pulse shape discrimination
  - Typical pulse shape in CANDLES III

τ of CaF_2 = ~1000nsec
LS = ~20nsec



In CANDLES system . . .

- short pulse(LS scintillator~a few 10ns)and long pulse(CaF_2=~4μsec)
- CaF_2 selection by using FADC → rejection of backgrounds

→realized 4π active shield

Backgrounds in CANDLES

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

Possible to reduce by good energy resolution
current energy resolution 6%(4.27MeV)

γ-ray from neutron capture

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

Radioactive contaminations in CaF_2 crystals

Pile-up events

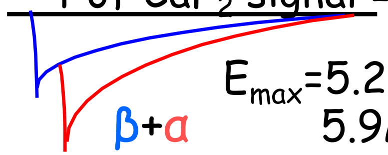
^{232}Th ・・ ^{212}Bi → β 64% (Q_β = 2.25MeV) → ^{212}Po ($T_{1/2}$ =0.3μsec) → α (Q_α = 8.95MeV) → ^{208}Pb stable

Th-chain

^{208}Tl events

^{212}Bi → α 36% (Q_α = 6.09MeV) → ^{208}Tl ($T_{1/2}$ = 3.1min) → β+γ (Q_β = 4.99MeV) → ^{208}Pb stable

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



E_{max}=5.2MeV(Th)
5.9MeV(U)

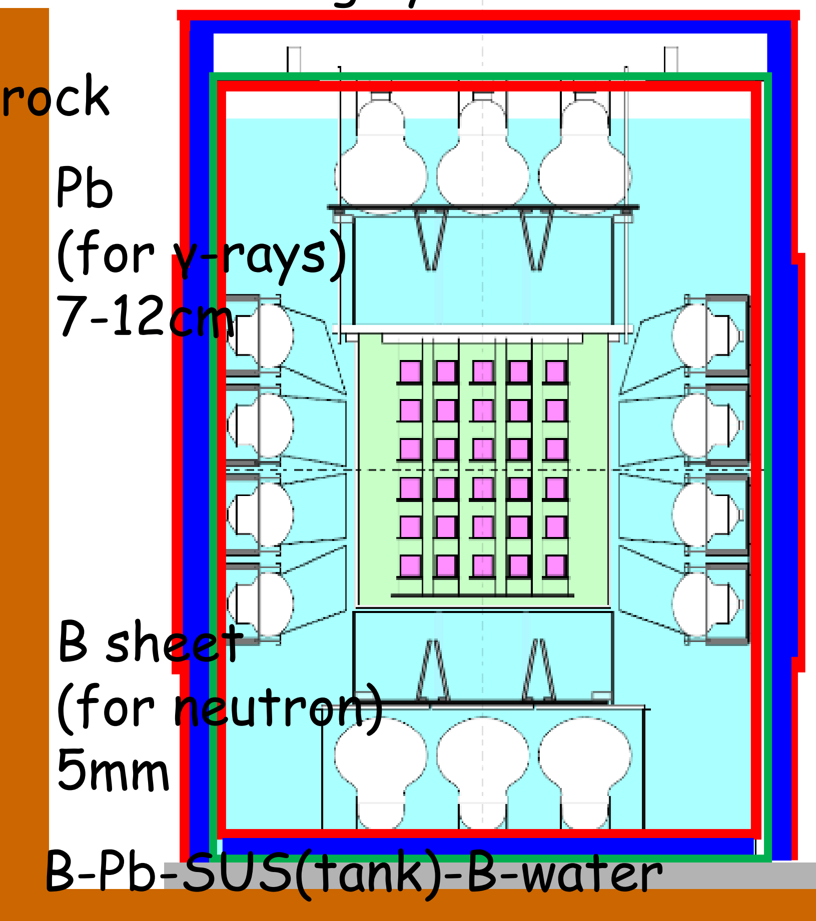
^{212}Bi and ^{208}Tl($T_{1/2}$=3分) . . .
rejection by ^{212}Bi tagging
(α-γ particle identification)

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

Shielding system

Toward "background free measurement"

Schematic view of
the shielding system



- CANDLES tank(stainless steel)
- Pb (γ-ray shield)
- B sheet (neutron shield)

Shielding system : BG ~1/100

Pb bricks
- 7 ~ 12 cm in thickness
- reduce γ-ray BG from (n,γ) reaction in rock.
- BG γ-rays from rock will decrease by factor of ~1/120

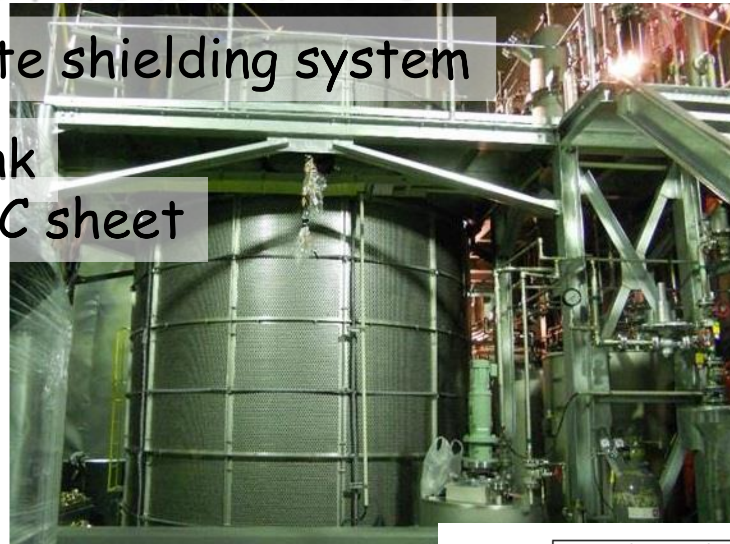
B sheet
- B_4C loaded silicone rubber sheet ~ 5mm in thickness
- reduce thermal neutron → reduce BG from (n,γ) in main tank.
- N-capture events will decrease by factor of ~1/30

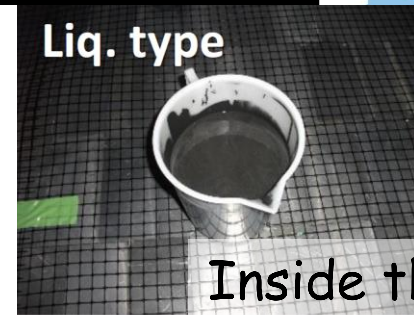
Construction of the shielding system

Shieldings inside/outside the tank
BG rate : ~ 1/100

Shielding system

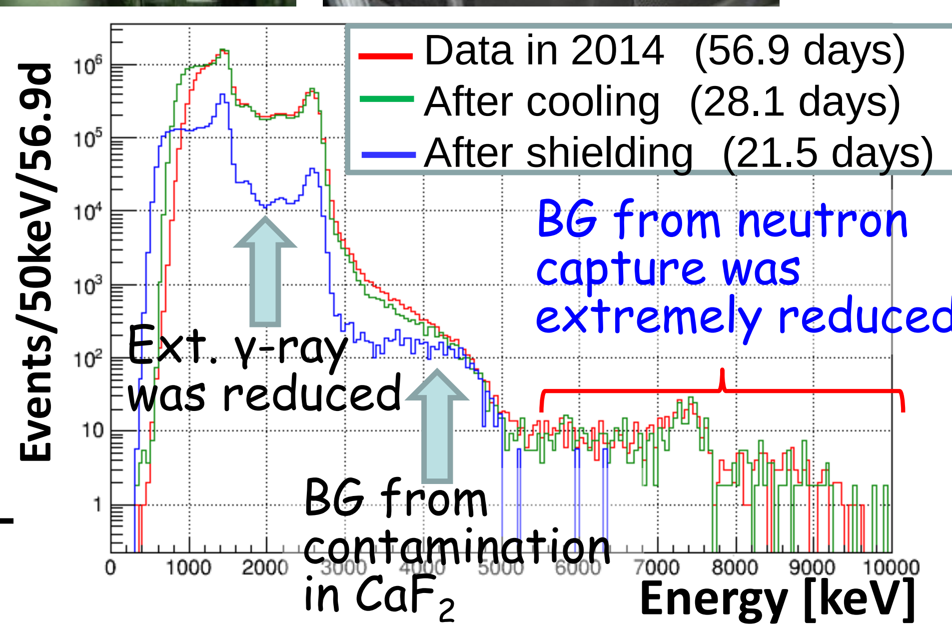
- Construction was finished in 2016





- BG reduction factor
  - Energy spectra before/after shield construction

γ-rays from neutron capture were reduced by shielding system
~ 1 / 100 ~ 1/70

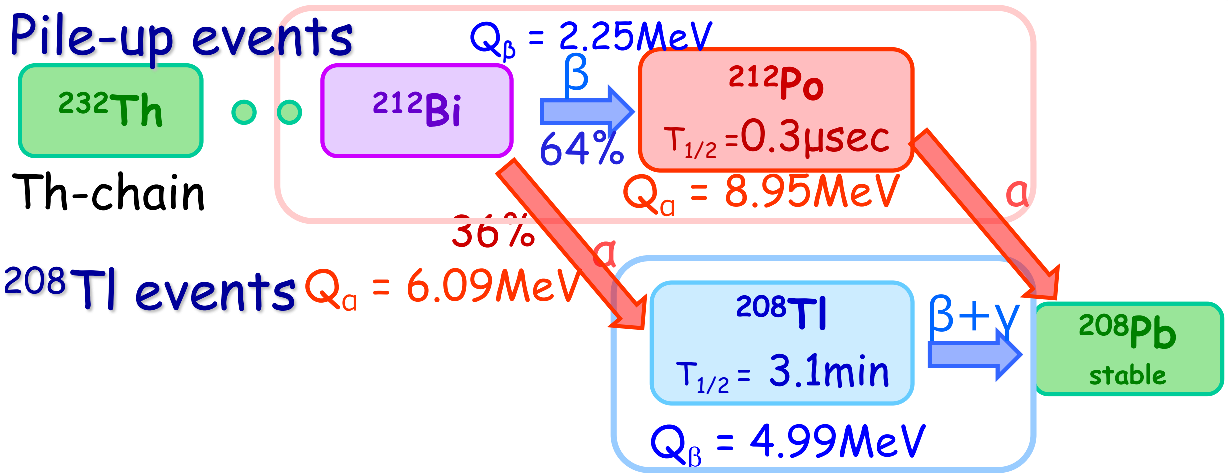


Backgrounds in CANDLES

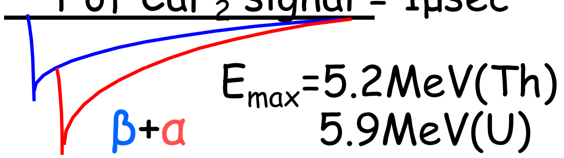
γ-ray from neutron capture

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

Radioactive contaminations in CaF_2 crystals



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



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

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

Rejection of pile-up events

- Pile-up events : $^{212}Bi \rightarrow {}^{212}Po$ decay
  - Radioactive contamination in CaF_2 : Th-chain

Th-chain

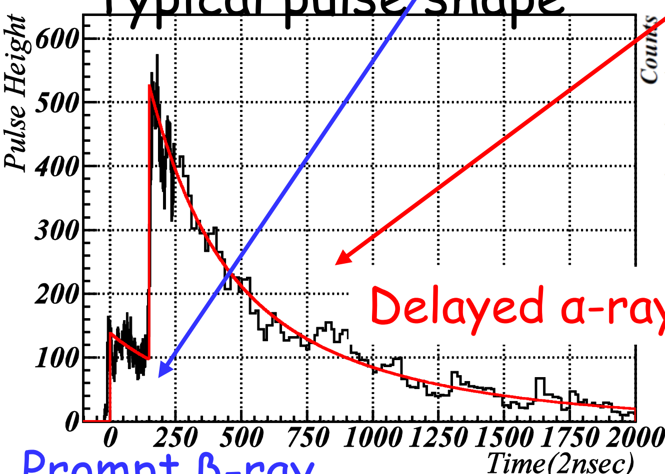
^{232}Th
$T_{1/2}$ =1.1x10^{10}year

Pile-up $T_{1/2}$ = 0.3μsec

^{212}Bi Q_{β}=2.2MeV (prompt) → β 64% → ^{212}Po Q_{α}=7.8MeV (decayed) → α

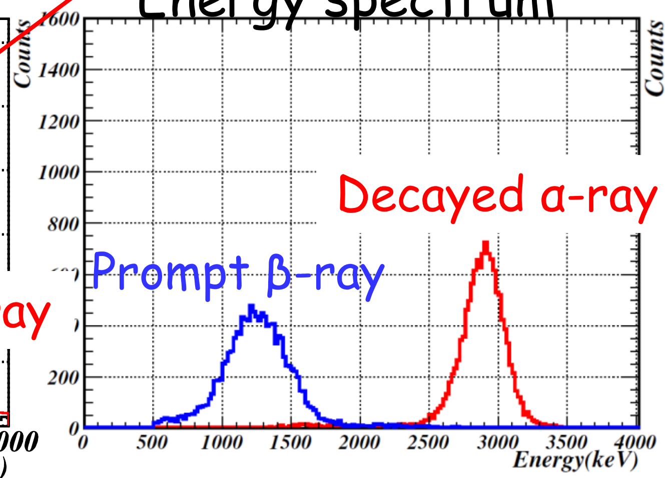
Maximum energy : 5.2MeV

Typical pulse shape

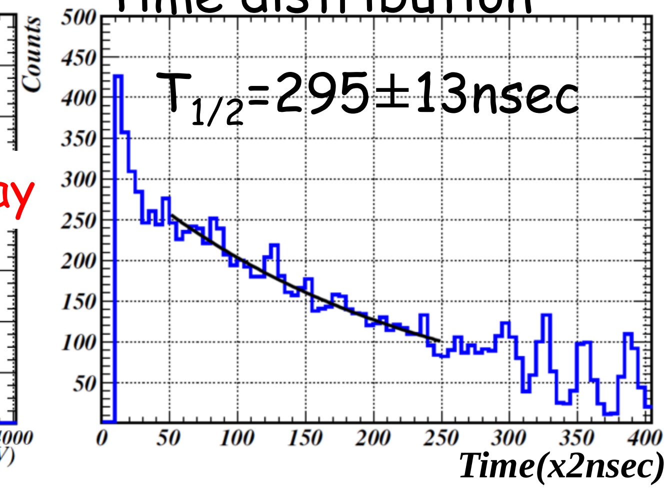


Prompt β-ray

Energy spectrum



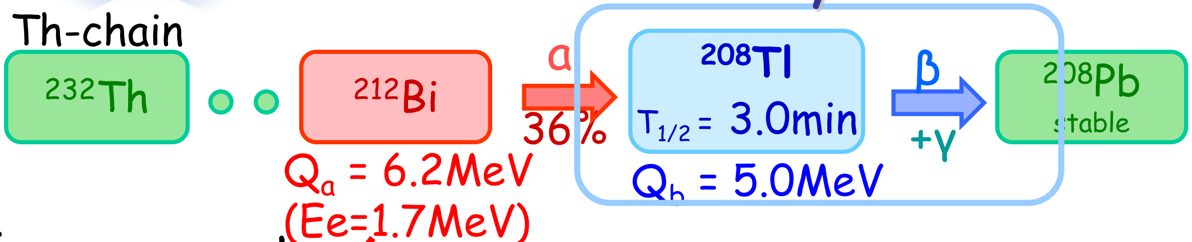
Time distribution



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

^{208}Tl rejection : ^{212}Bi tagging

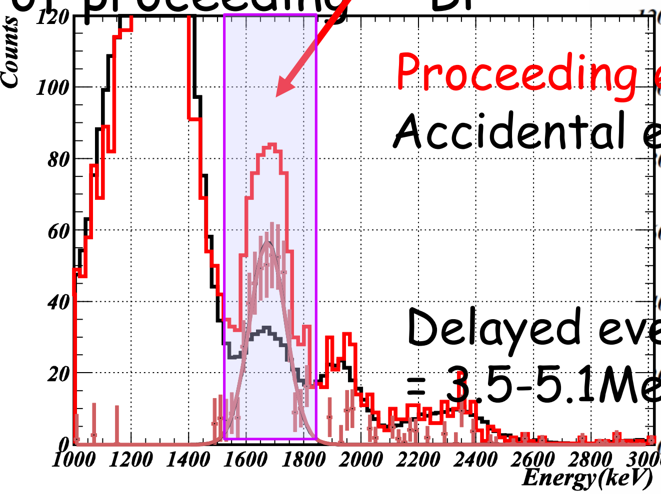
^{212}Bi→^{208}Tl →^{208}Pb decay



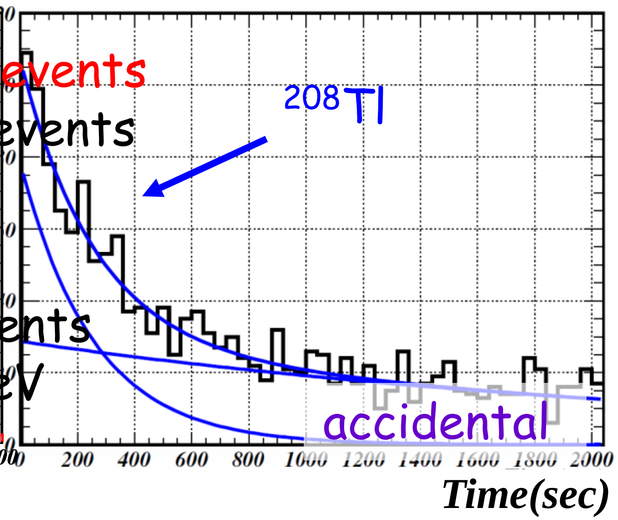
E_{max}=5.0MeV

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

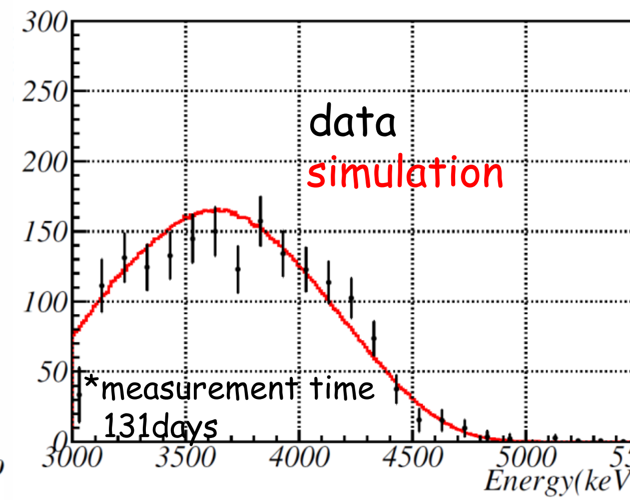
Energy spectrum of proceeding ^{212}Bi



Δt distribution



^{208}Tl energy spectrum



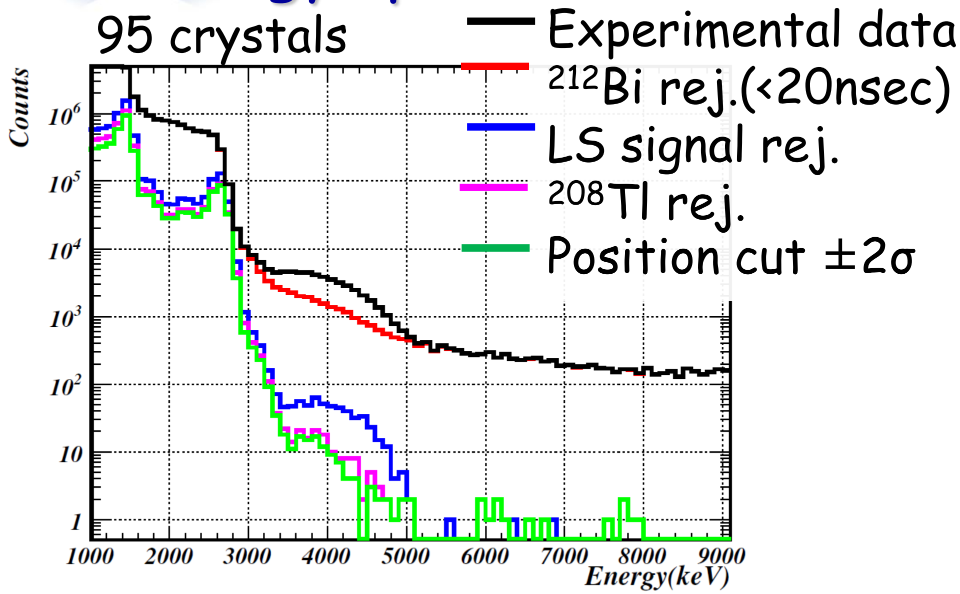
Half-life = 178±55sec

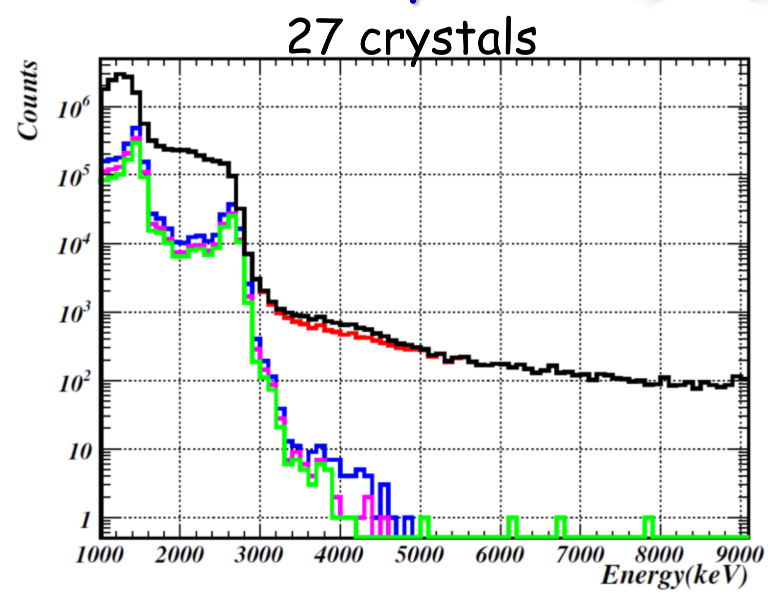
- we can reject ^{208}Tl event by ^{212}Bi tagging
  obtained half life 178sec (^{208}Tl 183sec)
- current rejection efficiency ~75%, acceptance~83%

Preliminary

Energy spectra

Energy spectra : Measurement time 131days





Num of event	95 crystals			27crystals(high purity crystals)		
	Qββ	4-5MeV	5.5-6.5MeV	Qββ	4-5MeV	5.5-6.5MeV
without ^{208}Tl cut	115	257	8	12	23	1
with ^{208}Tl cut	19	49	6	3	6	1
Position 2σ cut	10	34	6	0	2	1

No event in high purity crystals

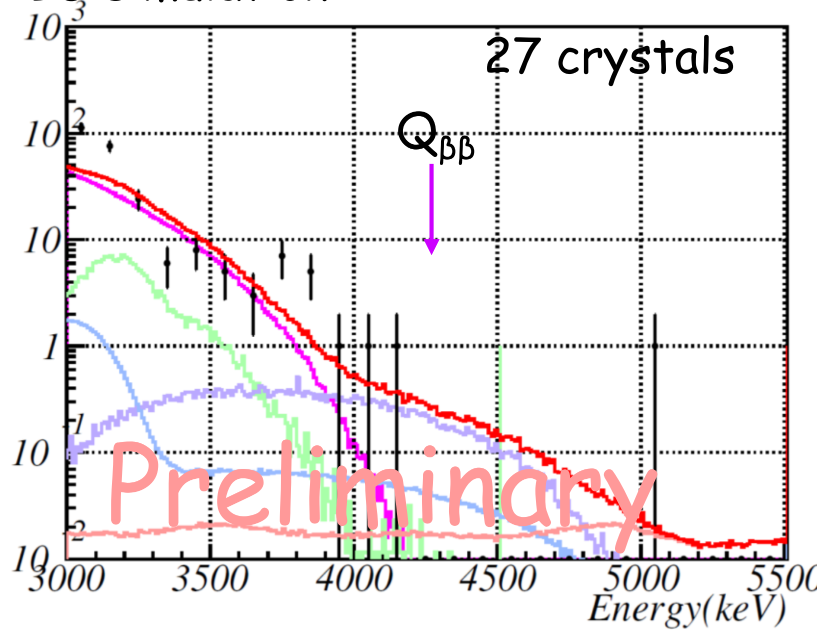
Result

Result of measurement for 131days

	results
$0\nu\beta\beta$ efficiency	0.39±0.06
Num. of eve.(exp)	0(27CaF), 10(95CaF)
Expected BG	~1.2,~11
Half life of ^{48}Ca	>6.2×10^{22}year(27crystals) >3.8×10^{22}year(95crystals)
Sensitivity	3.6×10^{22}year(27crystals) 6.2×10^{22}year(95crystals)

- ● experimental data
- simulation(total)
- γ-ray from N capture
- contamination : ^{208}Tl
- $2\nu\beta\beta$
- other BG

Energy spectrum and BG simulation



(Chi^2<1.5, -3σ<SI<1σ)、
-2σ<position<2σ、
with ^{208}Tl cut

* ELEGANT VI
  measurement time : 4947kg・day(2 years <)
  half life limit : 5.8×10^{22} year

Summary

- CANDLES
  - Measurement of ^{48}Ca double beta decay
  - We installed the shielding system in 2016.
    - BG from neutron capture is reduced by 1/70~1/100
  - Obtained half-life limit : >6.2×10^{22}年
    - We updated half-life limit of ^{48}Ca.
    - Now we continue the measurement.
  - Future
    - We will apply ;
      - Scintillating bolometer by using CaF_2(pure)
      - Enrichment of ^{48}Ca :$^{48}CaF_2$(pure) scintillator
        - Now on stage of "cost effective" mass production

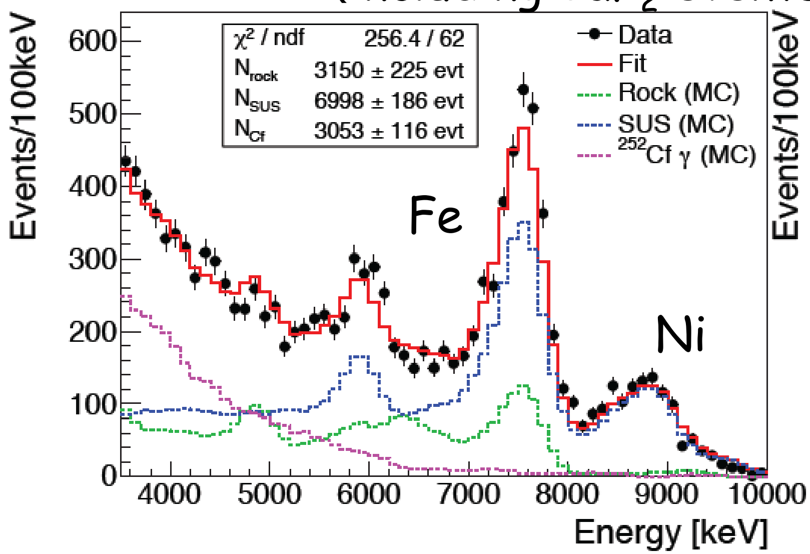
Background from neutron capture

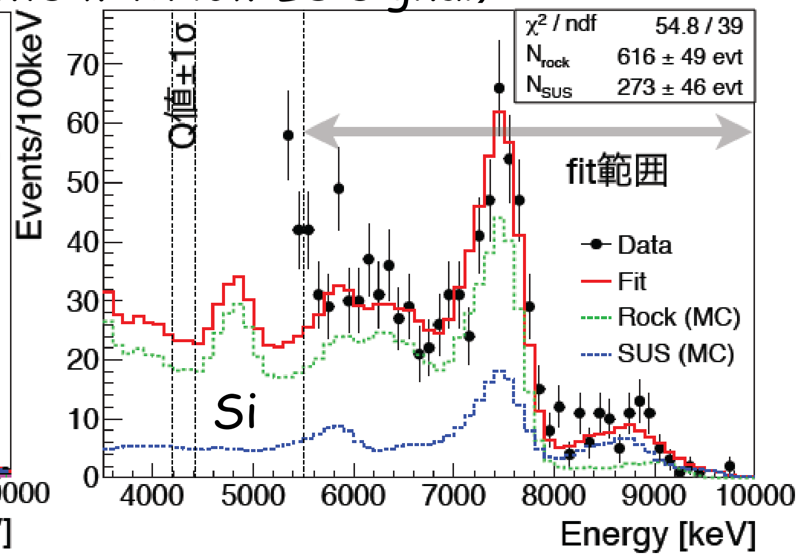
- For design of shielding system : neutron capture on Fe, Ni, Si
  - Neutron source (^{252}Cf) run : rock, main tank
    - Where neutron was captured on?
  - Measurement with/without ^{252}Cf

Energy spectra

^{252}Cf run(3hours) Normal run (without ^{252}Cf)(88day)

(including CaF_2 events with low LS signal)





High energy region : represent energy spectrum by (n,γ) in stainless, rock
→design of shielding system

Pulse shape discrimination between α and γ-ray

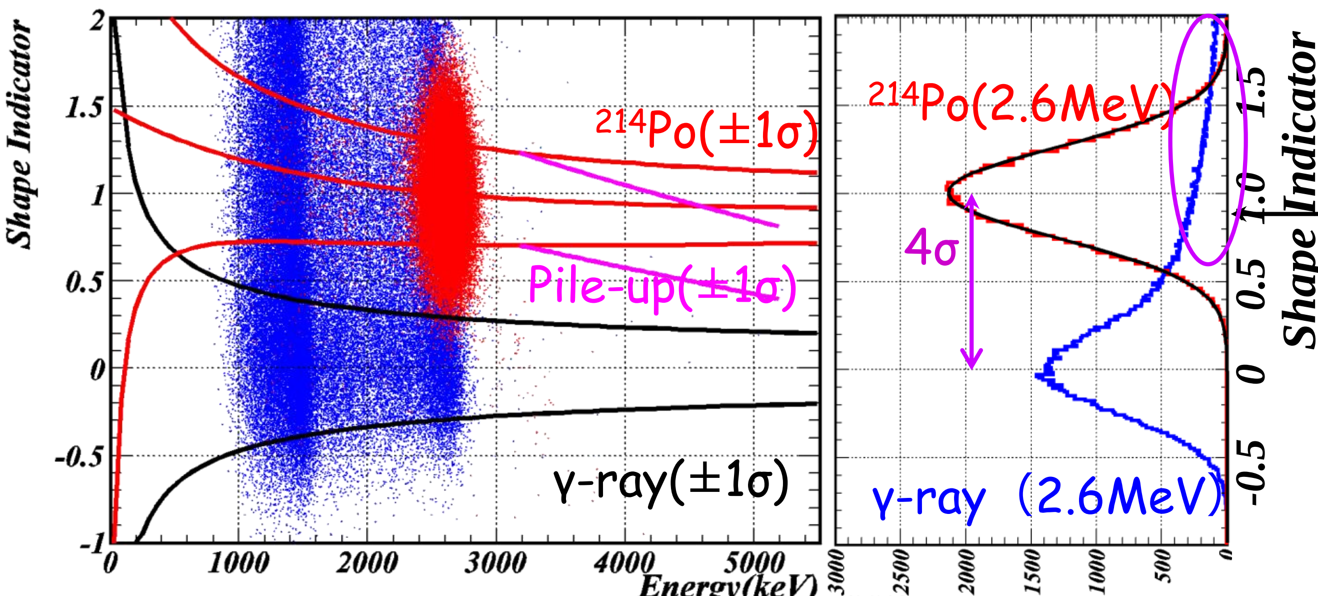
Particle identification between α and γ-ray

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-signal +small LS signal

mean :-0.008(γ-ray)
:1.005(α-ray)
σ :0.260(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 pile-up event) at 4.27MeV (γ-ray:3%)

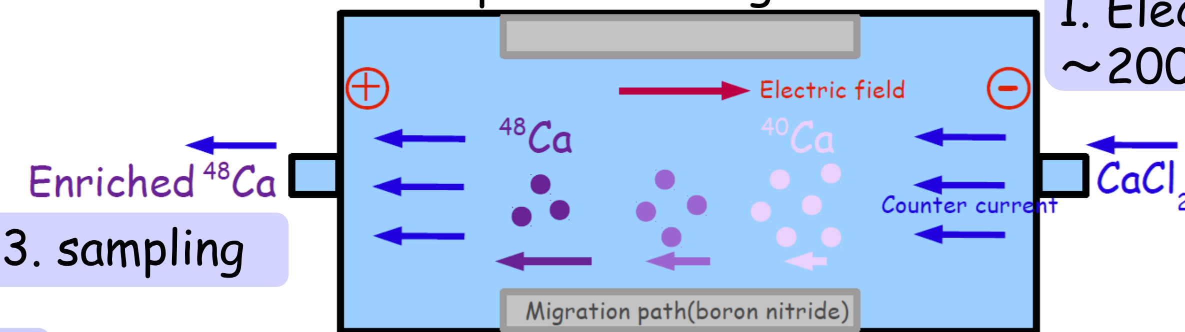
- for rejection of β-α pile-up events
- for identification of prompt ^{212}Bi event

MCCCE

-multi-channel counter-current electrophoresis-

Multi-channel counter-current electrophoresis

Conceptual drawing of MCCCE



1. Electric field: ~200V/cm

2. Flow rate: ~1mm/sec

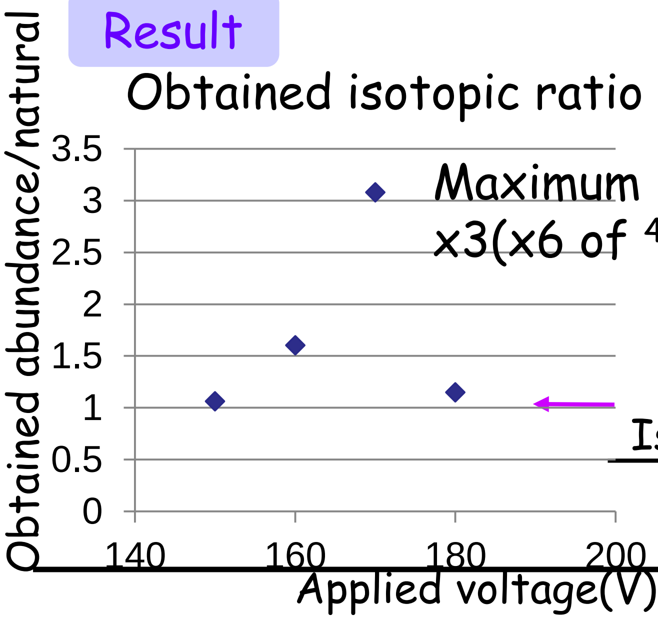
3. sampling

Migration path: 1cm~

Pumps for control of flow speed

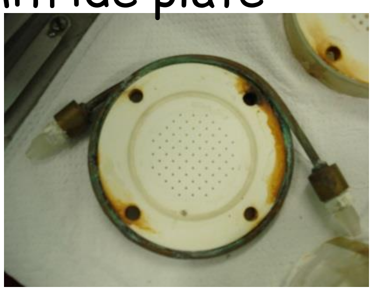
Result

Obtained isotopic ratio



Maximum isotopic ratio x3(x6 of $^{48}Ca/^{40}Ca$)

Boron nitride plate



$$\frac{\text{Isotopic ratio of obtained solution}}{\text{Isotopic ratio of Feed solution}}$$

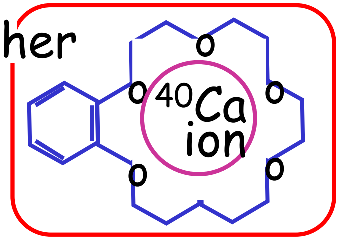
Principle was demonstrated.
→stable driving, large amount

Enrichment by using Crown Ether

Experimental setup

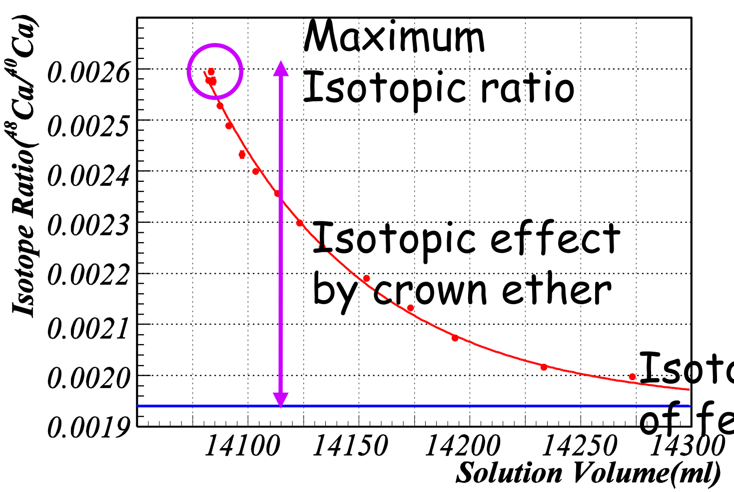
- Crown-ether rings adsorb Calcium ions
- For calcium, ^{40}Ca adsorption in crown-ether is slightly prior

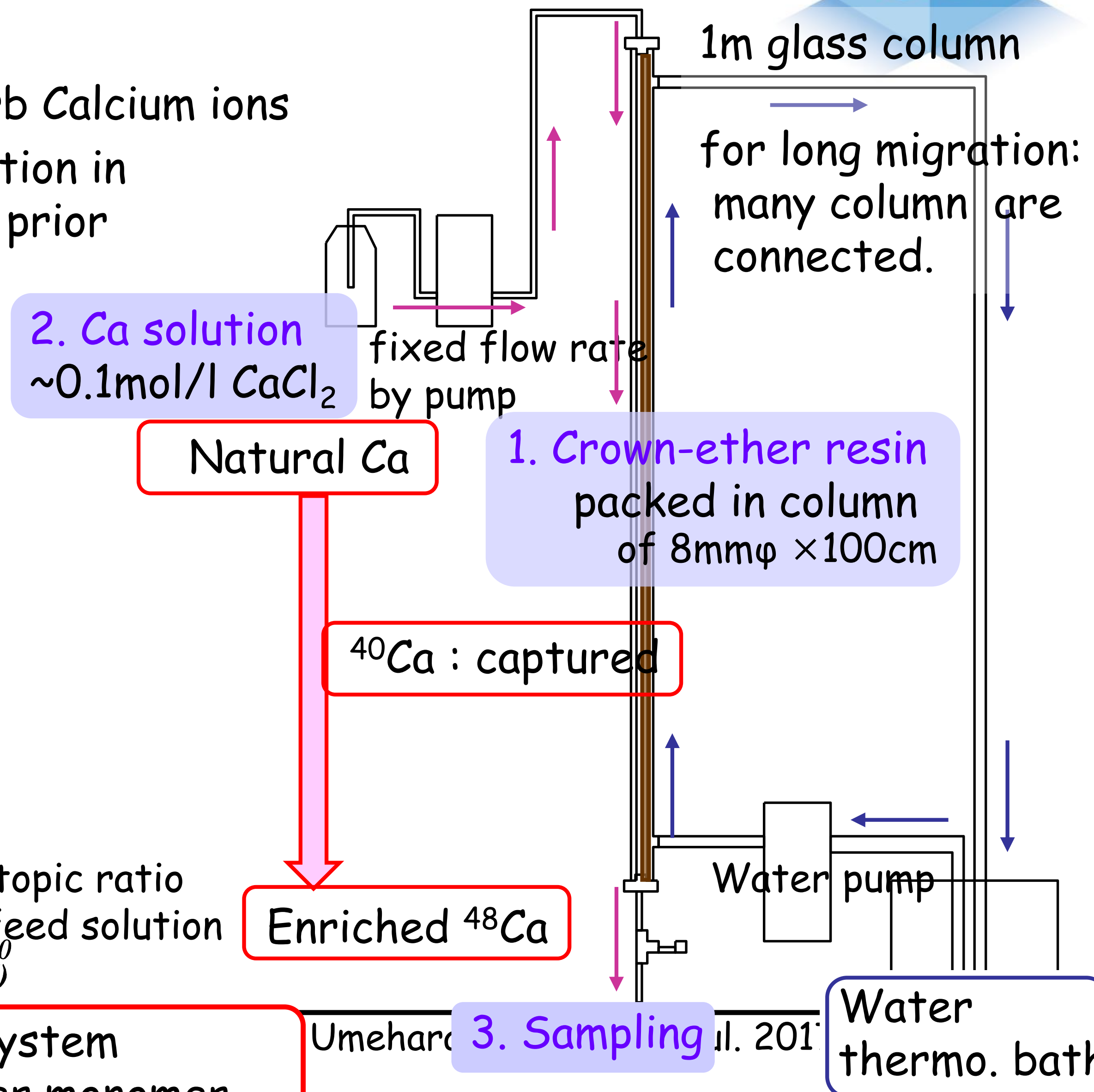
Crown-Ether



Result

Obtained isotopic ratio





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Next R&D : cost effective system
e.g. crown-ether monomer

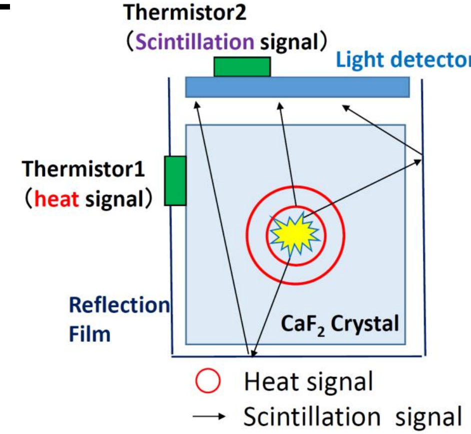
Scintillating bolometer

- Scintillating bolometer
  - bolometer : for good energy resolution
    - Reduce BG from $2\nu\beta\beta$ events
  - But . . . other background
    - α-ray from contamination in CaF_2

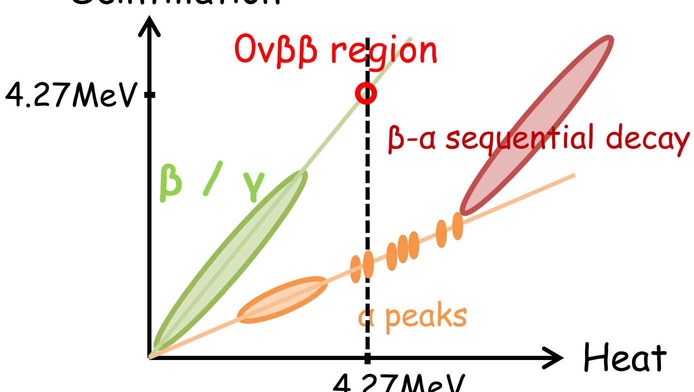
Scintillating bolometer : particle identification

for background free measurement

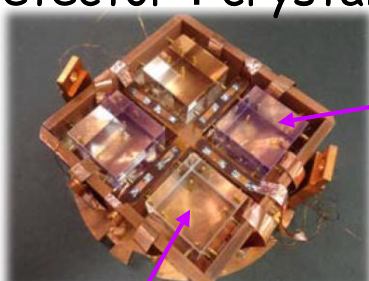
Scintillating bolometer



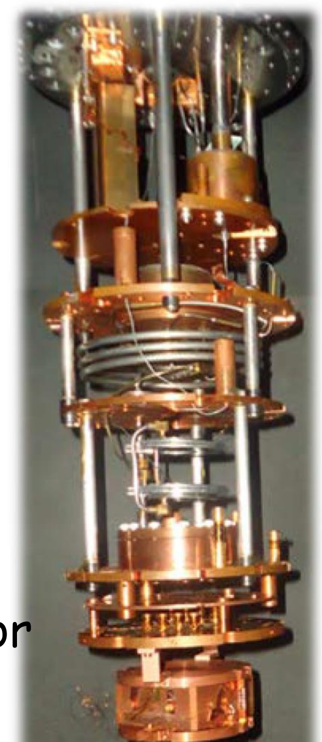
Particle identification by scintillating bolometer



detector : crystal part



Dilution refrigerator



Cooling test (now ~1K)
Signal reading test

future : CANDLES sensitivity

CANDLES series

	CANDLES III	Next CANDLES	
crystal $CaF_2(^{48}Ca)$	0.19% 3.2kg × 96 crystals 305kg(350g)	2% $^{48}CaF_2$ 2 ton(25kg)	50% $^{48}CaF_2$ 2 ton(610kg)
Energy resolution	(6%)	2.8%	1.0%(Req.)
$\langle m_\nu \rangle$	0.5 eV	0.08	0.009

Current detector

CaF_2 cooling system、~2% ^{48}Ca

bolometer ~50% ^{48}Ca

Energy spectra in CANDLES III <mν>=0.5eV

In CANDLES IV <mν>=0.08eV

In CANDLES V <mν>=0.009eV