CANDLES for the study of ^{48}Ca double beta decay

OGAWA, Izumi(小川　泉)
for the CANDLES collaboration

Candles

Outline

1. ELEGANT VI@Oto
2. CANDLES Project
    1. BG reduction/rejection
    2. CANDLES III@Osaka
    3. CANDLES III@Kamioka
3. R&D for future large detector
4. Summary

Double beta decay of ^{48}Ca

Candles

- Largest Q value (4.27 MeV)
  - next largest; ^{150}Nd (3.3 MeV)
  - large phase space factor
  - almost background free (γ: 2.6 MeV, β: 3.3 MeV)
- Low Natural abundance → 0.187%
  - large detector
  - enrichment
- Next generation detector : fight against BG!
  - $\langle m_\nu \rangle \propto T^{-1/2} \propto M_{\mathrm{det}}^{-1/2}$ if background free
  - $\langle m_\nu \rangle \propto T^{-1/2} \propto M_{\mathrm{det}}^{-1/4}$ if background limited

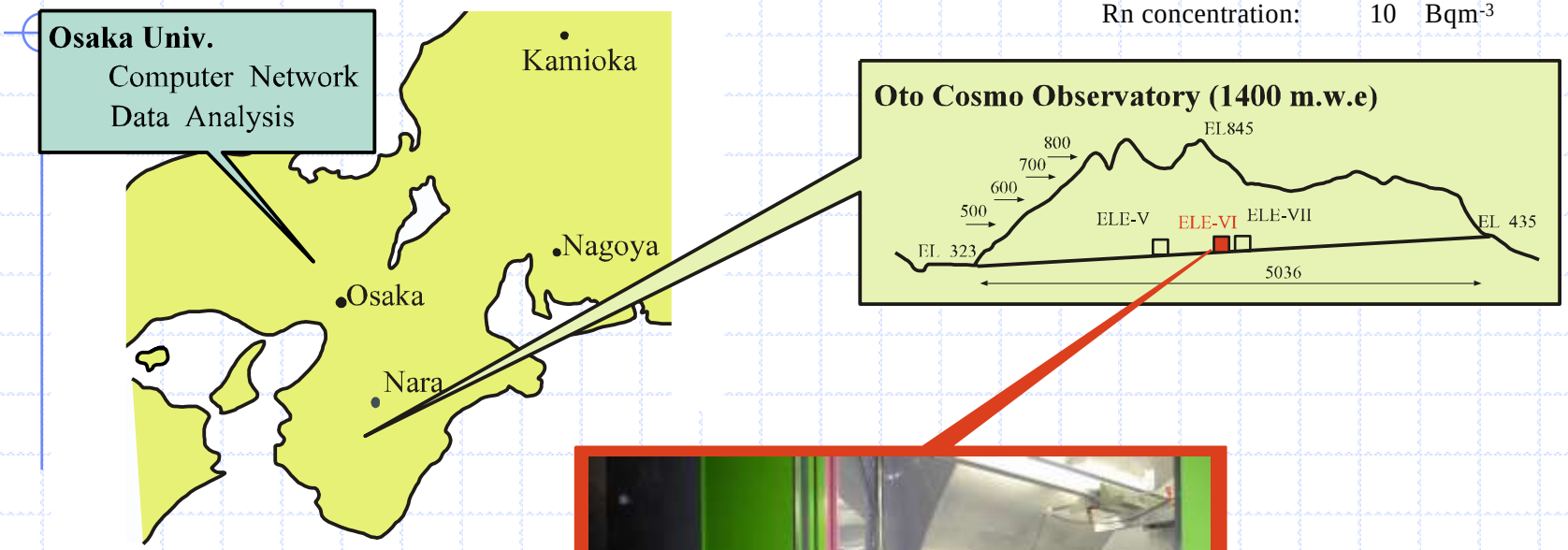
ELEGANT VI
@ Oto Cosmo Observatory

Oto Cosmo Observatory

Cosmic ray: $4.0 \sim 10^{-7}$ $cm^{-2}sec^{-1}$

Neutron flux: $4.0 \sim 10^{-5}$ $cm^{-2}sec^{-1}$

Rn concentration: 10 Bqm^{-3}

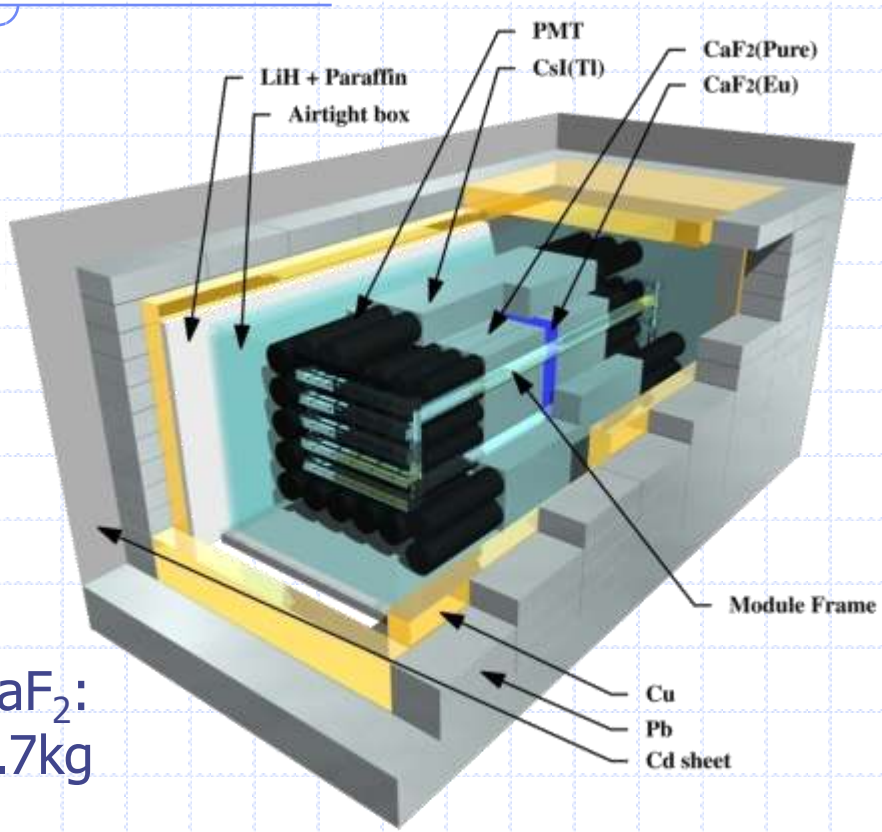


The tunnel which is originally constructed for the railway is 5 km long, and its maximum depth is about 470 m. Because of the natural ventilation due to the relatively strong wind inside the tunnel, the radon concentration is two or three orders of magnitude lower than the Kamioka underground laboratory.

ELEGANT VI detector
CaF_2 scintillator array

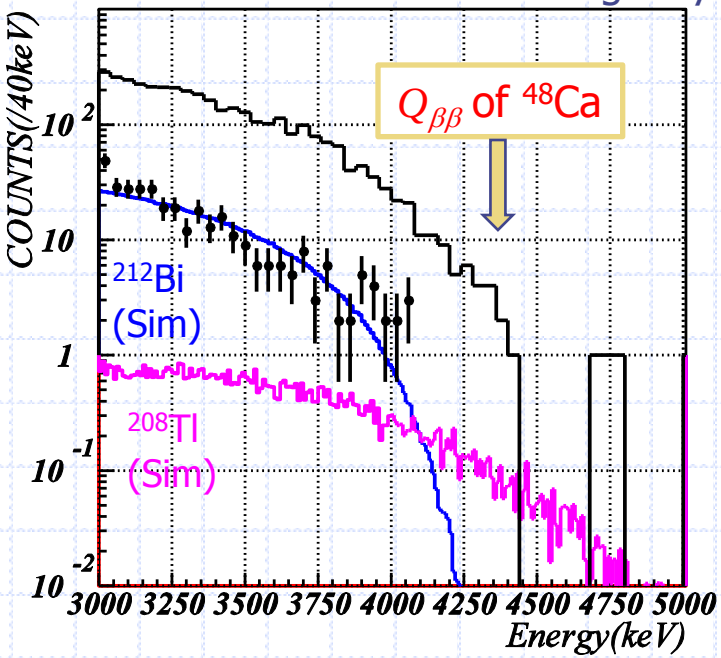
Spin-coupled DM search
^{48}Ca double beta decay search

ELEGANT VI (4π active shield)



CaF_2: 6.7kg

Surrounded by H_3BO_3 loaded-water tank



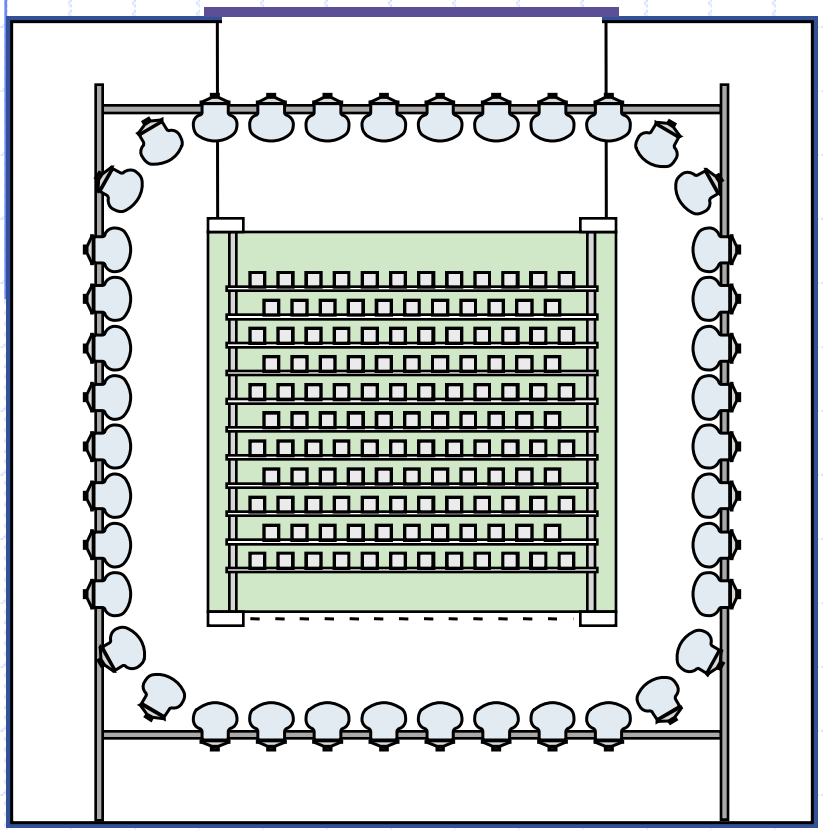
Phys. Rev. C **78**, 058501 (2008)

$T_{1/2}^{0\nu\beta\beta} > 5.8 \times 10^{22}$ year (90% C.L.)

$\langle m_\nu \rangle < (3.5 - 22)$ eV (90% C.L.)

CANDLES

CAlcium fluoride for studies of Neutrino and Dark matters by Low Energy Spectrometer



- undoped CaF_2 (CaF_2(pure))
  - ^{48}Ca ($Q_{\beta\beta}$=4.27 MeV)
  - Atten. length > 1 m
  - Low radioactive impurities
- Low background detector
  - 4π active shield (LS)
  - Passive shield (Water, LS)
  - Pulse shape information
- Good energy resolution
  - large photo-coverage
  - Two phase LS system

Background reduction/rejection

- External BG
  - conventional shield ⟸ Water (rel. Low cost)
  - 4π active shield ⟸ LS and CaF_2 (difference in decay time)
- energy window ($2\nu\beta\beta$)
  - high energy resolution ⟸ High light collection efficiency
- Internal BG(U, Th)
  - Reduce internal radio impurities ⟸ High purity CaF_2 crystal
  - Reject successive decay events ($\beta \Rightarrow \alpha$) ⟸ Pulse shape information

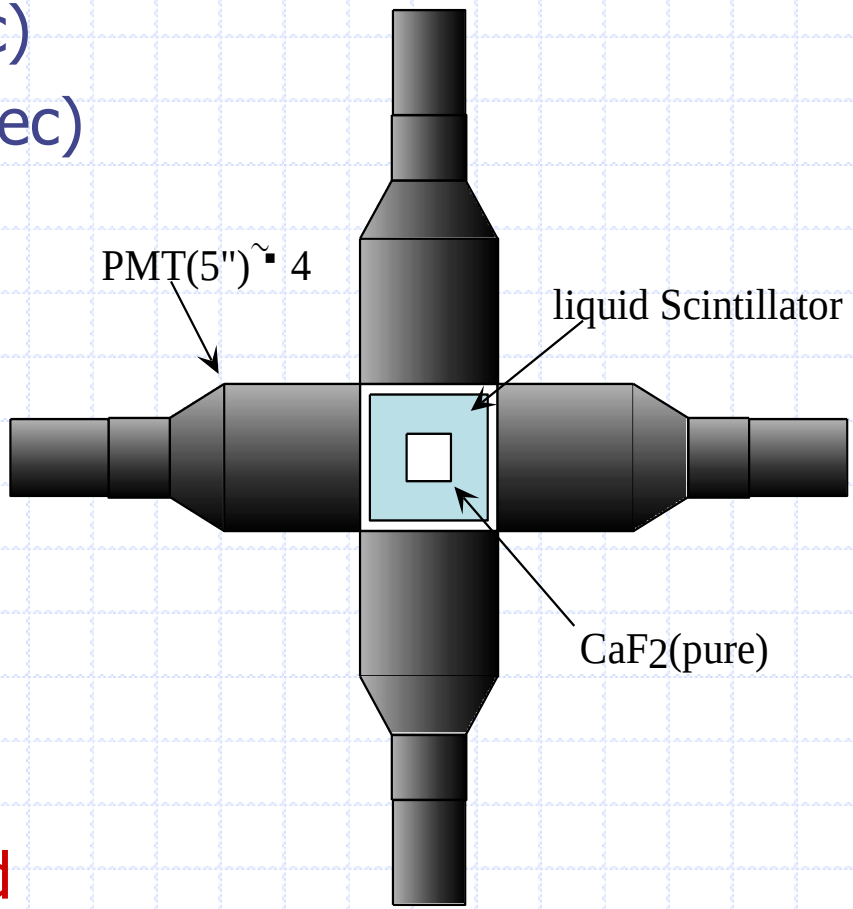
Candles

BG reduction / rejection — 4π active shield —

CANDLES I

- POP (Proof of Principle) Detector

- CaF_2(pure) crystal (~1 μsec)
  in liquid scintillator (~10 nsec)
  (with w.l. shifter)
  viewed by 4 PMTs (5 inch)

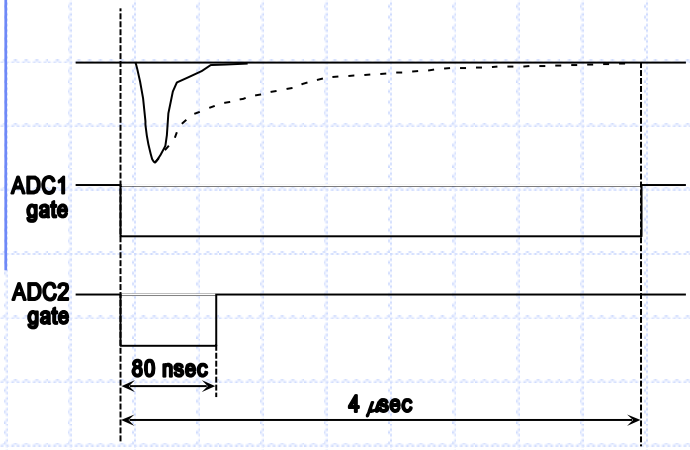


- LS : mineral oil
  + DPO (3 g/l)
  + Bis-MSB (0.3 g/l)

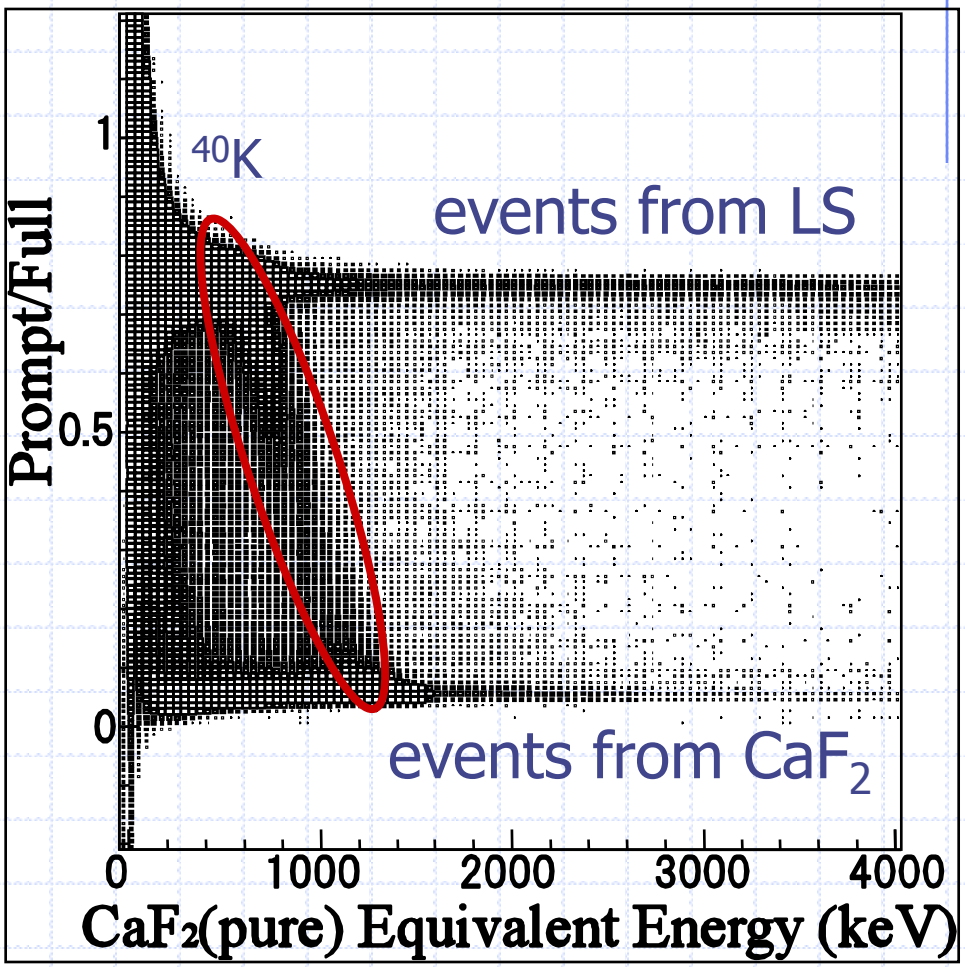
→ 4π active shield

Performance Test (4π active shield)

2 ADCs with
different gate width



Clear separation
between CaF_2 and LS



BG reduction / rejection — Energy resolution — (BG from $2\nu\beta\beta$ events)

Improve light collection efficiency

- Keep high transparency for both(CaF_2(UV), LS(vis.)) scintillation light

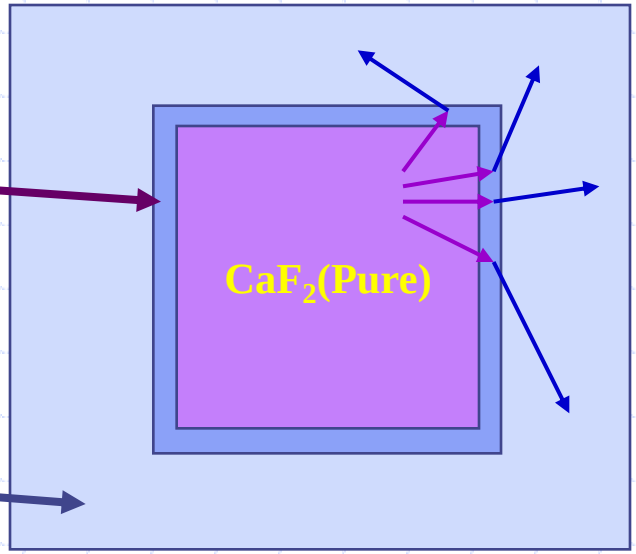
  CaF_2 crystal, LS, pure water, acrylic vessel,…

  - Undoped CaF_2 (attenuation length > 1m)
    - cf. CaF_2(Eu) ~10 cm
  - Shift wavelength of scintillation light from CaF_2 scintillators; UV ⇒ visible

- Large photo-coverage
  - Large (13,17 inch) PMT

Two Phase System

- Concept of Method
  - Conversion Phase
    - large conversion eff.
    - good transparency for UV
  - Veto Phase
    - large light output with aromatic solvent (absorb UV light)
    - good transparency for visible light



CaF_2 Emission (~285nm)

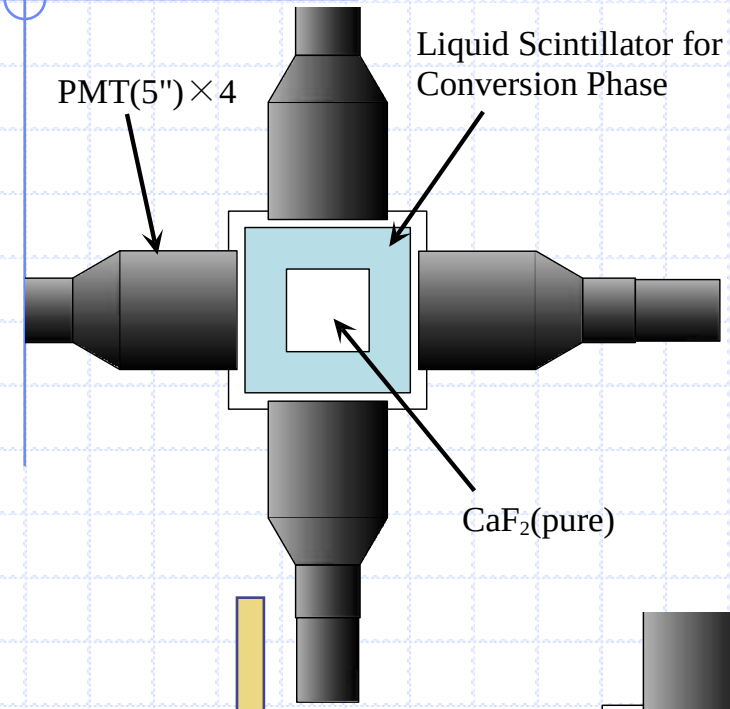
⇩

Conversion by WLS (350~400nm)

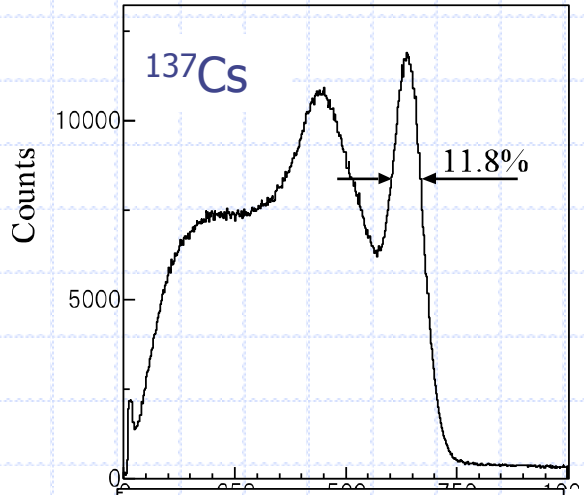
⇩ propagate

PMT

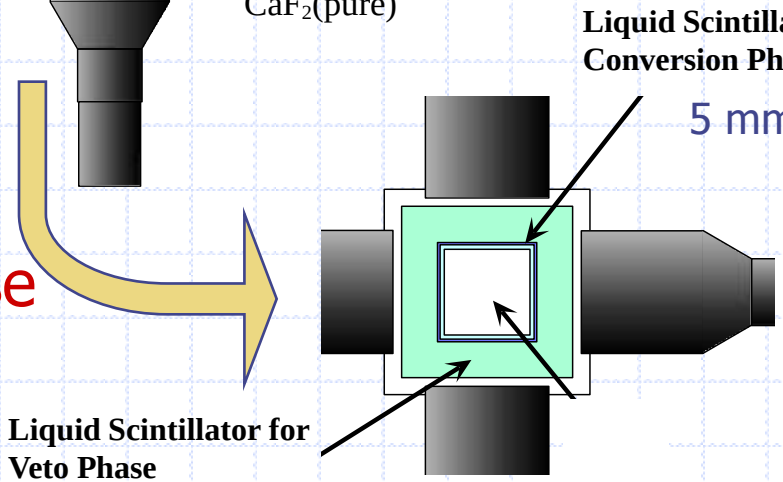
Performance of two phase system

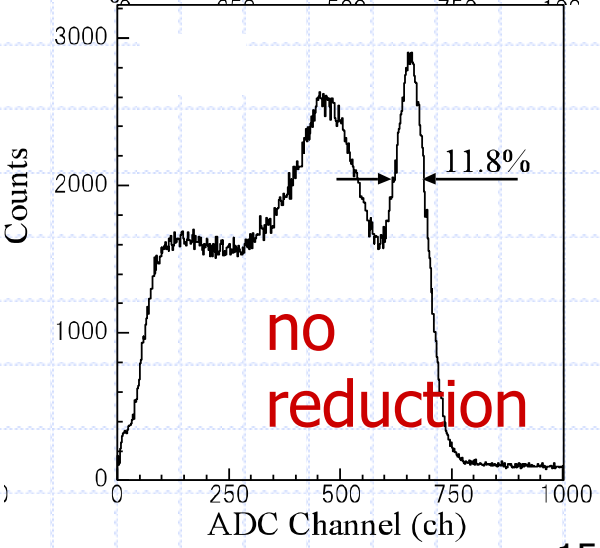


conversion phase only
(5 cm thickness)



Two Phase system





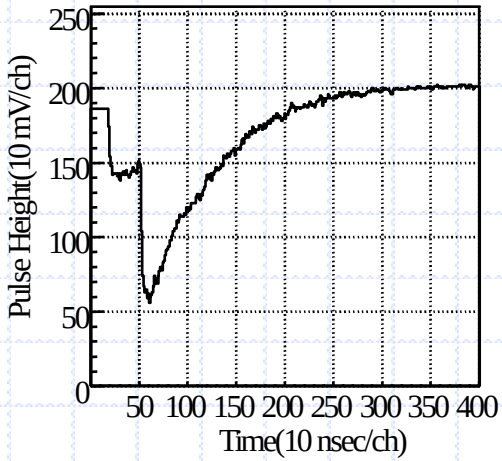
Candles

BG reduction / rejection — Internal BG (U, Th)—

Succesive decays in CaF_2 scintillator

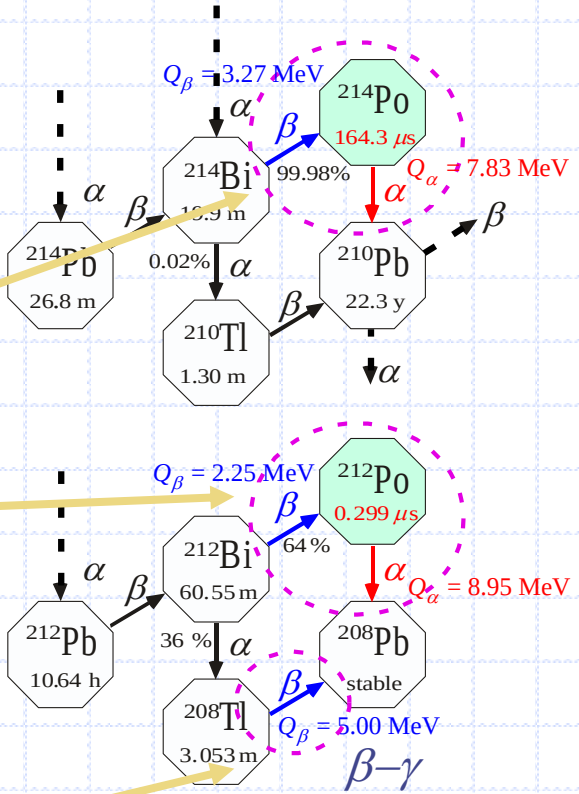
Candles

- BG
  - Successive decays in U, Th



^{214}Bi (U)

^{212}Bi (Th)



$$E_{vis} = Q_\beta + Q_\alpha \times f \approx Q_{\beta\beta}$$

f : Quenching factor for α

- ^{208}Tl : $\beta - \gamma$

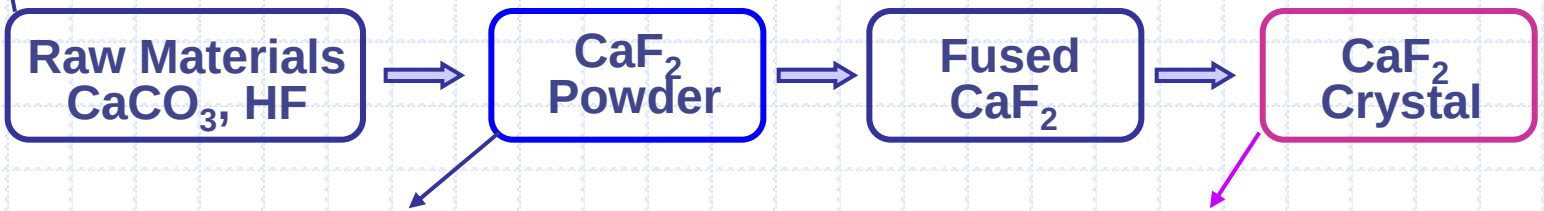
E_{max}=5.8 MeV (U)
5.3 MeV (Th)

Development of High Purity CaF_2 Crystals

Candles

CaF_2(Eu) in ELEGANT VI
U-chain(^{214}Bi) :1100 μBq/kg
Th-chain(^{220}Rn) : 98 μBq/kg

U and Th (ICP-MS)



Radioactivities in CaF_2 Powder (HPGe measurement) ⟷ Radioactivities in CaF_2(pure) Crystal (α-ray measurement)

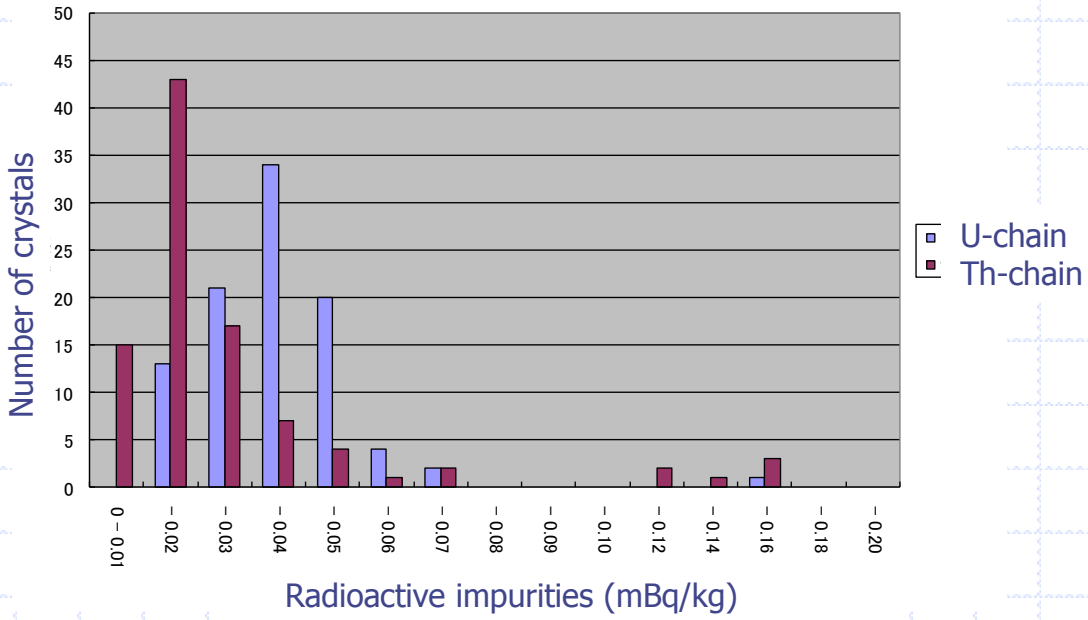
Powder selection
Crystal growing

101 crystals

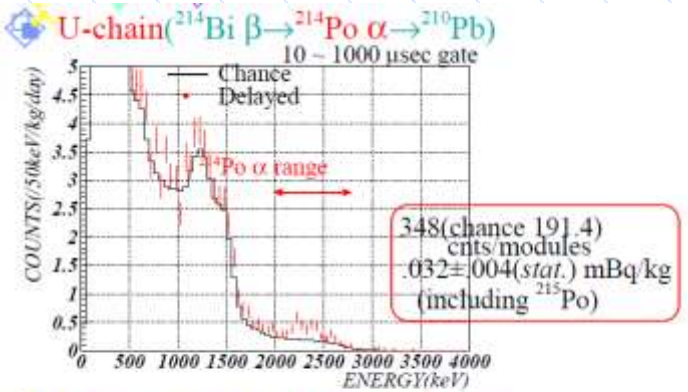
U-chain(^{214}Bi) ~36 μBq/kg …1/30 of Previous Crystals (14±5 μBq/kg ;Best)
Th-chain(^{220}Rn) ~28 μBq/kg …1/3 of Previous Crystals (6±1 μBq/kg ;Best)

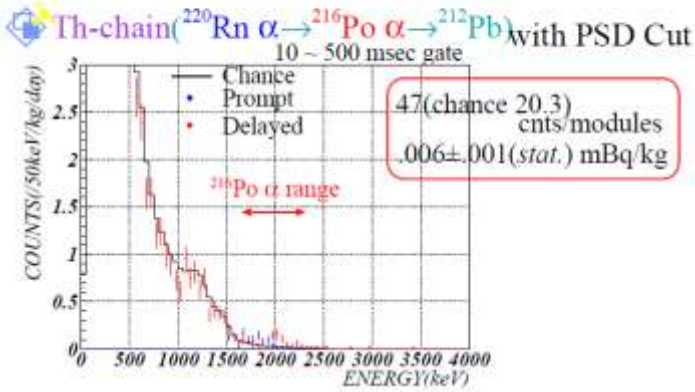
Radio active impurities in each CaF_2

- delayed coincidence ; $\beta-\alpha$, $\alpha-\alpha$
  - at Oto Cosmo Observatory



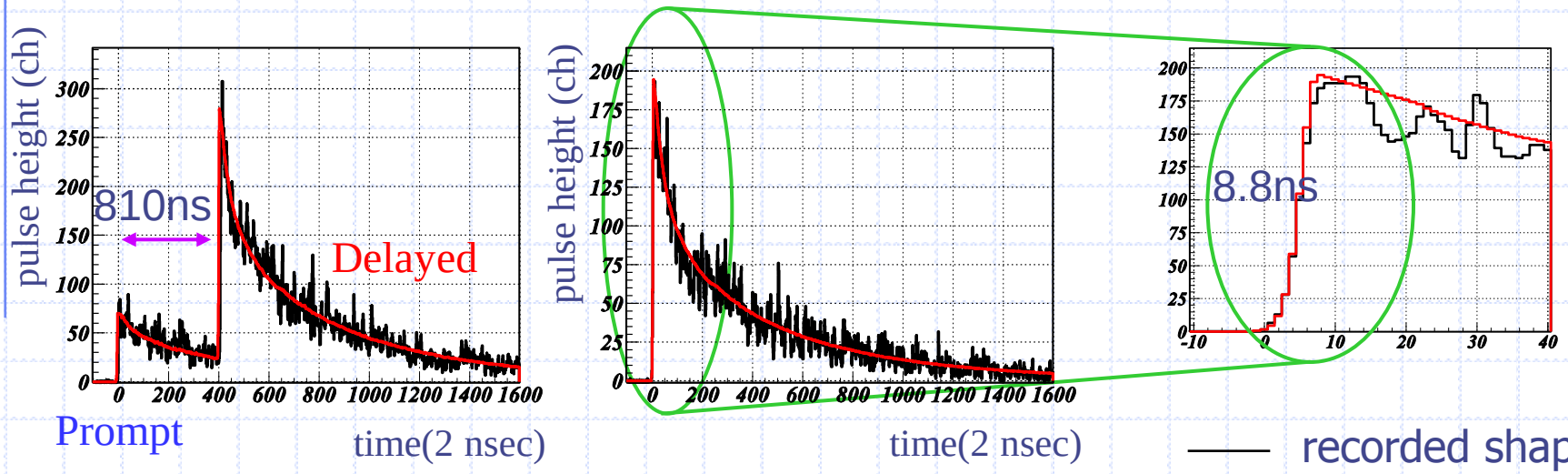
ex.)

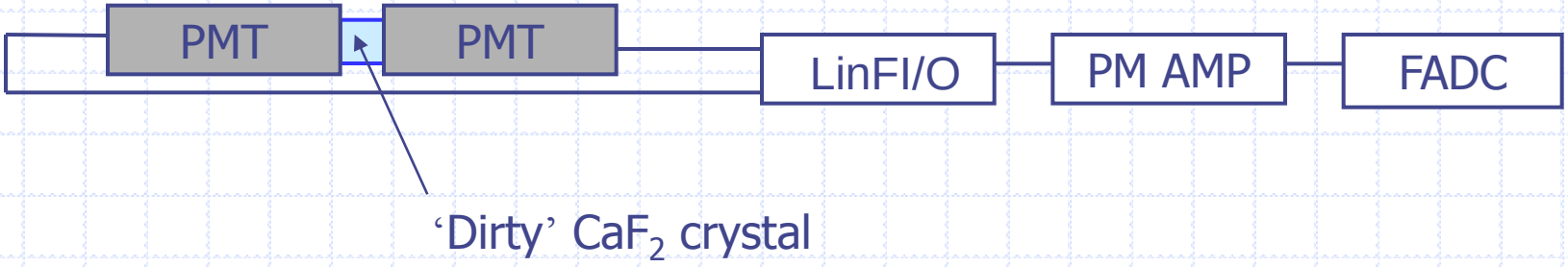




Rejection of Double Pulse(DP)

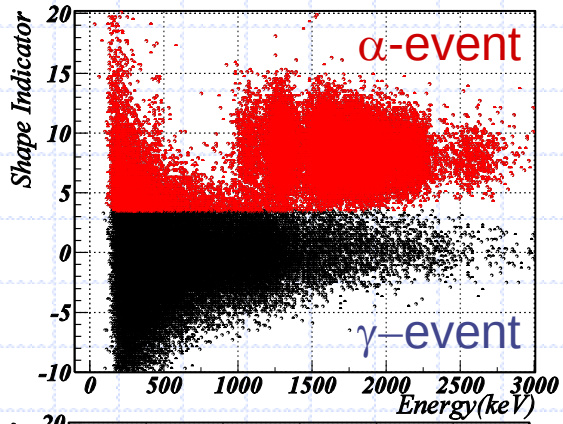
Typical Pulse Shapes

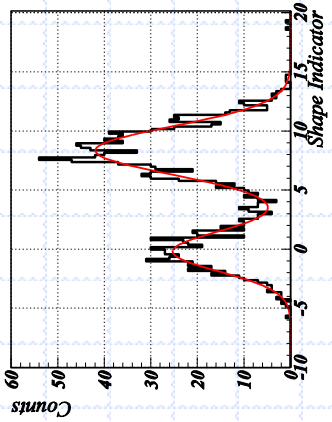


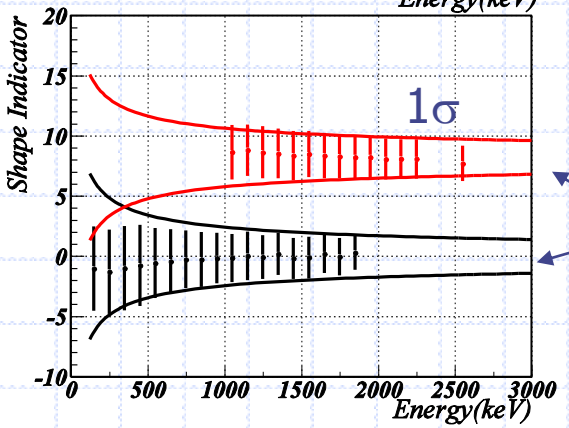


Pulse Shape Discrimination

- Pulse Shape discrimination
  - Shape Indicator (PRC **67**(2003) 014310)

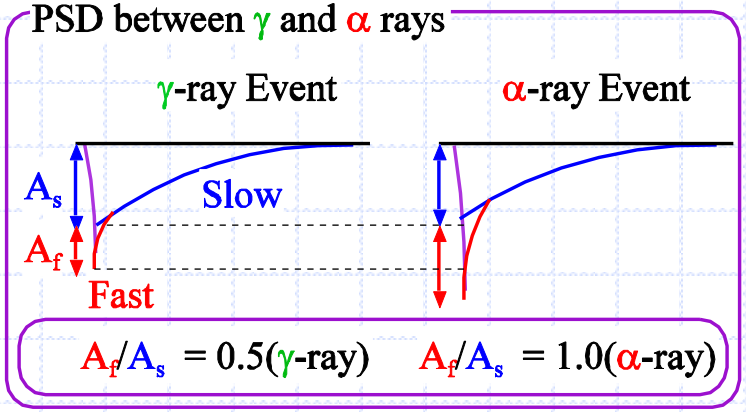






mean value:
no energy dependence (>1 MeV)

Difference in decay shape between α and γ rays



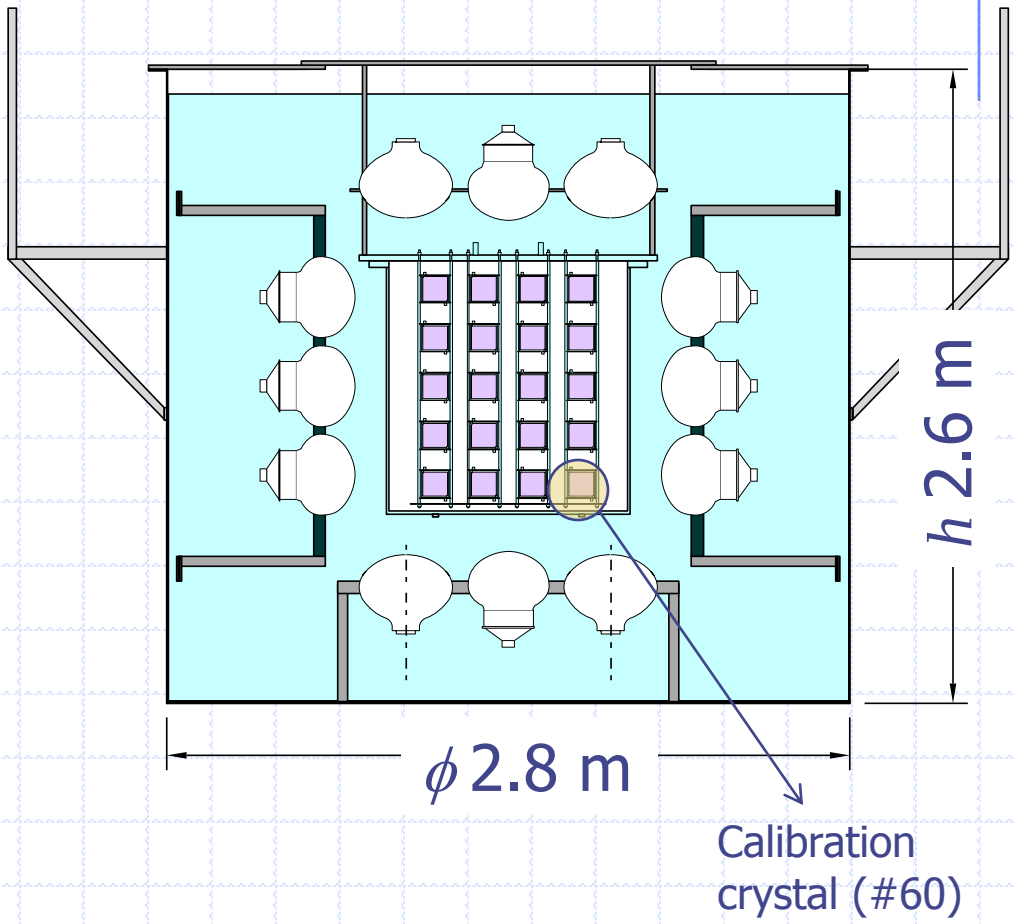
CANDLES III

CANDLES III (prototype)

- Constructed at Osaka Univ. (sea level)
  - small version for R&D
  - check the performance of CANDLES
- CaF_2 modules
  - 10^3 cm^3 × 60 crystal; 191 kg
  - with conversion phase
- Liquid scintillator
  - ϕ1000 × h1000 acrylic container
- H_2O Buffer : passive shield
  - ϕ2800 × h2600
- PMTs
  - 15” PMT (× 8) : R2018
  - 13” PMT (× 32) : R8055

1 “calibration” crystal (#60)
(High Contamination in U, Th)
65 mBq/kg (U-chain),
28 mBq/kg (Th-chain)

CANDLES III (prototype)



CaF_2 module

- CaF_2 + conversion phase + acrylic case

half filled

filled

Index 1.44@586nm (CaF_2)

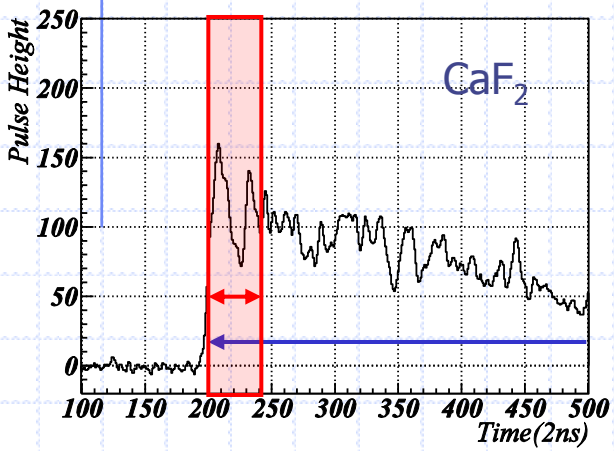
Index 1.46@586nm (Mineral Oil)

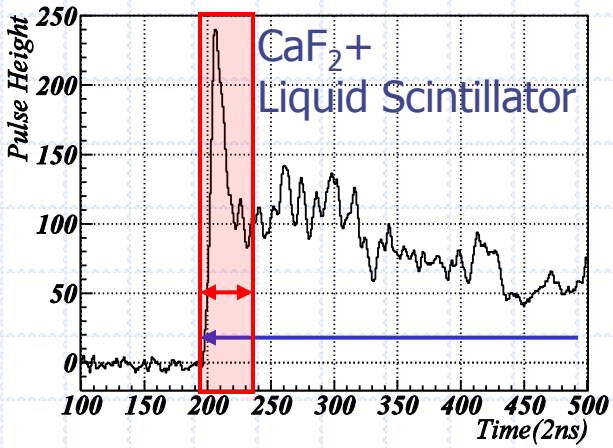
LS tank

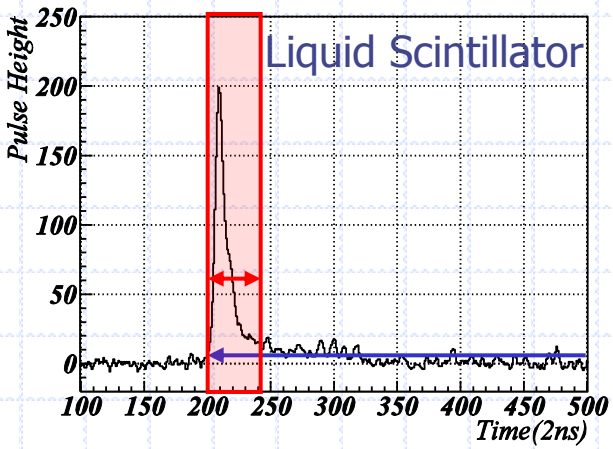
- 60 CaF_2 modules installed

Rejection of LS Events

- Rejection by using Pulse shape information
  - Typical Pulse Shapes



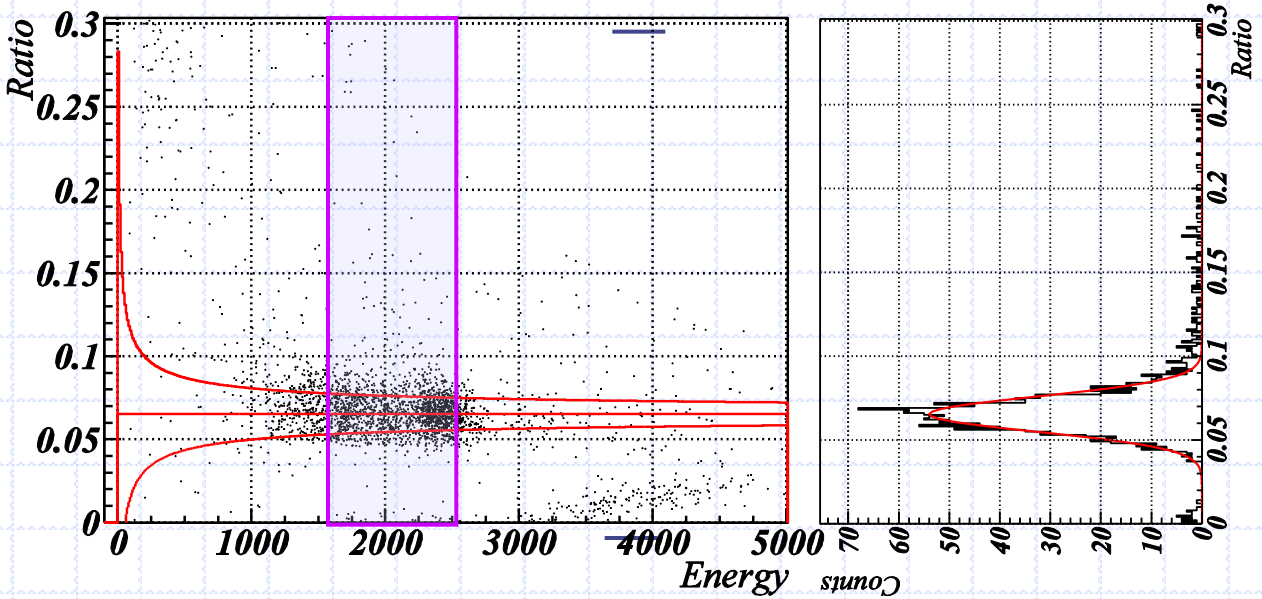




$$\text{Charge Ratio} = \frac{\text{charge in partial gate}}{\text{charge in full gate}}$$

Identification of CaF_2 Signal

- Charge Ratio determined by α-ray Events
  - α-ray events in calibration crystal (#60)

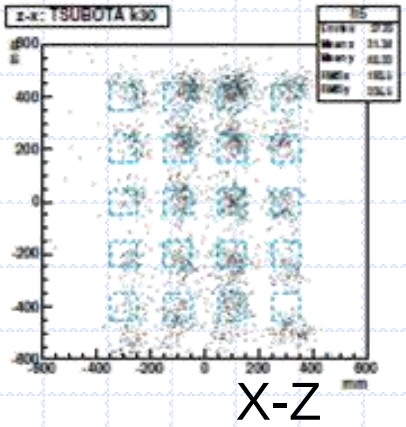


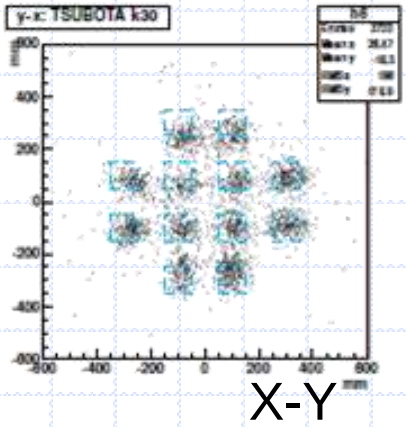
mean : 0.065
σ : 0.009

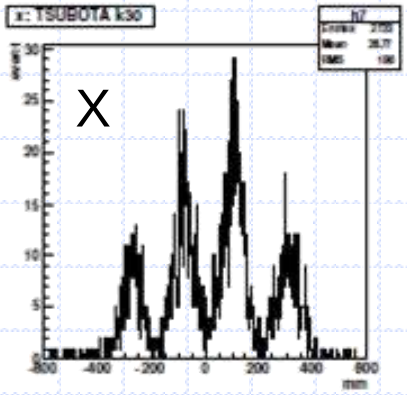
Charge Ratio = 0.065±0.009 (α-ray)
~ 1

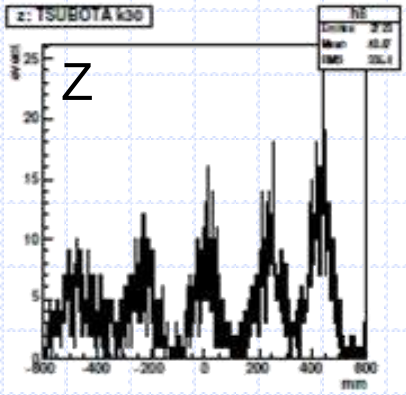
Identification of CaF_2 signal (2)

- Position reconstruction
  - Total charge of each PMT



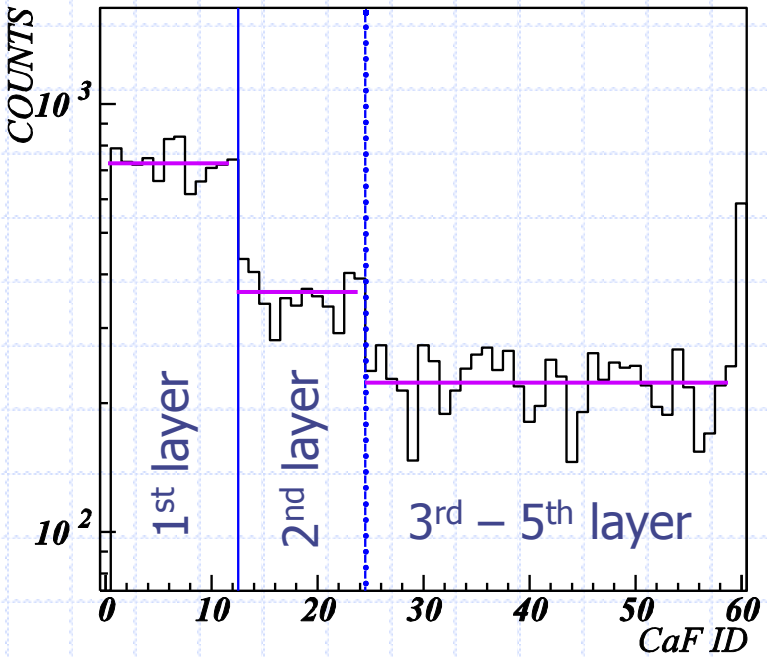






Event Rate dependence on z-axis

- Background Rate near Q-value for each CaF_2 Crystal
  - after rough ratio cut
    (LS events are rejected)



Obtained Energy Spectra @sea level laboratory

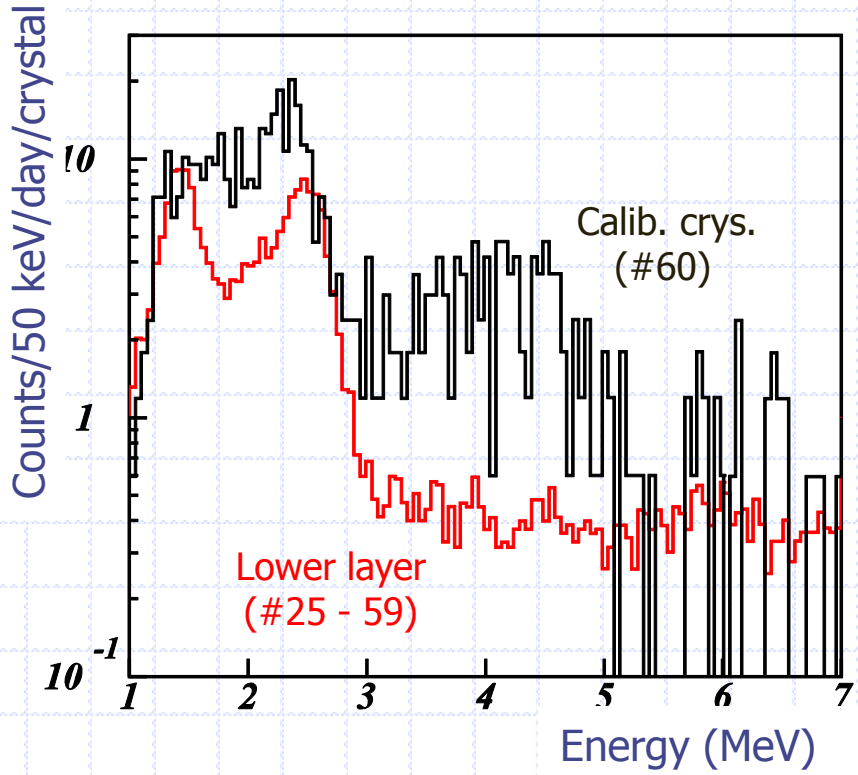
- LS veto & position cut
  - DP rejection & PSD not applied
- @ Surface lab.

  remaining BG

  ⇓ If all originate from cosmic ray…

  $\times 10^{-5}$ @ underground lab.
- further study

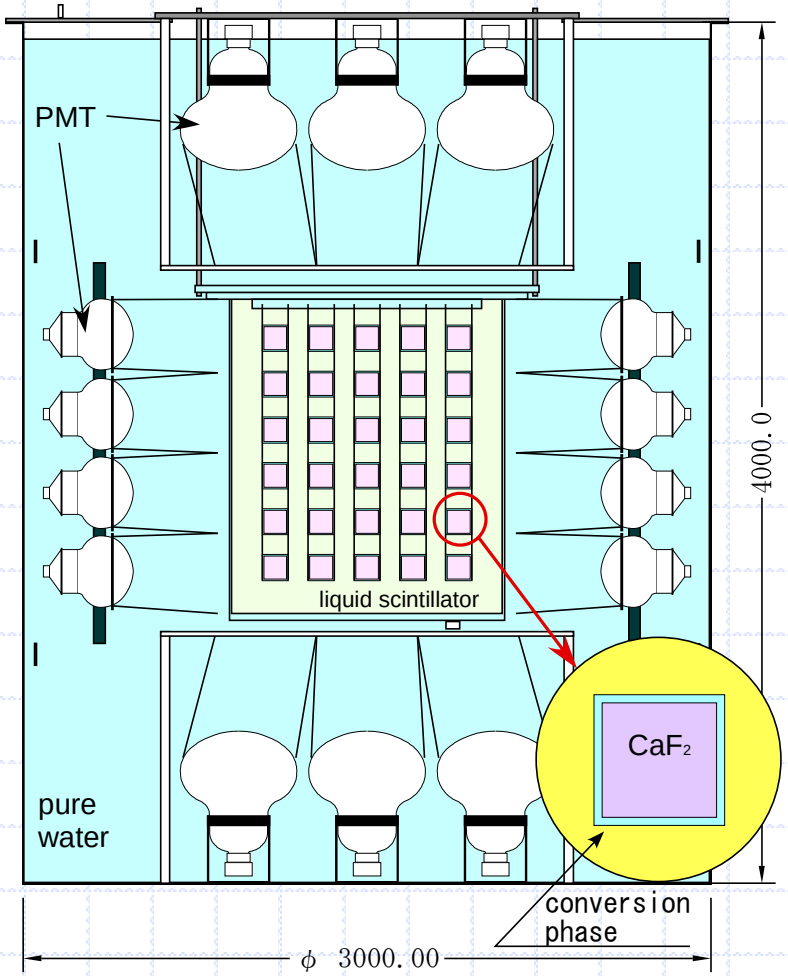
  origin and process of BG



CANDLES III (U.G.) @Kamioka

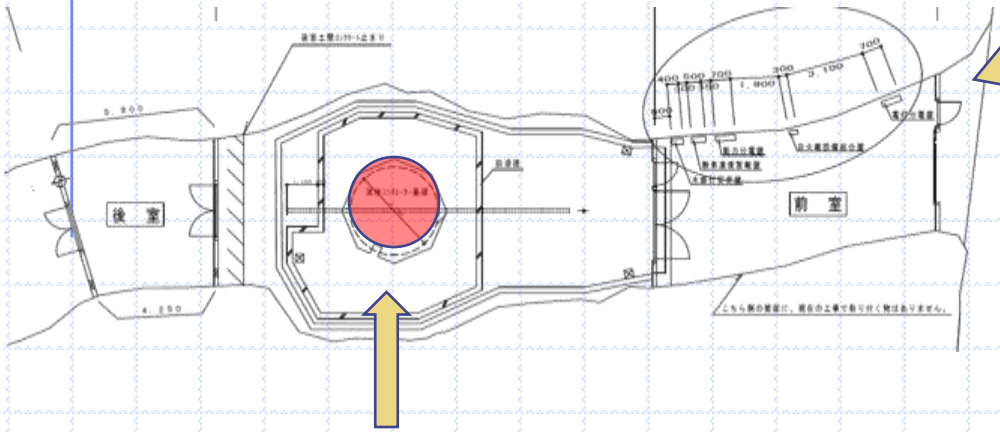
CANDLES III(U.G.)

- CaF_2(pure)
  - 10^3 cm^3 × 96 crystals; 305 kg
- Liquid scintillator
  - two phase system
  - Purification system
- H_2O Buffer
  - passive shield (larger tank)
- PMTs
  - 17” PMT (×14) : R7250
  - 13” PMT (×56) : R8055
- photon trans. simulation
  ⇨ energy res. ~4.0 % @ $Q_{\beta\beta}$
- Kamioka underground lab.

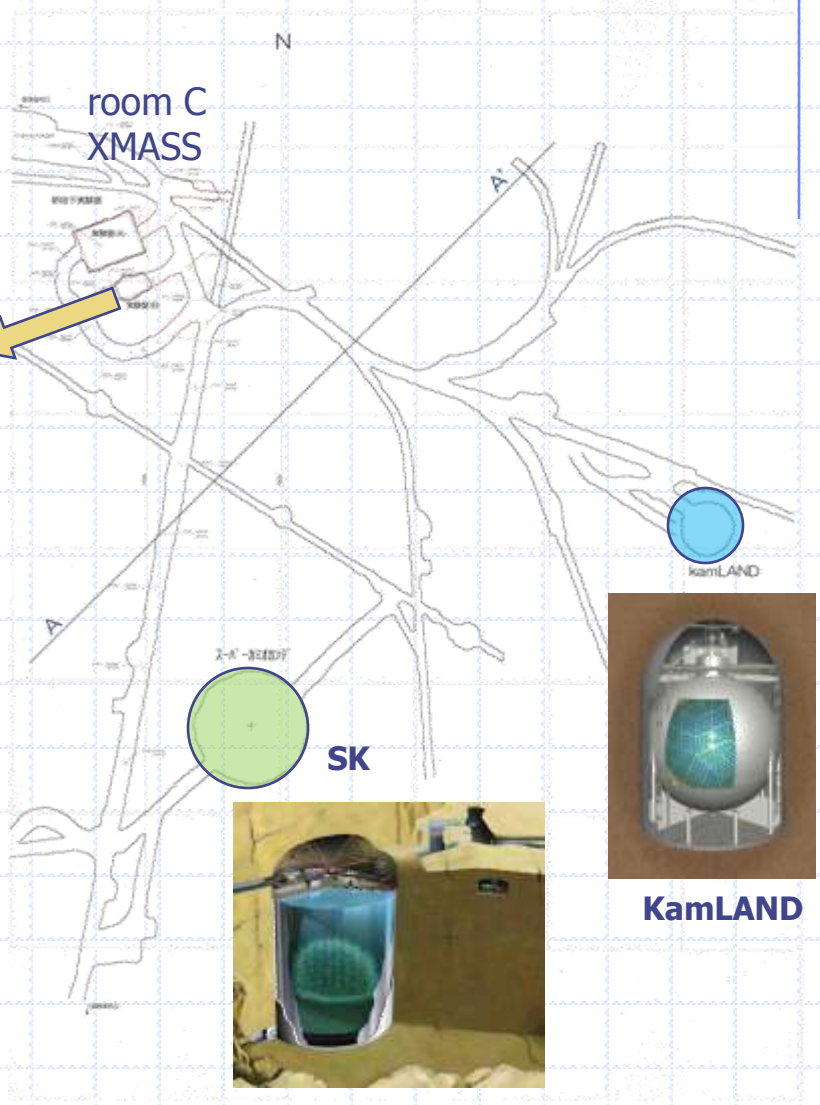


Kamioka new exp. room

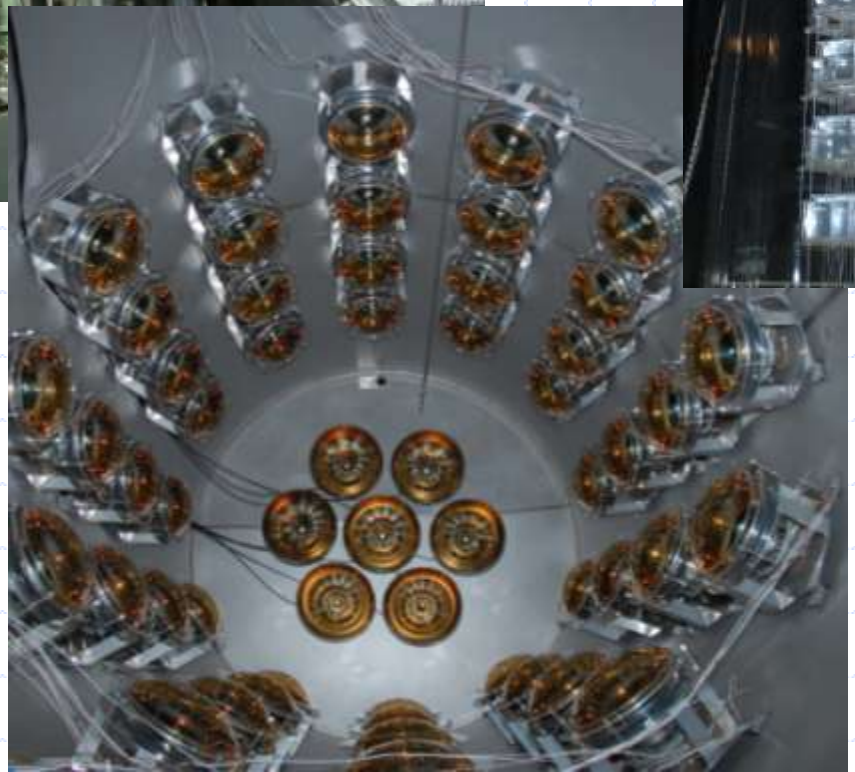
- experimental room D



CANDLES III(U.G.)



CANDLES III (U.G.)



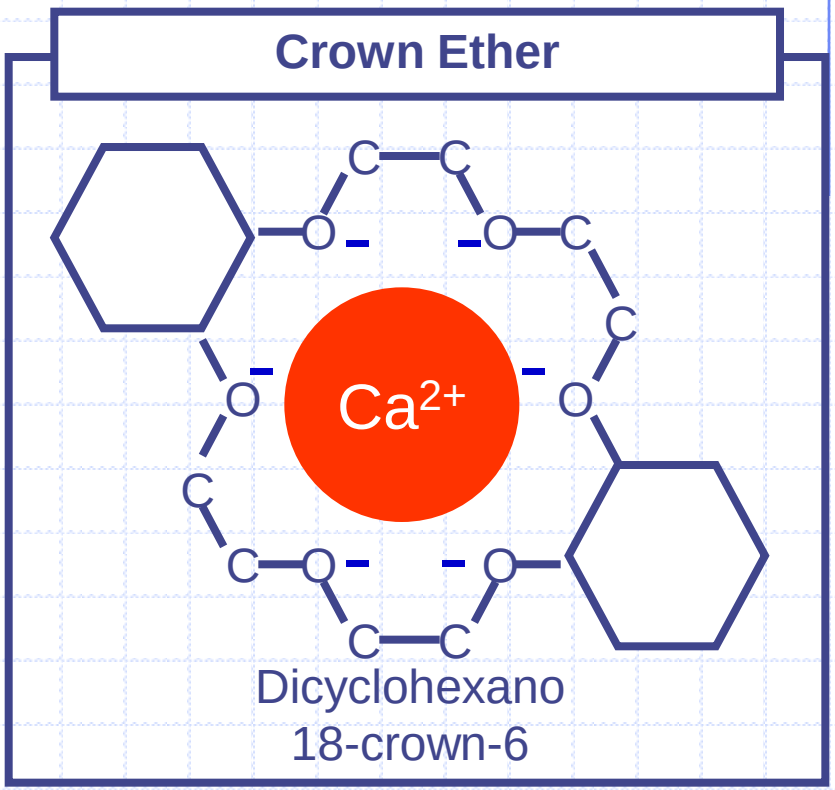
R&D for future large detector

To reach IH mass region

- Enlarge the detctor
  - Purification of CaF_2 crystals ; <1 μBq/kg
    further R&D is underway
- Enrichment of ^{48}Ca
  - Chemical processing with Crown Ether

Crown Ether

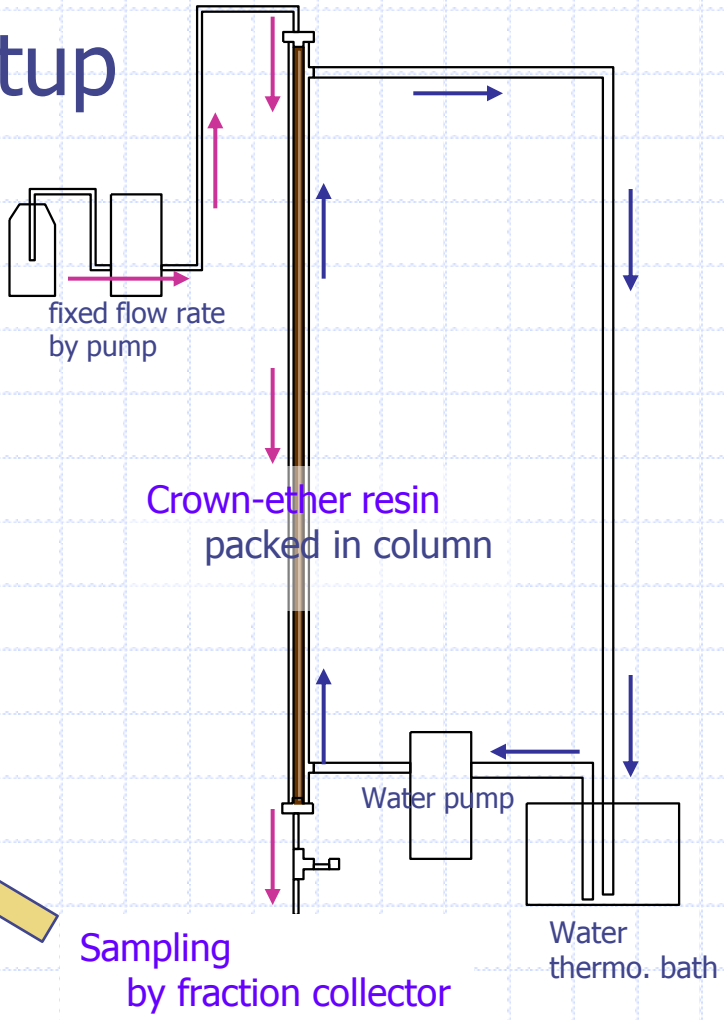
- Held by electrostatic attraction between negatively charged O^- of the C-O dipoles & ion (Ca^{2+})
- How well the ion fits into the crown ring
- Liquid (aq-salt)-liquid (org-crown) extraction in isotopic equilibrium



Chromatography

Experimental Setup

Breakthrough method



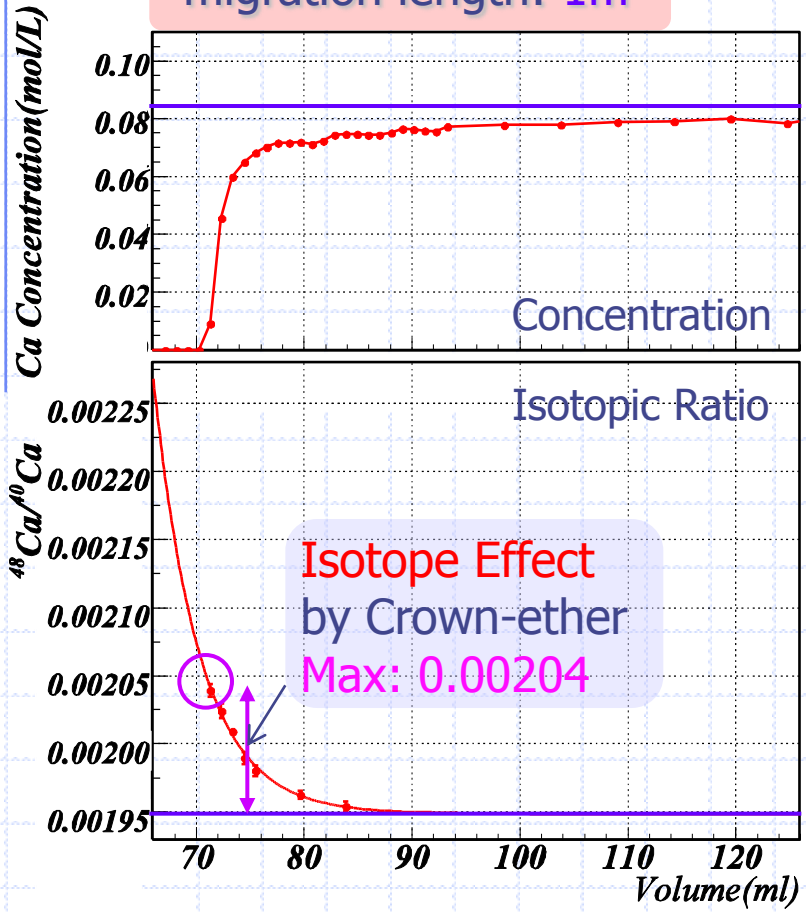
Measurement of

- Ca concentration
- isotopic ratio

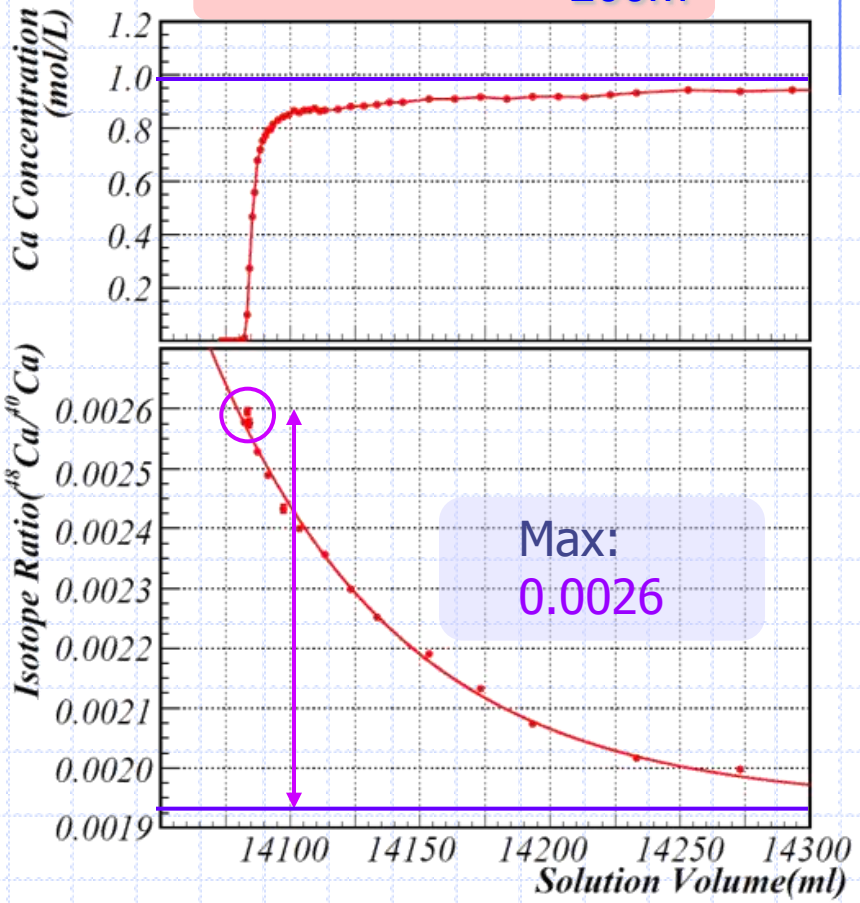
^{48}Ca Enrichment by crown-ether

Candles

migration length: 1m



200m



Further efforts for mass production

Summary

- CANDLES project
  - Study of ^{48}Ca double beta decay
- CANDLES III @Osaka University
  - R&D study for underground experiment
  - further study of BG
- CANDLES III(U.G.) @Kamioka
  - Under construction
  - Expected BG: 0.18 ev/year
- R&D efforts for future large detector
  - purification of CaF_2 crystal
  - enrichment of ^{48}Ca
    - Optimizing the parameters (temp., flow rate, …)

CANDLES Collaboration

- Osaka U.（大阪大学）
  T. Kishimoto, I. Ogawa, S. Umehara, K. Matsuoka, Y. Hirano, Y. Tsubota, G. Ito, K. Yasuda, H. Kakubata, M. Miyashita, M. Nomachi, Y. Kohno, M. Saka, S. Ajimura
- Fukui U.（福井大学）
  Y. Tamagawa, T. Hayashi, Y. Maekawa, S. Isogai, T. Sato, T. Jinno
- Hiroshima U.（広島大学）
  R. Hazama
- Kyoto Sangyo U.（京都産業大学）
  K. Okada
- Saga U.（佐賀大学）
  H. Ohsumi
- Tohoku U.（東北大学）
  S. Yoshida
- Tokyo Institute of Technology（東京工業大学）
  Y. Fujii
- U. Tokushima（徳島大学）
  K. Fushimi