CANDLES

for the study of 48Ca double beta decay and its future prospect

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Osaka University

CANDLES Collaboration

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Univ. of Fukui
Tokushima Univ.
Osaka Sangyo Univ.
Tsukuba Univ.
Saga Univ.
Wakasa Energy Center

Osaka University, Graduate school of science
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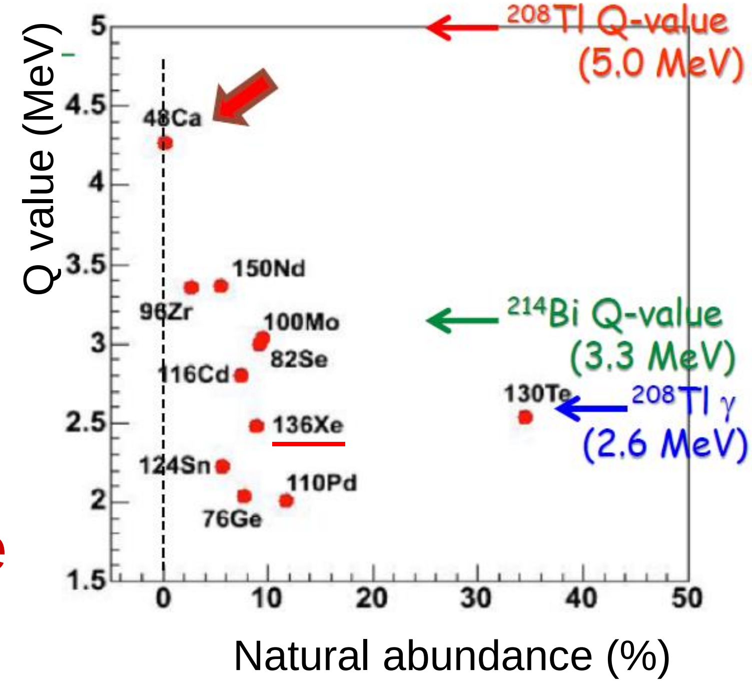
Saga University
大隅秀晃

The Wakasa wan Energy Research Center
鈴木耕拓

Candles

Why ^{48}Ca

- Highest Q value
  - 4.27 MeV, (^{150}Nd: 3.3 MeV)
  - Least BG（γ: 2.6 MeV, β: 3.3 MeV）
  - Large phase space factor
- Small natural abundance:
  - 0.187%
  - Separated isotope → expensive
- Next generation
  - $<m_\nu> \sim T^{-1/2} \sim M^{-1/2}$ (no BG) M: mass
    $\sim M^{-1/4}$（BG limited）
  - Enrichment:　mass＋S/N：500 times
  - High resolution：bolometer（crystal）
- Beyond inverted hierarchy
  - ^{48}Ca + enrichment + bolometer



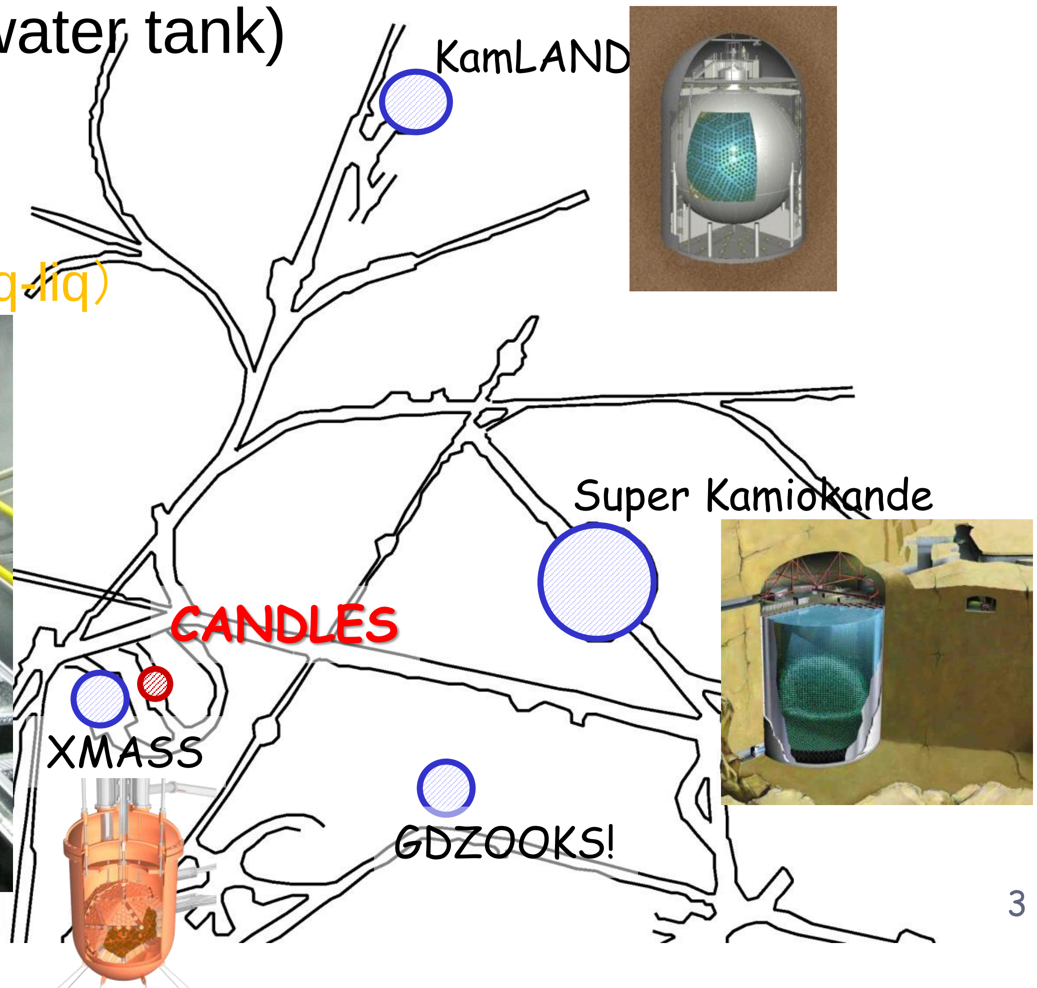
CANDLES

Nuclear matrix element
→ neutrino mass

CANDLES III @ Kamioka

- CANDLES III
  - Site: Kamioka U.G.L. ~1000 m
  - Size: 3mΦ × 4mh (water tank)
  - Liquid scintillator
    - Reservoir tank
    - Purification system（liq-liq）

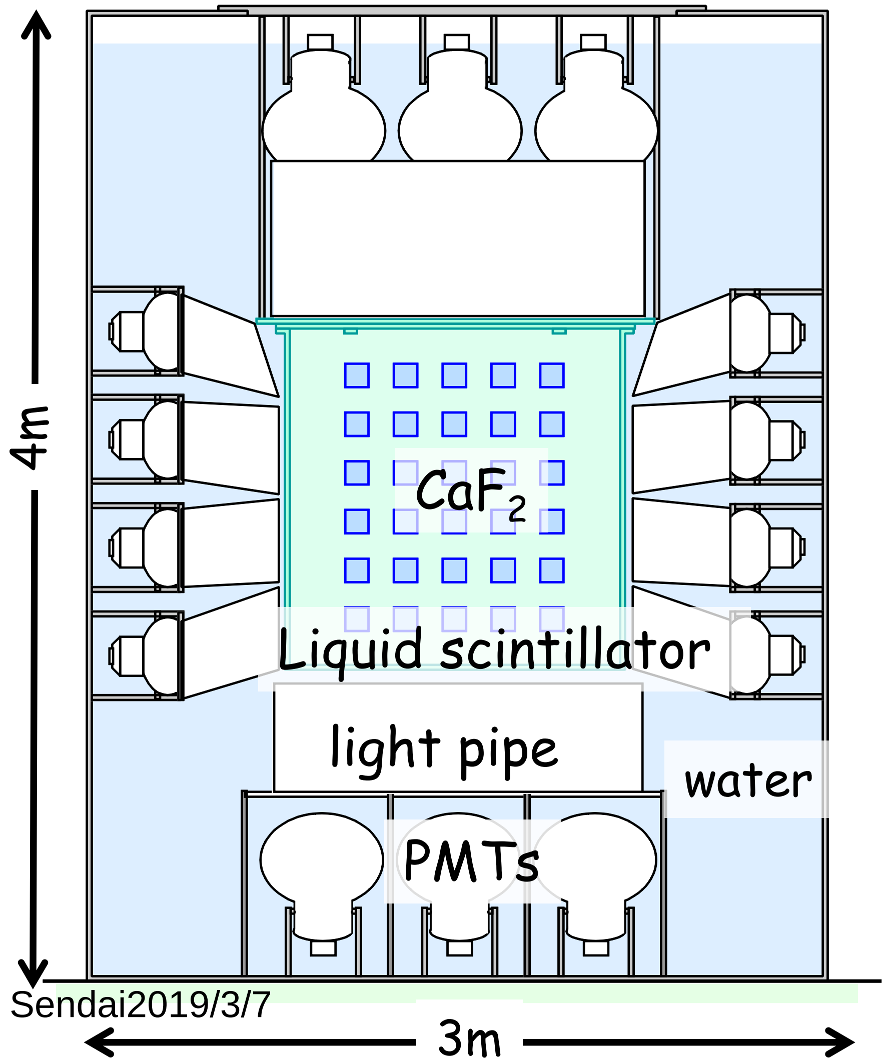
Kamioka Lab. Map



CANDLES III(UG)

CANDLES at Kamioka underground laboratory

CANDLES III



- **CaF_2 scintillator (CaF_2(pure))**
  - 305 kg (96 × 3.2kg)
  - $\tau \sim 1\mu sec$
- **liquid scintillator (LS)**
  - 4π active veto
  - $2m^3$
  - $\tau \sim$ a few 10nsec
- **PMT's**
  - 13inch PMT × 48
  - 20inch PMT × 14
- **light pipe**
  - light collection : energy resolution
- **Veto**

Pulse shape difference

CaF_2(pure) : ~$1\mu sec$

Liquid scintillator : a few 10 nsec

CANDLES III(UG)

CANDLES at Kamioka underground laboratory

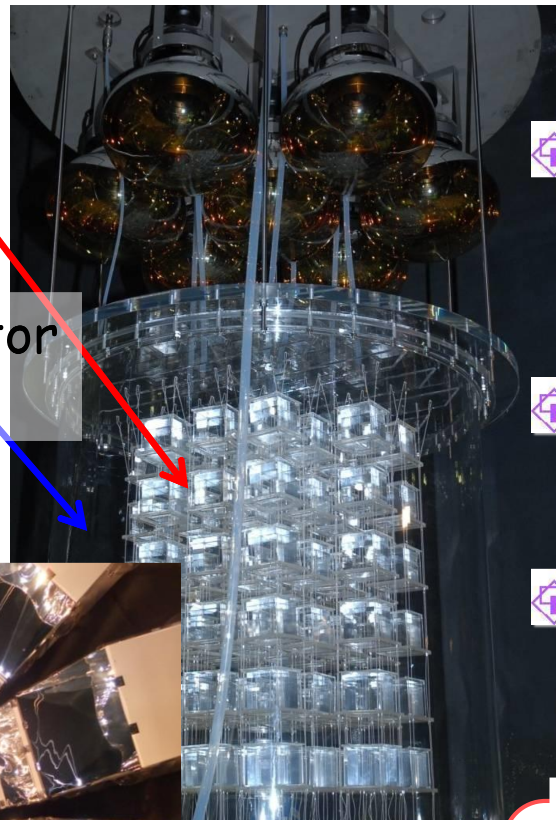
Candles

- CANDLES III

CaF_2 (305kg)

Liquid scintillator tank($2m^3$)

PMT
Light pipe



- **CaF_2 scintillator** **(CaF_2(pure))**
  305 kg (96 × 3.2kg)
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  4π active veto
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  13inch PMT × 48
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- **light pipe**
  light collection : energy resolution
- Veto

Pulse shape difference
CaF_2(pure) : $\sim 1\mu sec$
Liquid scintillator : a few 10 nsec

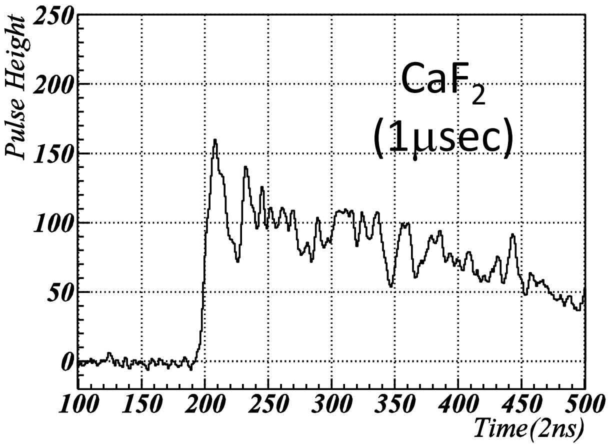
4π active veto by Liquid scintillator (LS)

Candles

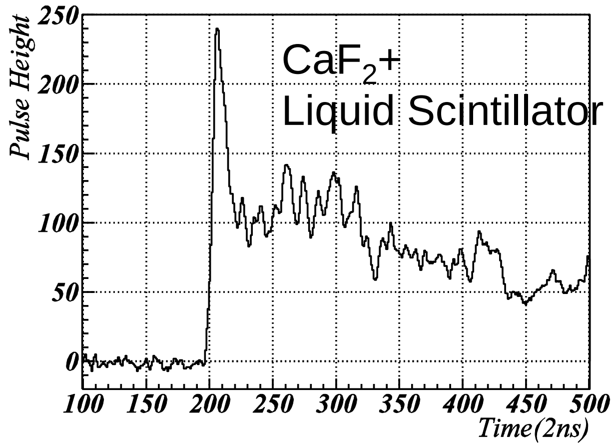
- Rejection of external γ–ray background

- Pulse shape information by 500 MHz Flash ADC.
- Distinguish event type by offline pulse shape analysis taking advantage of different decay time.

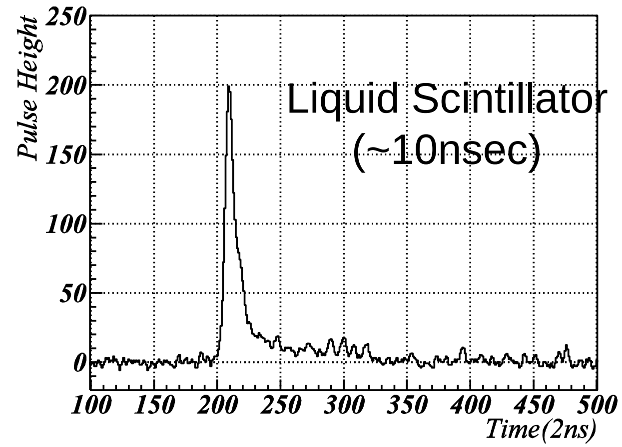
ββ signal !?

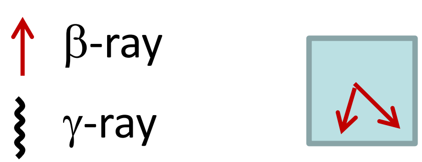


External γ BG

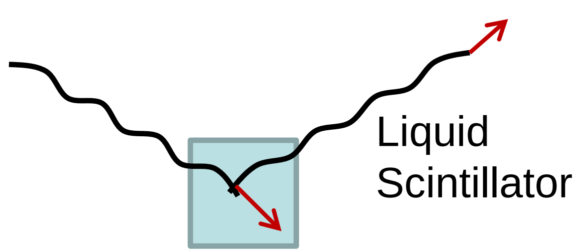


External γ BG

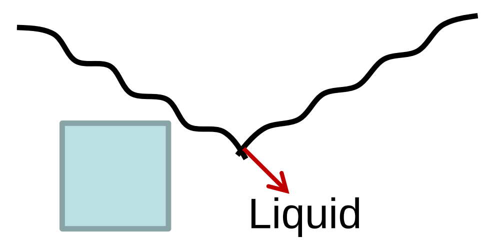




CaF_2



CaF_2

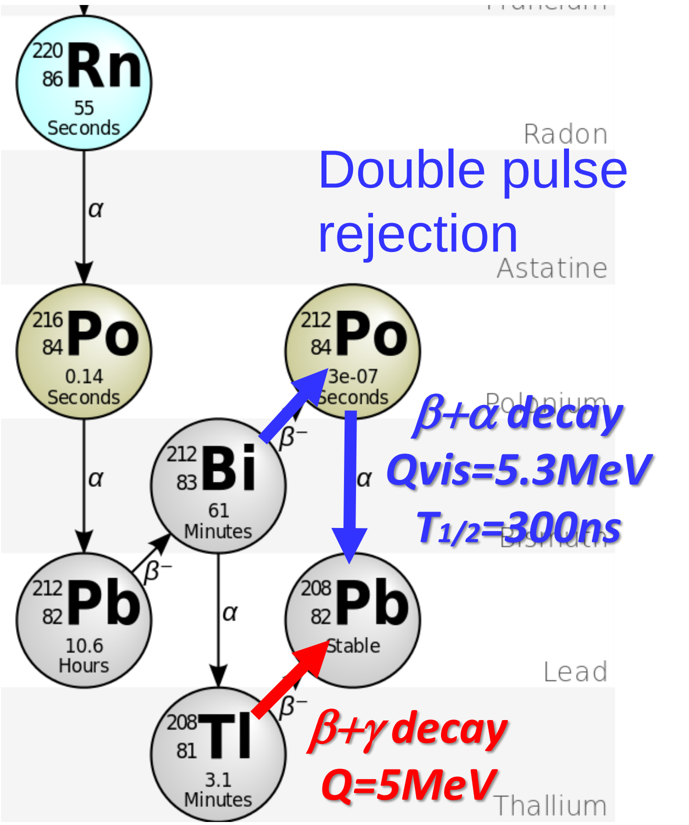


CaF_2

Liquid
Scintillator

Internal backgrounds and reduction

- External BGs were reduced by LS active shild.
- Remaining BGs originate from internal radioactivity of Th chain (^{208}Tl and ^{212}Bi-^{212}Po).
- 2νββ is not serious BG in current sensitivity. (it will be major BG after ^{48}Ca enrichment)
- We reject remaining BGs by analysis.



Preceding α rejection

Rejection of Double Pulse

Candles

Q_β = 3.27MeV

^{212}Bi

64%

Q_β = 2.25MeV

β

Q_α = 7.83MeV

^{212}Po

$T_{1/2}$ = 0.299μsec

Q_α = 8.95MeV

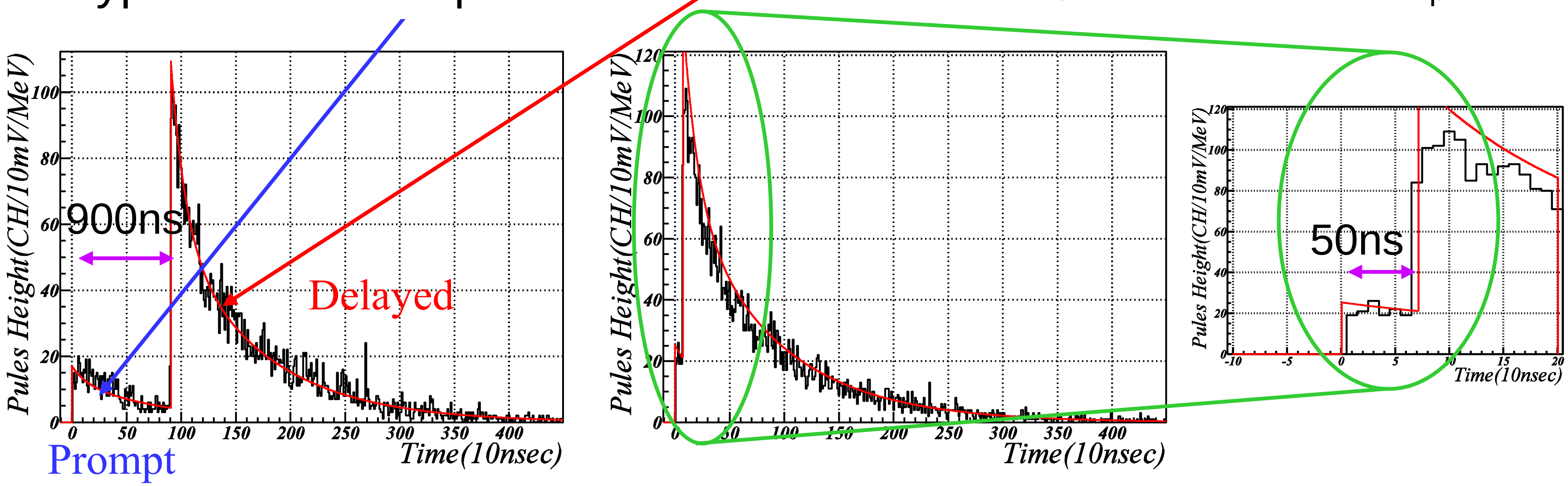
α

^{208}Pb

BG in $Q_{\beta\beta}$ region: Sum E

E_α(1/3 Quench) +$E_\beta \simeq$5.3 MeV

Typical Pulse Shape



Reduction

100MHz FADC (old) ΔT > 30ns(3ch) ; ~5%

500MHz FADC . . . ΔT > 10ns ; ~2%

^{208}Tl event cut

Th系列

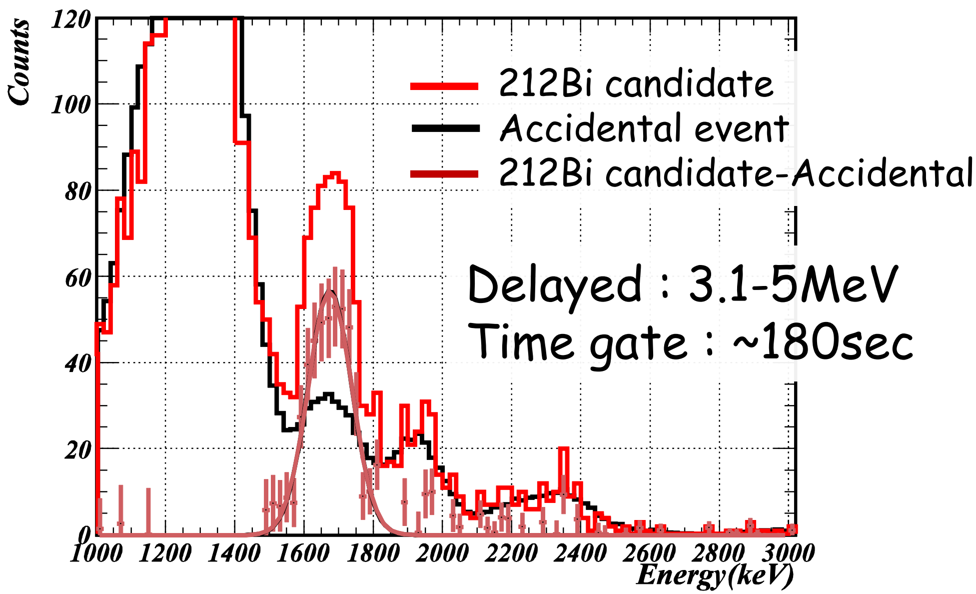
^{232}Th ・・・・ ^{212}Bi $T_{1/2}$=60.6m —α→ ^{208}Tl $T_{1/2}$=3.05min —β→ ^{208}Pb stable

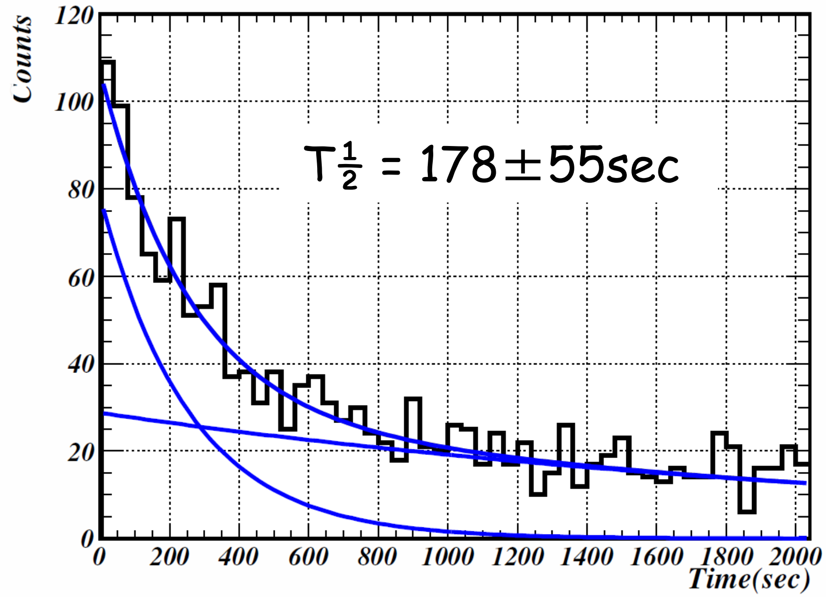
Q_α = 6.21MeV Q_β = 5.00MeV

α-β崩壊

Candles

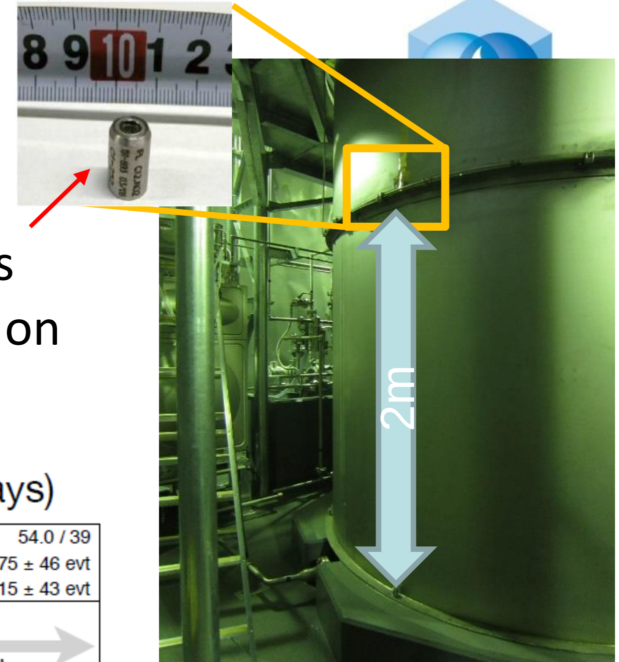
Eneryg spectrum of prompt events





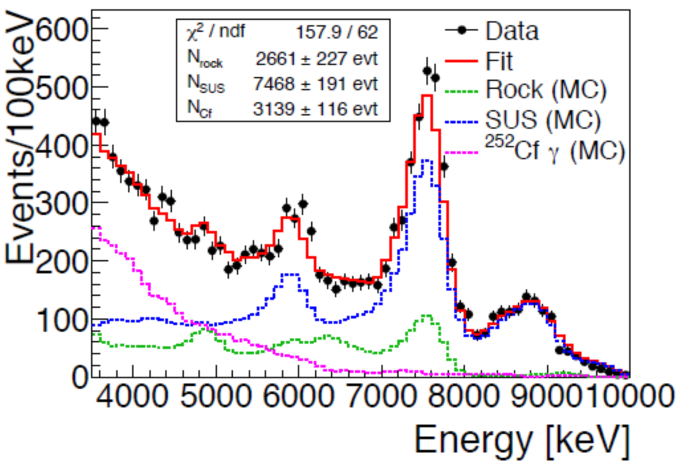
1. Find parent ^{212}Bi α-decay candidate by pulse shape analysis.
2. Apply 12min veto from ^{212}Bi candidate in the same crystal.

External backgrounds
-- Neutron source run --

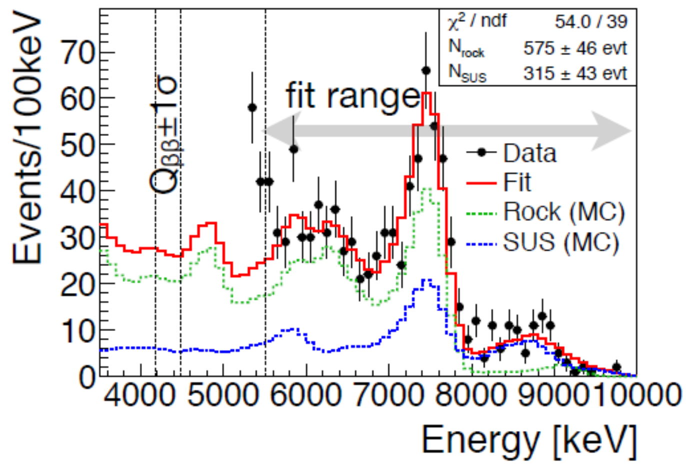


- To confirm our assumption that high E gamma ray BG's are from (n, γ) reactions, ^{252}Cf neutron source was set on the detector and data were taken.

^{252}Cf Run (3.1 hour)



Physics Run (88.1 days)



- Spectra for neutron source run and physics run are consistent.
- MC simulation of (n,γ) can well reproduce the BG spectrum.

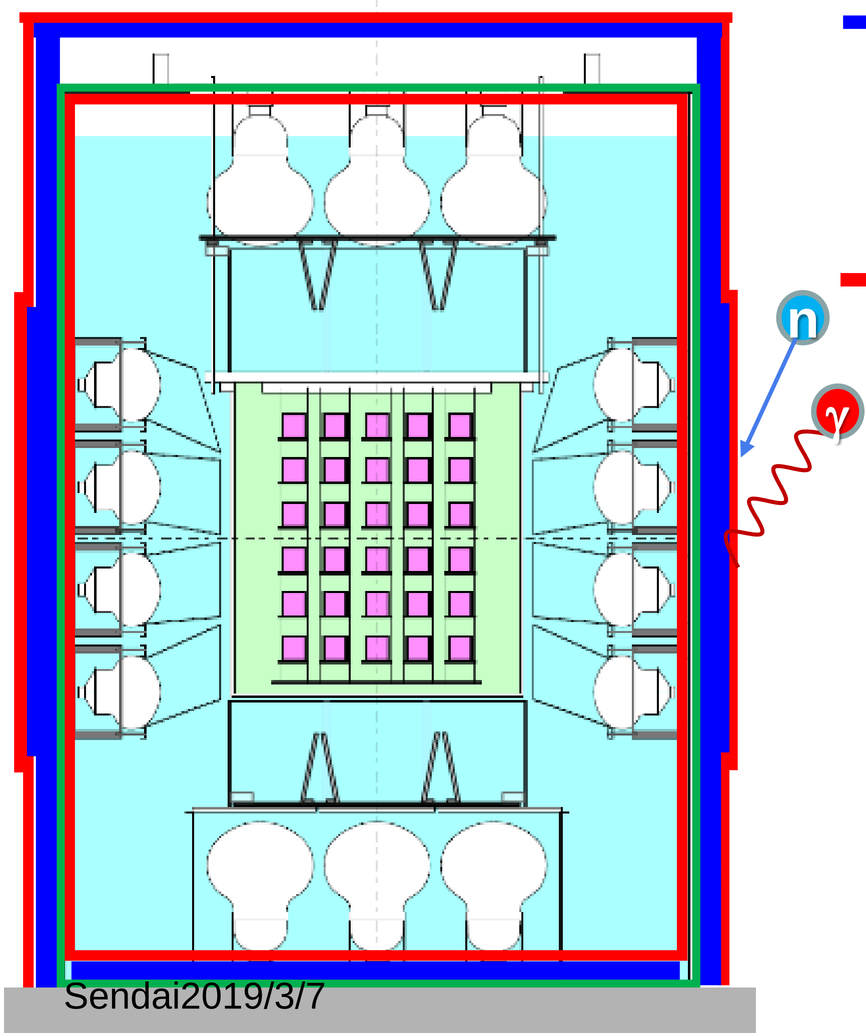
We identified main BG as (n,γ) !!

Neutron flux@Kamioka see K. Mizukoshi's Poster

Shield for (n,γ) background reduction

Candles

CANDLES shield overview



- CANDLES tank
- Pb shield (7-12cm)
  - Reduce γ-ray from surrounding rock
  - Effect of Pb (n,γ) is one order smaller than that of stainless tank
- Boron sheet (4-5mm)
  - Reduce n captured by stainless tank

- (n,γ) BGs in CANDLES is expected to become **1/80** by MC.
- Expected number of backgrounds after shield installation:

Rock : 0.34±0.14 event/year
Tank : 0.4±0.2 event/year

Pb shield construction

- **Pb shield construction was started from March 2015.**
- **All the collaborators worked very hard!**

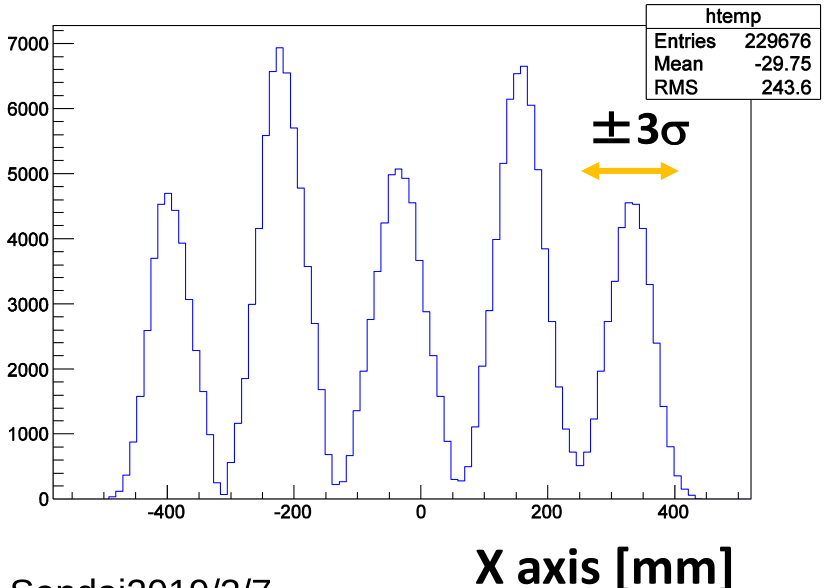
Position reconstruction and crystal selection

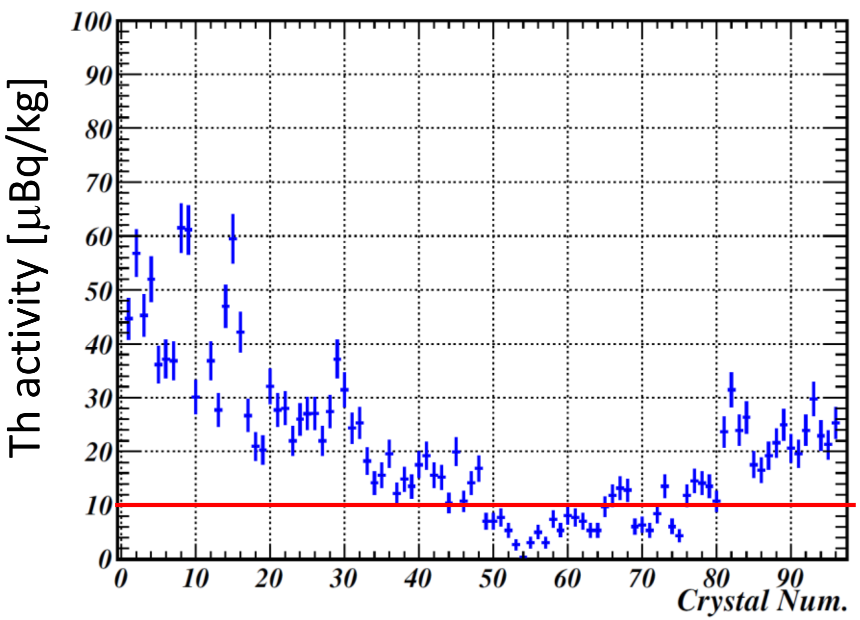
Candles

- Position of each event is reconstructed by weighted mean of observed charge in each PMT.

$$\frac{\sum Npe(i) \times \overrightarrow{PMT(i)}}{\sum Npe(i)}$$

- Crystal separation is ~7σ peak to peak.
- Crystal selection criteria is within 3σ from the peak.
- 27 clean crystals (Th contamination < 10 μBq/kg) out of 96 crystals are selected and the results are compared to all crystals.





Energy Spectra & Event Selecti

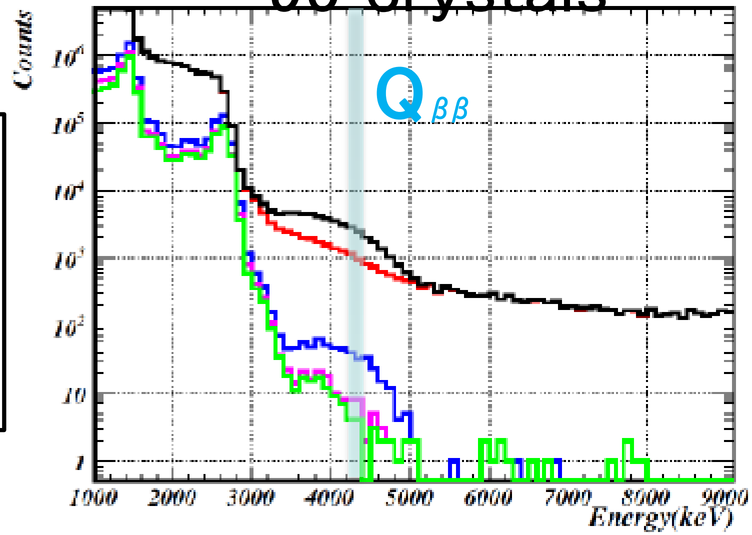
Preliminary

Candles

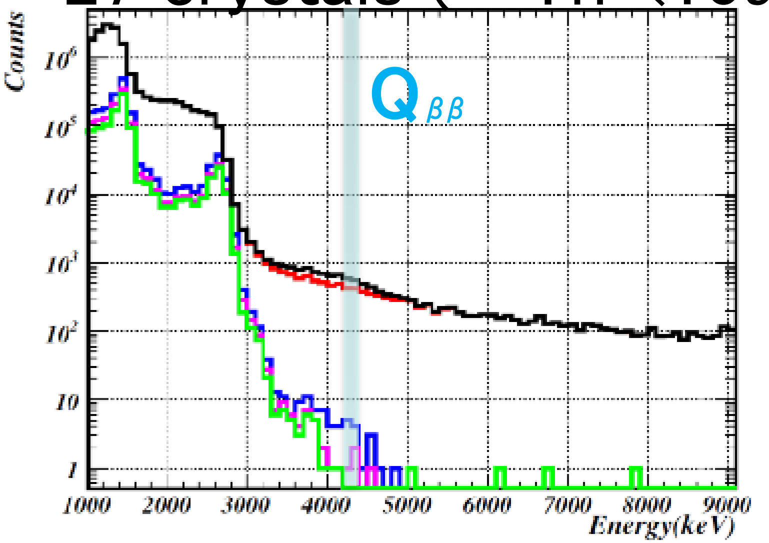
LiveTime : 131 days

Exp. Data
^{212}BiPo Cut
LS Cut
^{208}Tl Cut
Position Cut

95 crystals



27 crystals (^{232}Th <10uBq



# event	95 crystals			27 crystals		
	Qββ	4-5MeV	5.5-6.5MeV	Qββ	4-5MeV	5.5-6.5MeV
LS Cut	115	257	8	12	23	1
^{208}Tl Cut	19	49	6	3	6	1
Position Cut	10	34	6	0	2	1

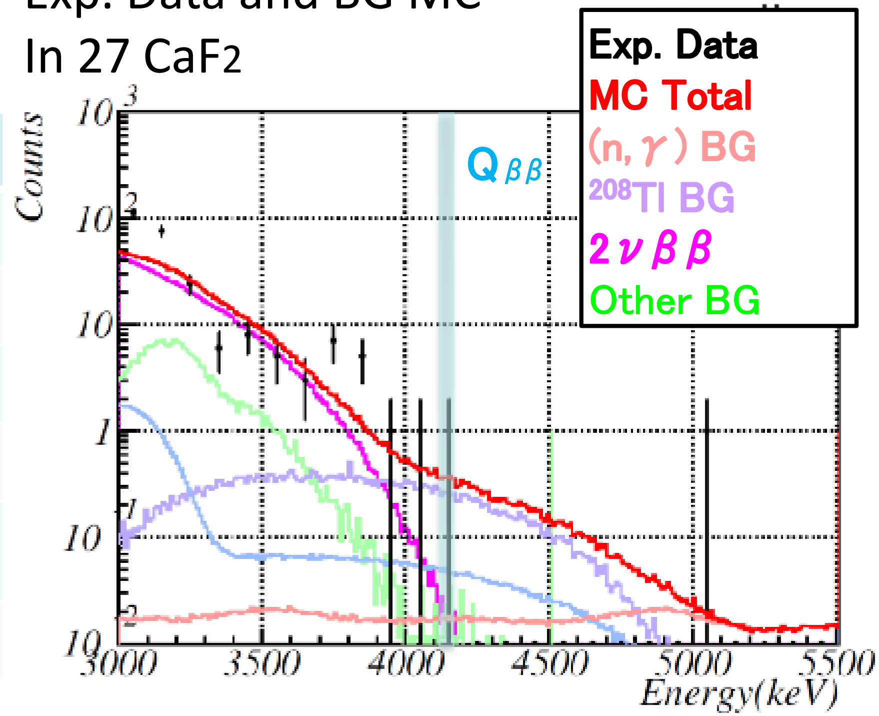
☑ No event in high purity crystals is confirmed.

Results

Preliminary

	95 CaF_2	27 CaF_2
Livetime	131	
$0\nu\beta\beta$ eff.	0.39 ± 0.06	
Event in ROI	10	**0**
Expected BG	~11	~1.2
$T^{1/2}_{0\nu\beta\beta}$ ^{48}Ca (yr)	>3.8x10^{22}	**> 6.2x10^{22}**
Sensitivity (yr)	6.2x10^{22}	**3.6x10^{22}**

Exp. Data and BG MC
In 27 CaF_2



*** ELEGANT IV**

Exposure : 4947kg・d (2yr<)

$0\nu\beta\beta$ eff. : 0.53

$T^{1/2}_{0\nu\beta\beta}$ ^{48}Ca : 5.8x10^{22} yr

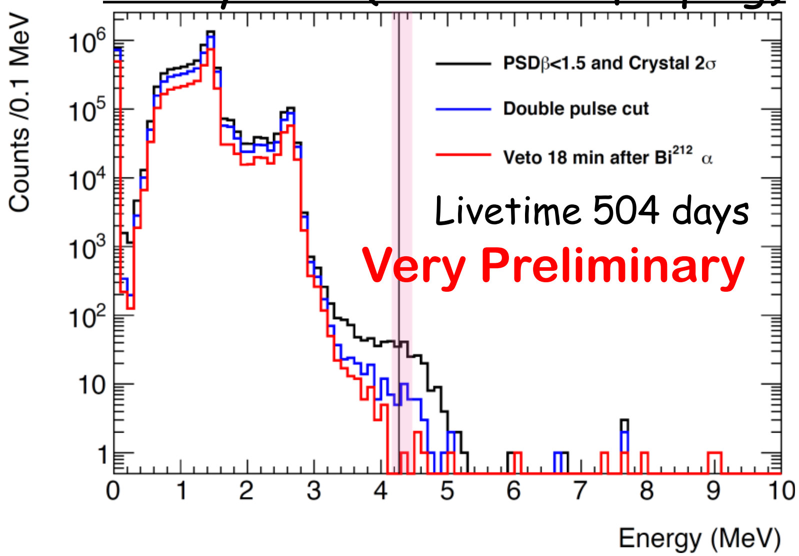
$\chi^2{}_\beta$<1.5, -3σ<SI<1σ
-2σ<position cut<2σ
Pileup cut > 20ns
^{208}Tl cut
-1σ<$0\nu\beta\beta$ window<2σ

CANDLES is now giving the best lifetime limit!

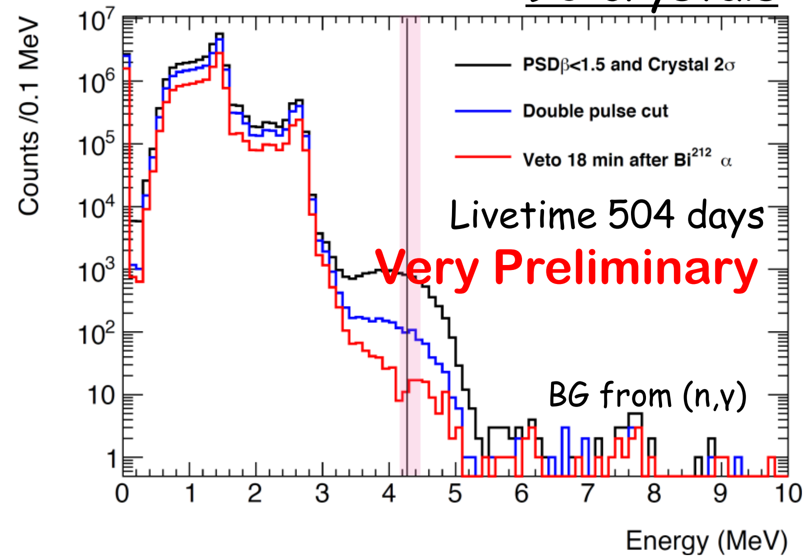
- **further measurement**
- **developments for future**

Updates

21 crystals (^{228}Th < 10 μBq/kg)



93 crystals



- Statistics : 504 days
  - The obtained spectra as expected from BG estimation
  - We have ~ 300 days more statistics (not yet finished analysis)
  - BG from (n,γ) is reduced by ~ 100 with shield installation.
- 0νββ analysis
  - CaF_2 Crystal x 21
    - ^{228}Th contents within crystal < 10 μBq/kg
  - All BG cuts are applied, but cut condition is not optimized yet.
    - LS veto & β-events cut
    - ^{212}Bi-Po sequential decay, ^{208}Tl veto after ^{212}Po-decay (18 min.)

Replace crystals

^{48}Ca enrichment

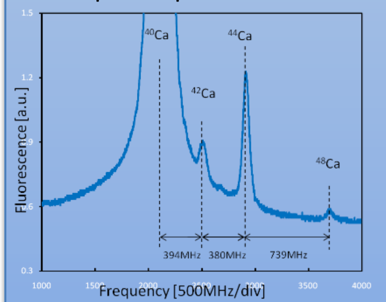
- Natural abundance of ^{48}Ca is 0.187%.
- ^{48}Ca has a room of 500 times improvement (S & S/N) by enrichment
- Commercial ^{48}Ca → too expensive (M$/10g but kg-ton)
- Enrichment is crucial for large volume ^{48}Ca DBD search.
- Challenges in CANDLES:
  - Crown ether resin + chromatography
    - 1.3 times
  - Crown ether + micro reactor
  - Laser separation
  - **Multi-channel counter current electrophoresis (MCCCE)**

Laser Isotope Separation of ^{48}Ca

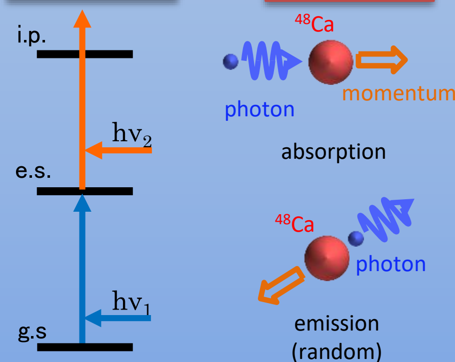
UNIVERSITY OF FUKUI

Principle

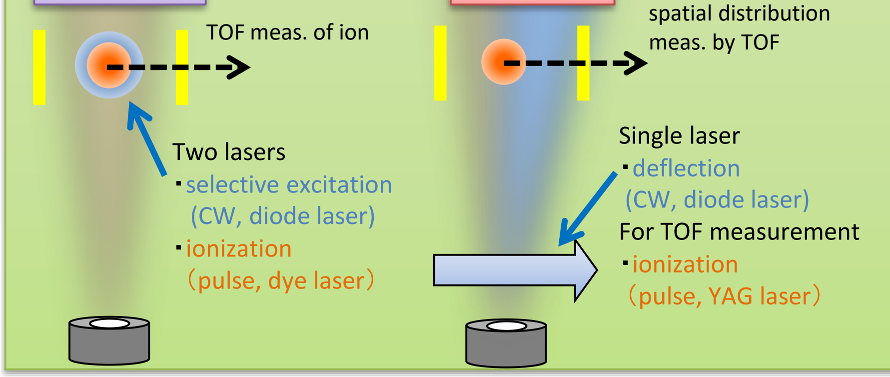
Absorption spectrum of Ca



isotope shift : a few hundred MHz
laser line width : <1 MHz



Experiment

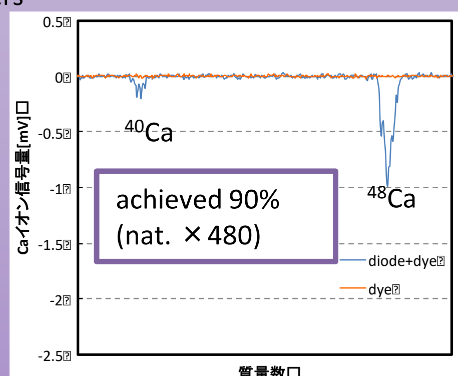


Ionization Method

Optimization of various parameters

- Excitation laser
  - power density
- Ionization laser
  - wavelength
  - power

High concentration
Small duty factor
pulse(10nsec, 10Hz)

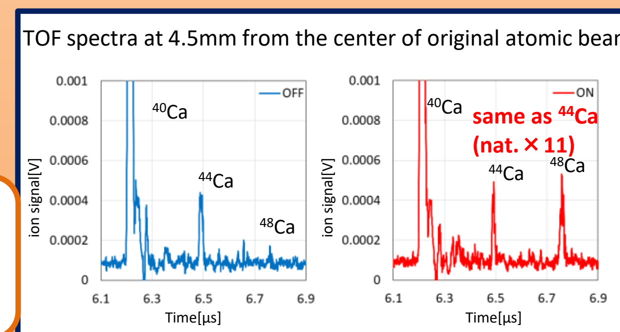


Deflection Method

We confirmed the enrichment of ^{48}Ca in the deflected atomic beam
Optimization of laser power density

Position of the collection plate will be adjusted to the optimal position

Mid. Concentration
Continuous operation



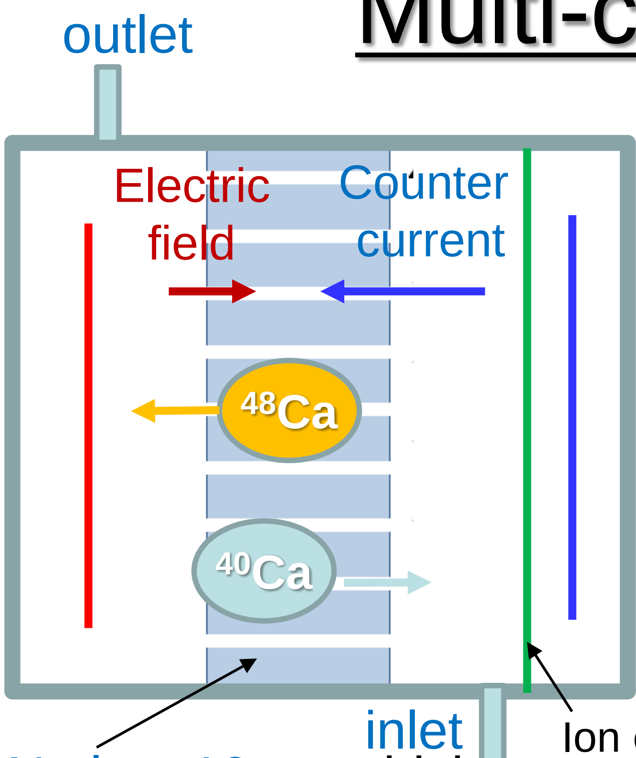
For the future mass production…

We continue R&D of Deflection Method

- Development of collection system of ^{48}Ca
- Increase atomic beam/laser power
- Optimization of various parameters

More details… see K. Matsuoka's Poster

Multi-channel counter current electrophoresis



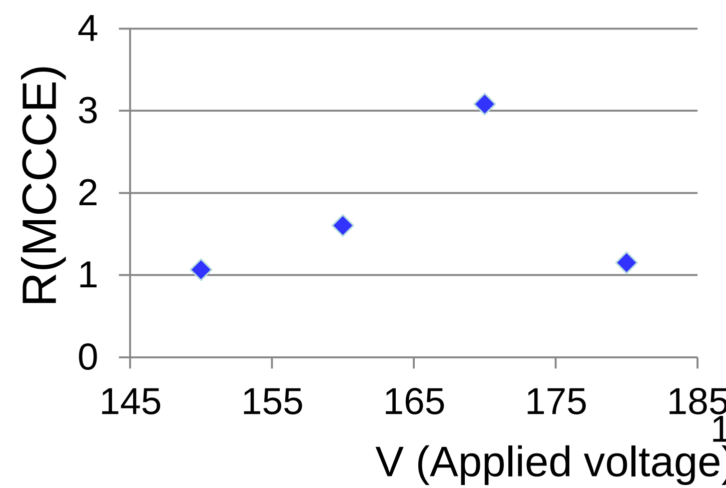
Ion exchange membrane

BN plate 10 mm thick
0.8mmΦ, every 4 mm
BN; Insulator but high thermal conductivity

- Separation using difference of migration speed between ^{40}Ca / ^{48}Ca.
- High power + effective heat removal
  - Migration path: thermal conductor and insulator (BN)
- Pulsed flow to get uniform flow speed

$$R(MCCCE) = \frac{43Ca/48Ca(MCCCE)}{43Ca/48Ca(natural)}$$

Enrichment
(48/43): 3.08
(48/40): 6



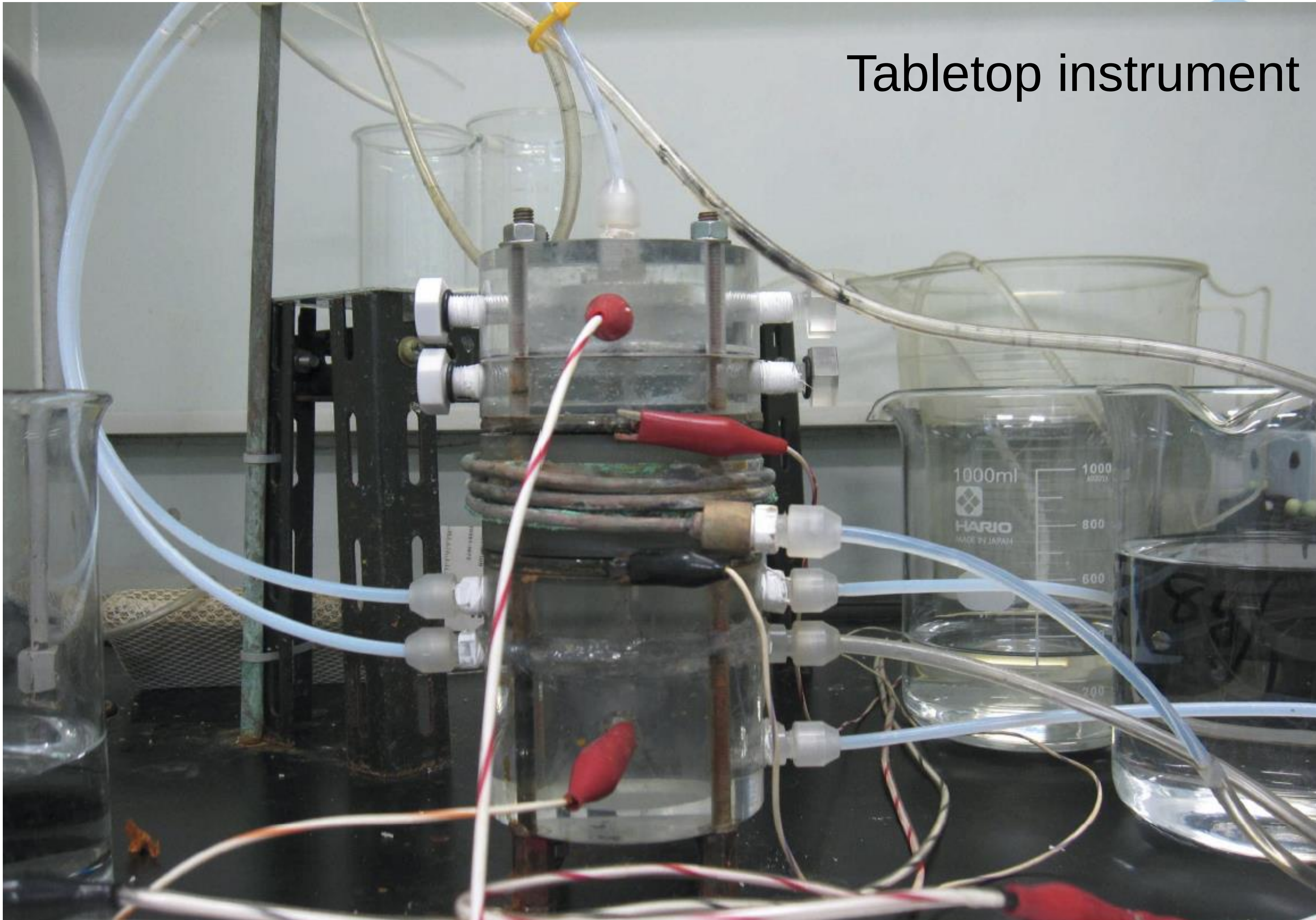
PTEP

Prog. Theor. Exp. Phys. **2015**, 033D03 (10 pages)
DOI: 10.1093/ptep/ptv020

Calcium isotope enrichment by means of multi-channel counter-current electrophoresis for the study of particle and nuclear physics

T. Kishimoto[1,2,*], K. Matsuoka[2], T. Fukumoto[3], and S. Umehara[2]

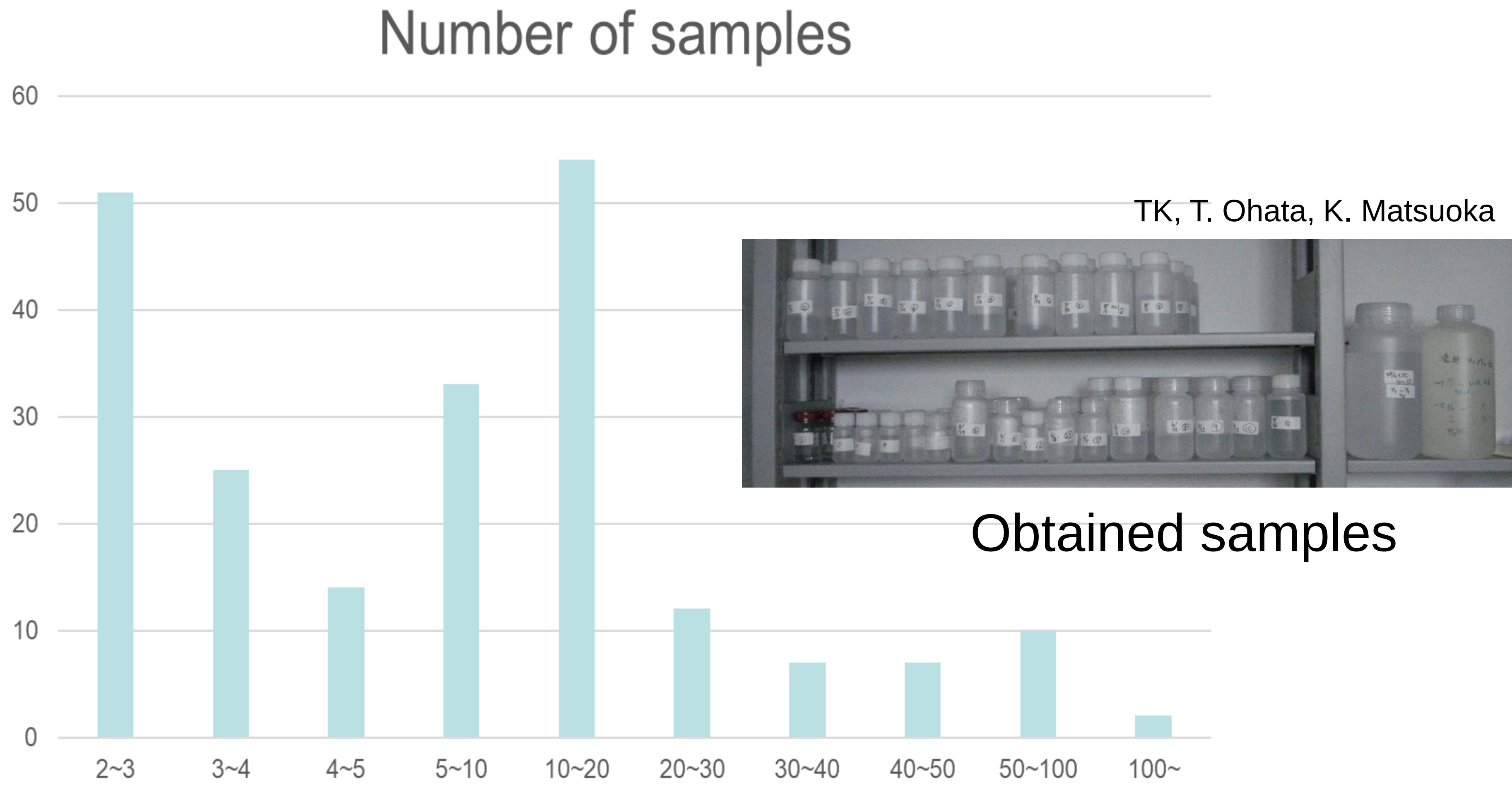
Tabletop instrument



history

- 2012: got MCCCE idea
- 2015: 10mm BN ~3 $^{48}Ca/^{43}Ca$, (6 $^{48}Ca/^{40}Ca$) PTEP
  - then faced difficulty
- 2017 year end
  - After 2 years struggle, results become reproducible
- 2018 February: ~10 times
- 2018 April: modification to give uniform T and E
  - ~a few 10's times
  - May: ~ 100 times
- Condition
  - BN 20 mm

Highly enriched samples



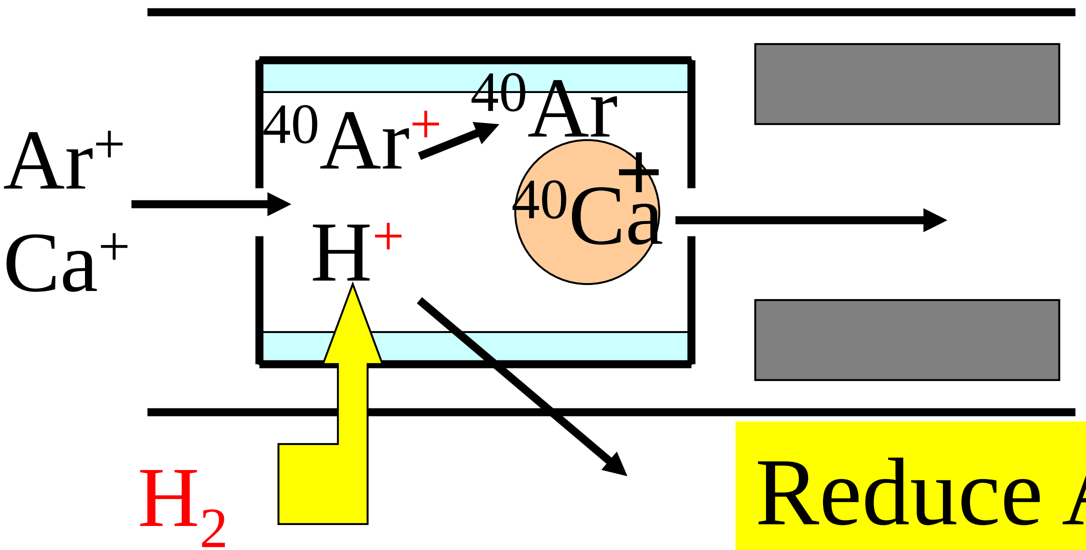
TK, T. Ohata, K. Matsuoka

Obtained samples

$^{48}Ca/^{43}Ca$ (Enrichment/natural)

$^{48}Ca/^{40}Ca$ ratio

- $^{48}Ca/^{43}Ca$ is so high then $^{48}Ca/^{40}Ca$?
  - We usually measure $^{48}Ca/^{43}Ca$, since no interference
  - Similar nat. ab. ^{48}Ca: 0.187%, ^{43}Ca: 0.135%
- ^{40}Ar forbids ^{40}Ca measurement in ICP-MS
  - Reaction(collision)-cell ICP-MS + reaction-gas (H_2, He, NH_3)



$Ar^+ + H \rightarrow H^+ + Ar$

Reduce $Ar^+ \rightarrow {}^{40}Ca$

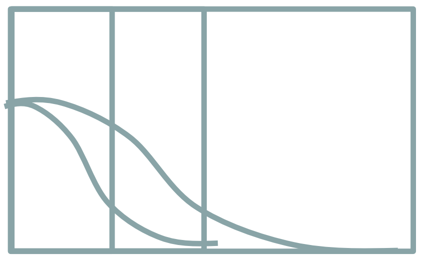
Enrichment

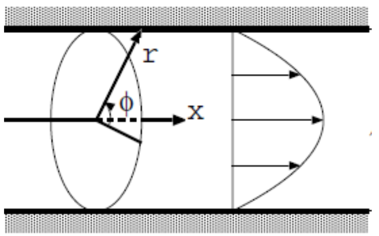
Candles

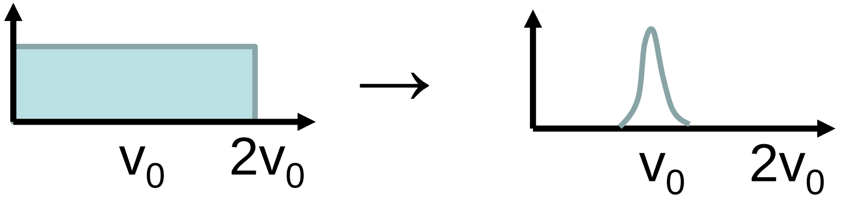
- Migration distance $l = \mu E t$
  - μ : mobility difference $\Delta\mu = \mu(^{40}Ca) - \mu(^{48}Ca)$
  - Separation $\Delta\ell = \Delta\mu E t$
- Diffusion: deteriorate separation
  - Diffusion constant : D $\sigma = \sqrt{2Dt}$
- Enrichment $\frac{\sigma}{\Delta\ell} \propto \frac{1}{E\sqrt{t}} \propto \frac{1}{E\sqrt{\ell}}$ increase of E t (ℓ)
- Yield ~5% (concentration) $Y = \frac{\Delta v}{v} \sim 5\% \sim \frac{\Delta\mu}{\mu}$
  - Migration speed difference ~ 5%
  - Long Migration distance ~ 20/0.05 ~ 400 mm
  - Enrichment and yields are consistent

Enrichment

- Enrichment → Reduction of ^{40}Ca
  - 10mm BN 1/6 → σ~10mm
  - 20mm BN 1/50 → σ~10mm
  - Width
    - Hagen-Poiseuille flow → (send pause, I sec)
    - Every 2mm times 200 → σ small (1/√200)







$$\sigma = \frac{400}{\sqrt{12}} \sim 115mm$$

$$\sigma = \frac{2}{\sqrt{12}}\sqrt{200} \sim 8mm$$

Next step

- 40mm BN 1/300 → σ~14mm
  - 99.7% enrichment is possible
  - Practical goal is set to 80% enough for DBD

$$\sigma = \sqrt{BN_{thickness}}$$

80%

Production of enriched ^{48}Ca

Candles

- Current system
  - 16(10)% ($^{48}Ca/^{40}Ca$)
  - 12 cm^2, 0.01 N → 0.1mg/day
- Next system
  - 80% or more
  - 1.2m^2, 0.03 N → 0.3g/day → 100g/year
  - Tons; require plant → further needs
    - Our field
    - Other fields (beam, medical use,..)

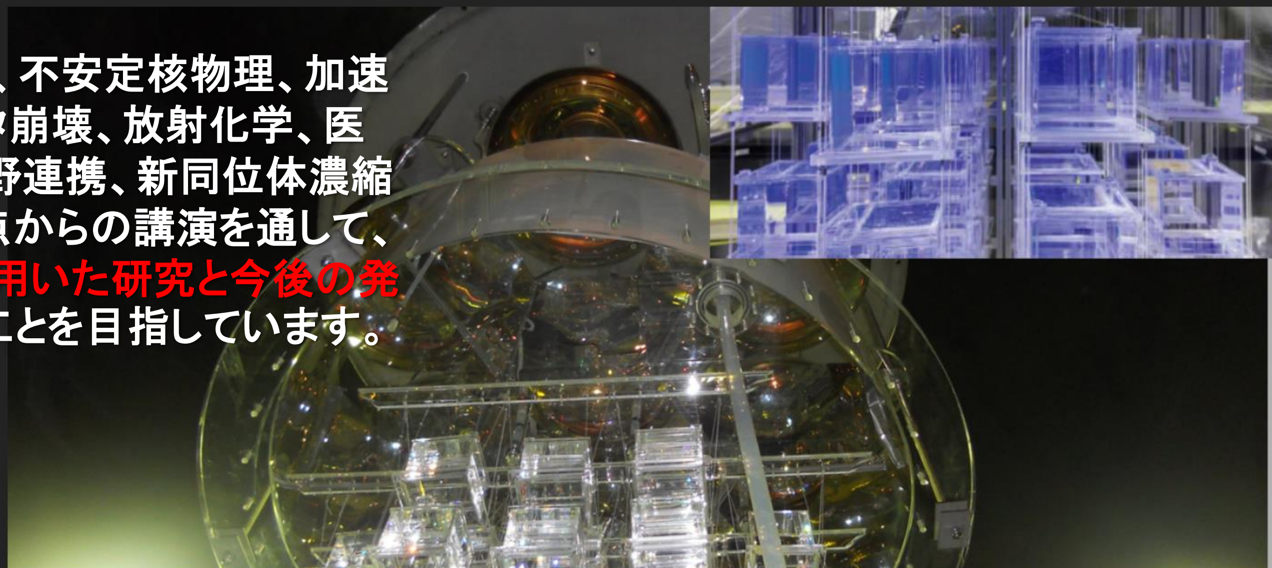
    } plant
  - CANDLES works for 80%

研究会 「同位体濃縮と基礎科学」

Mar. 21 Osaka

"Workshop for Isotope Enrichment and Basic Science"

本研究会では、不安定核物理、加速器、二重ベータ崩壊、放射化学、医学利用、異分野連携、新同位体濃縮法といった視点からの講演を通して、**濃縮同位体を用いた研究と今後の発展を概観**することを目指しています。



研究会概要

日時： 2019年3月21日（木）12:25～17:00
受付開始は12時です。

会場： 大阪OBPクリスタルタワー20階A会議室
http://www.crystaltower.jp/map.html

参加料： 無料

○会議のプログラム

12:25–	岸本忠史	「はじめに」
12:30–	中村隆司（東工大理）	「ビーム物理と濃縮同位体」
13:00–	宮武宇也（KEK）	「超重核質量の直接測定と48Ca」
13:20–	依田哲彦（RCNP）	「加速器技術と濃縮同位体」
13:40–	野海博之（RCNP/KEK）	「ハドロン物理と濃縮同位体」
14:00–	井上邦雄（東北大RCNS）	「136Xeの二重ベータ崩壊」
14:30–	休憩	
15:00–	篠原厚（阪大理）	「放射化学と超重元素」
15:30–	中野貴志（RCNP）	「加速器が拓くイノベーション」
16:00–	畑澤順（阪大医）	「放射性同位体の医学利用」
16:30–	岸本忠史（RCNP）	「新同位体濃縮法と基礎科学」

Development for CaF_2 Scintillating Bolometer:

- Sei Yoshida, ….

- Collaborative research with Korean colleague
  Yong-Hamb Kim (IBS & KRISS)
  Minkyu Lee (KRISS)
  Inwook Kim
  Do-Hyoung Kwon
  Hyejin Lee
  Hye-Lim Kim

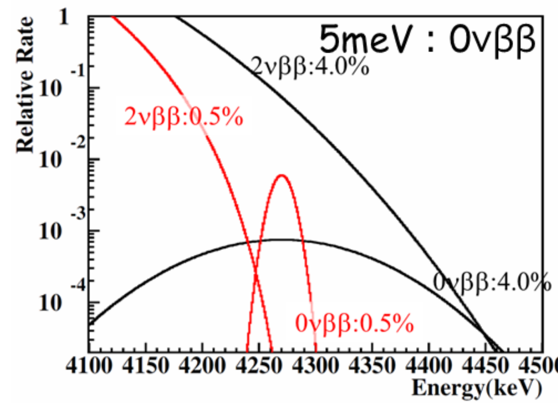
Background Candidates for CaF_2

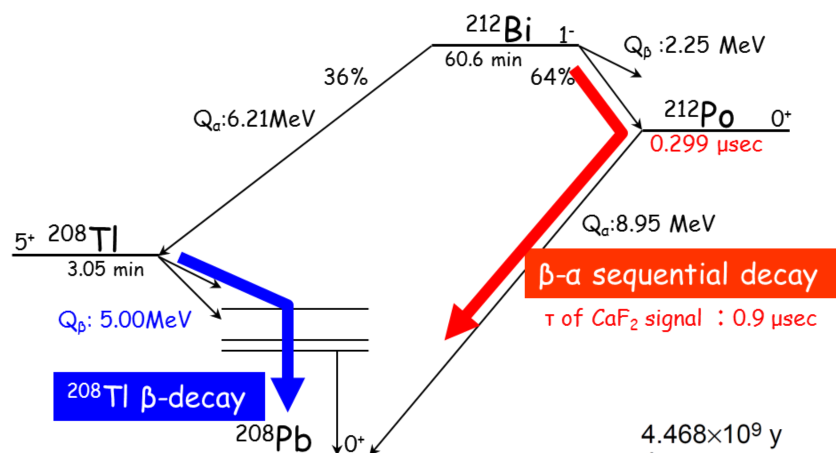
- Tail of $2\nu\beta\beta$ spectrum
  - Improving energy resolution

Scintillator → Bolometer

- ^{48}CaXX internal radioactivities
  - Th-chain (β-α sequential decays) → Bolometer
  - Th-chain (^{208}Tl)
    → Segmentation, Multi-crystal
  - Environmental neutrons
    - Improving resolution + Multi-crystal

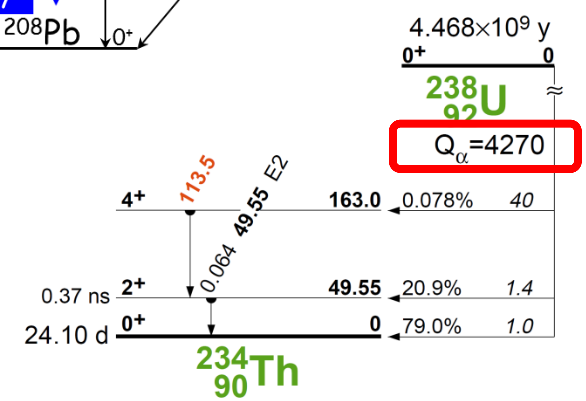
Possible to further reduce
the BG by developing Bolometer





- But... new BG candidate
  - Q value of ^{48}Ca : 4267.98(32) keV @ arXiv:1308.3815
  - Q-value of ^{238}U (α-decay) : 4270 keV

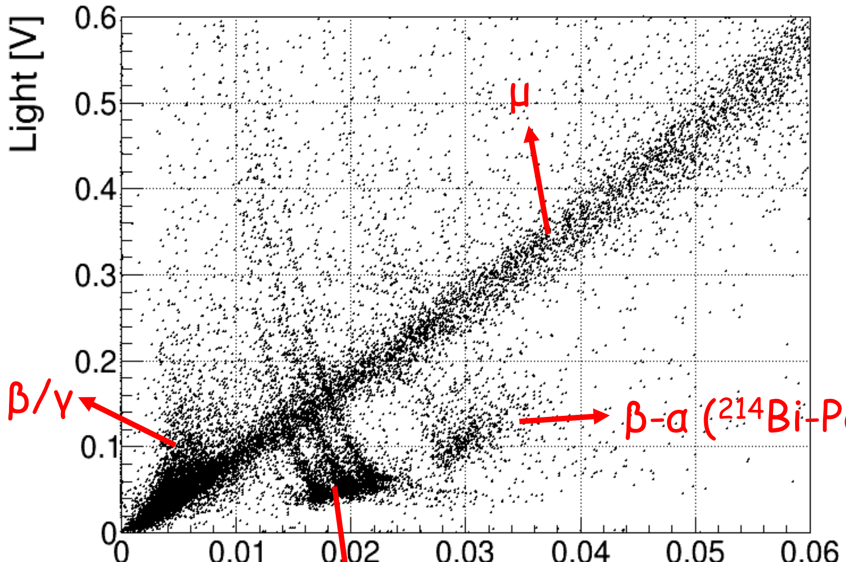
  Impossible to avoid
  → required particle ID

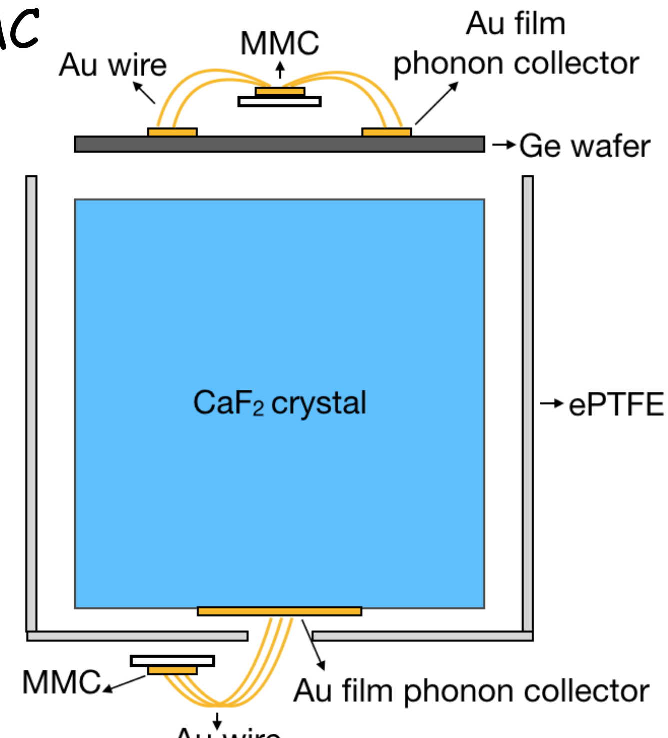


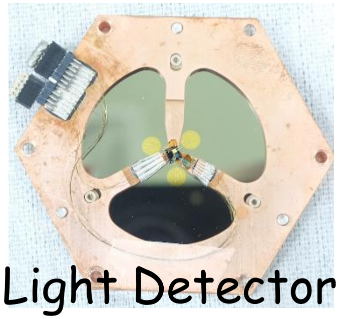
→ **Developing CaF_2 Scintillating Bolometer**

CaF_2(pure) Scintillating Bolometer

- First Challenge using CaF_2(pure) and MMC
  - Crystal: CaF_2(pure)
    - Volume: 300g (5cmφ × 5cm)
    - Emission peak : 280nm
    - Light output: 25,000 photons/MeV



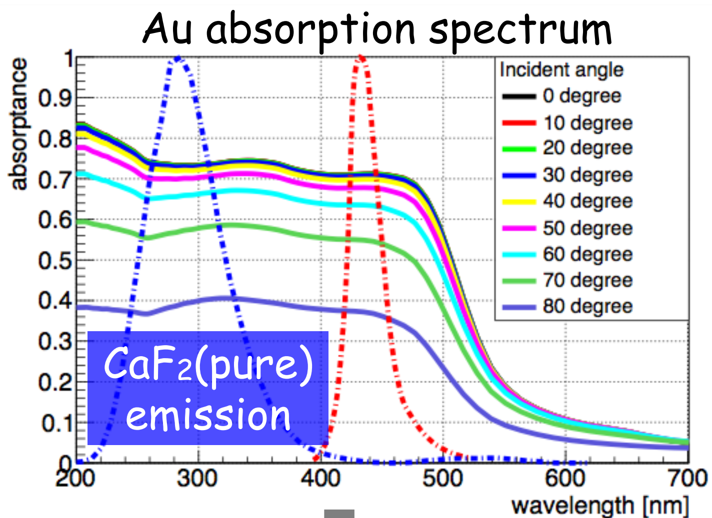


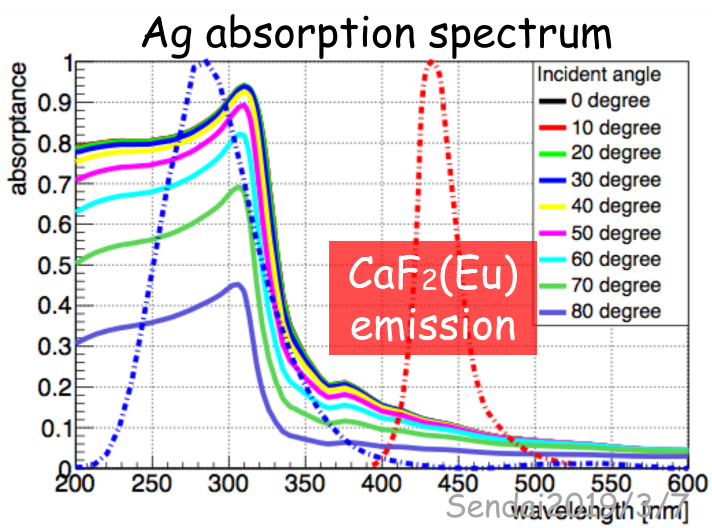


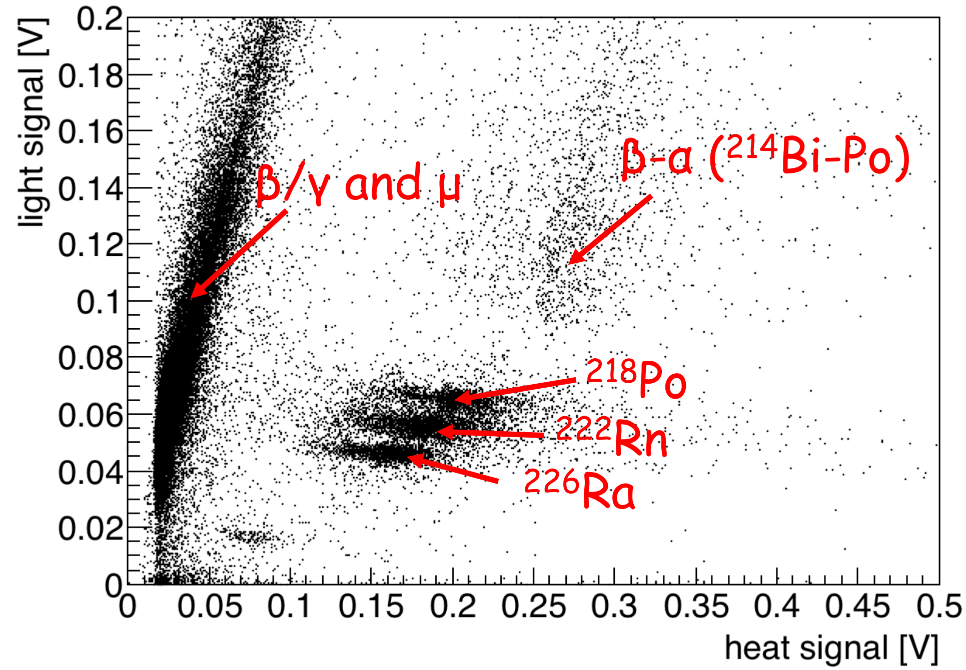
- Problem
  - UV scintillation of CaF_2 is absorbed on Au-deposit for heat signal. There is position dependence of scintillation absorption. ➔ make worse E-resolution.

CaF2(Eu) scintillating Bolometer

- New trial to overcome UV absorption
  - CaF_2(Eu) +Ag-deposit instead of CaF_2(pure) + Ag-deposit





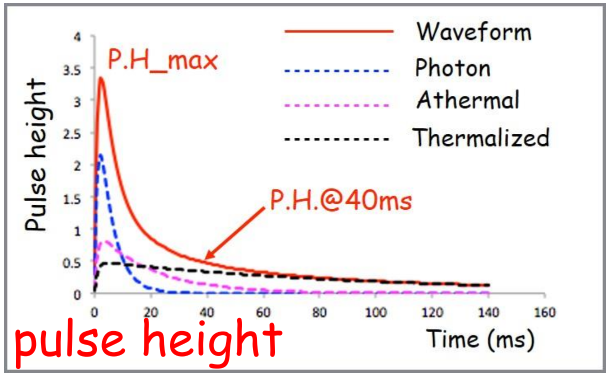


- ✓ Improved light signal properties.
- ✓ In the heat channel, peaks of α's are widely spread.
  (due to position dependence)
- ✓ Due to doping Eu ?

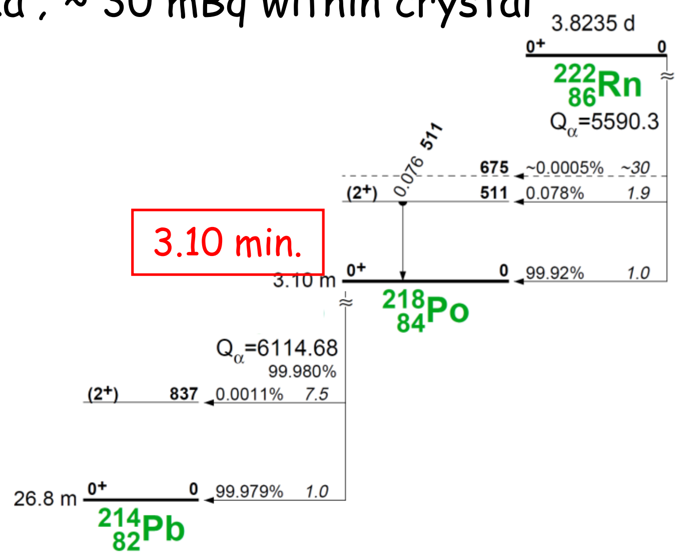
see Xiaolong Li's Poster

E-Resolution w.o. position dependence

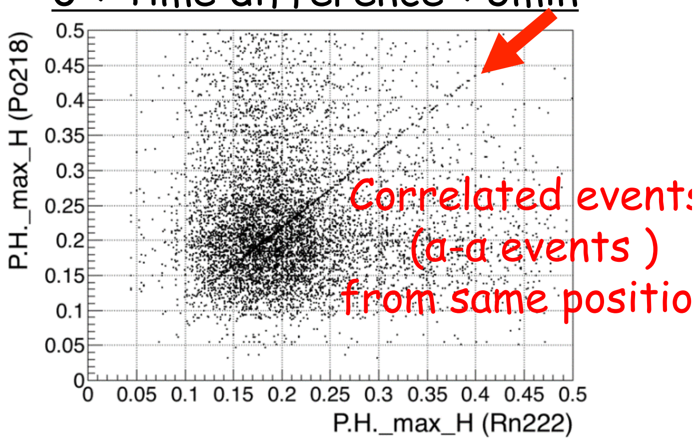
- Evaluate energy resolution w/o position dependence
  - We use contaminated CaF_2 crystal for R&D, ^{226}Ra ; ~ 30 mBq within crystal
  - Delayed coincidence ($^{222}Rn \rightarrow {}^{218}Po \rightarrow {}^{214}Pb$)
  - Apply energy , PID parameter, Δtime cuts

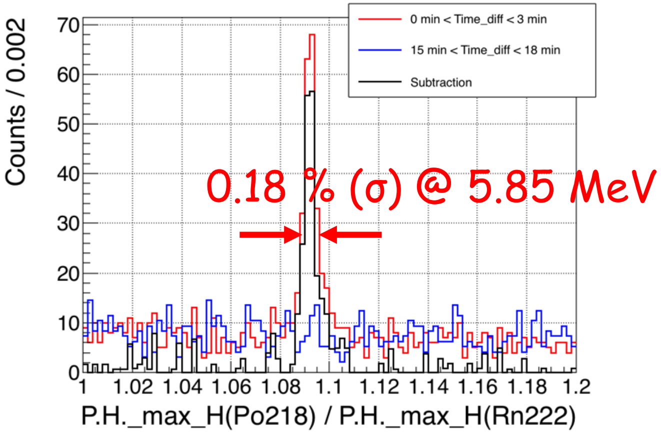


using maximum pulse height



0 < Time difference < 3min



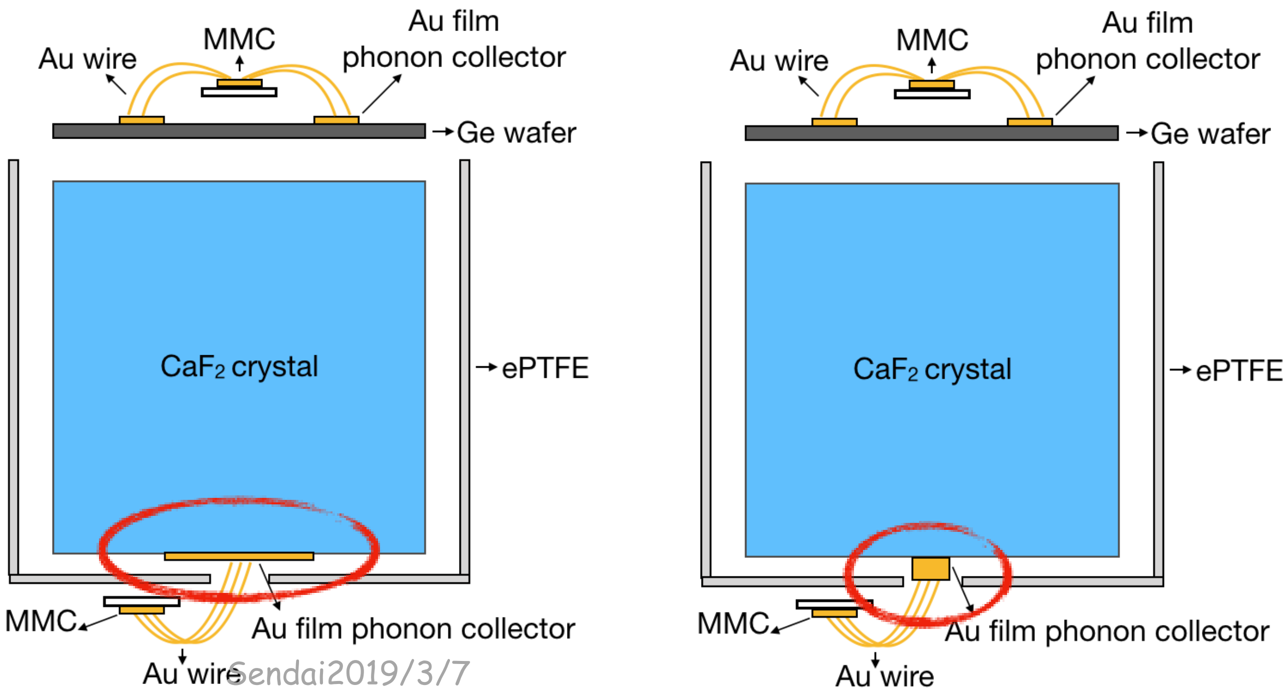


Evaluated energy resolution without position dependence, < 0.2% (σ) @ $Q_{\beta\beta}$

Prospects for the development

- Improving E-resolution of CaF_2(pure) scintillating bolometer
  - Radio-pure CaF_2(pure) crystal had been developed.
  - Doping Eu may affect phonon propagation in CaF_2 crystal.

- New trial in the next step
  - CaF_2(pure) crystal with <u>smaller but thicker Au-deposit</u> phonon collector.
    - Smaller → reducing scintillation absorption effect
    - Thicker → increasing the strong electron-phonon interaction.



CANDLES project

Candles

- CANDLES:
  - CANDLES III(UG): current detector
    - First result gives the best limit
    - Measurement and analysis underway
    - CaF_2 crystals with low BG (will be replaced)
- Future prospect
  - Enrichment ^{48}Ca
    - MCCCE works for future tons
  - Bolometer
    - CaF_2 Scintillating Bolometer

CANDLES
to normal hierarchy
Still lot to do
Promising

Candles

Thank you !!

CANDLES for the Study of ^{48}Ca double beta decay and its future prospect

T. Kishimoto
Osaka University

CANDLES Collaboration

Osaka University, Graduate school of science
岸本忠史、吉田斉、鈴木耕拓、角畑秀一、Wang Wei、Chan Wei Min、Van Trang、
石川貴志、田中大樹、田中美穂、土井原正明、前田剛、太畑貴綺、鉄野高之介

Osaka University, RCNP
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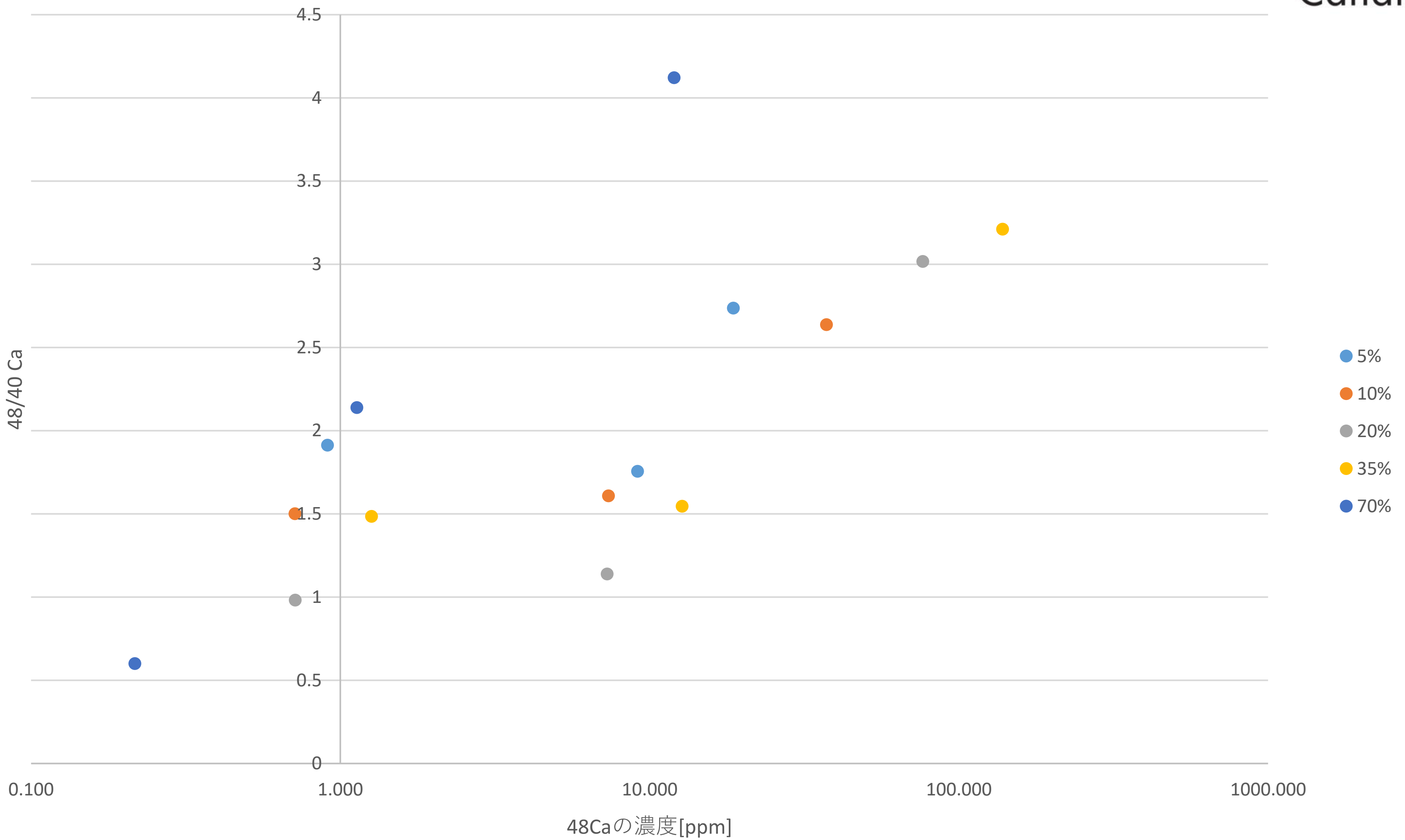
Fukui University
玉川洋一、小川泉、中島恭平、川村篤史、富田翔悟、藤田剛志、原田知優、坂本康介、
吉澤真敦、犬飼祐司

Tokushima University
伏見賢一

Osaka Sangyo University
硲隆太、中谷伸雄

Tsukuba University
飯田崇史

Candles


48/40 Ca
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0.100
1.000
10.000
100.000
1000.000
48Caの濃度[ppm]
5%
10%
20%
35%
70%