CANDLES計画と世界の二重ベータ実験の状況

小川　泉

Double beta decay

- ニュートリノを放出する二重ベータ崩壊
  - 標準模型内；実験的に確認済み
- ニュートリノ放出を伴わない二重ベータ崩壊
  - 未確認　$T_{1/2}^{0\nu\beta\beta} \geqq 10^{25}$ years
    - cf.　H.V. Klapdor-Kleingrothaus *et al.*　$T_{1/2}^{0\nu\beta\beta} = 1.19 \times 10^{25}$ years
  - 確認されると
    - ニュートリノはマヨラナ粒子である
    - レプトン数保存則の破れ　⟺　物質／反物質の非対称性
    - 有効マヨラナニュートリノ質量

$$\left[T_{1/2}^{0\nu}(0^+ \rightarrow 0^+)\right]^{-1} = G^{0\nu}(E_0, Z)\left|M_{0\nu}\right|^2 \boxed{\langle m_\nu \rangle^2}$$

次世代検出器

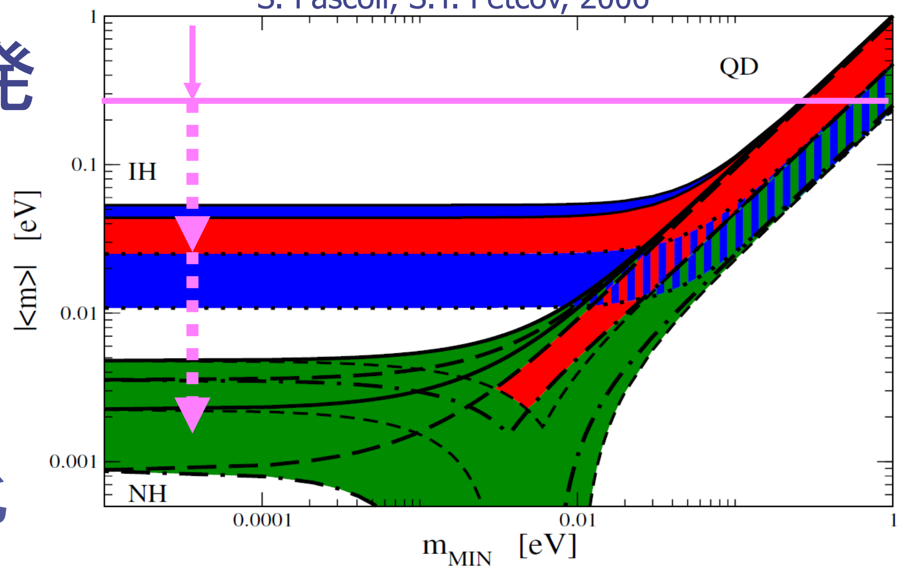
- 高感度検出器の開発
  - 大型検出器
    - $N_{\mathrm{target}} > 10^{26}$
  - 低バックグラウンド化
    - BGがある場合

$$\langle m_\nu \rangle = (2.50 \times 10^{-8}\ \mathrm{eV}) \left[\frac{W}{fx\epsilon G^{0\nu}|M^{0\nu}|^2} \right]^{1/2} \left[\frac{b\Delta E}{\boxed{MT}} \right]^{1/4}$$

    - BGが無視できる場合

$$\langle m_\nu \rangle = (2.67 \times 10^{-8}\ \mathrm{eV}) \left[\frac{W}{fx\epsilon G^{0\nu}|M^{0\nu}|^2} \right]^{1/2} \times \frac{1}{\sqrt{\boxed{MT}}}$$

S. Pascoli, S.T. Petcov, 2006



プロジェクト

◆二重ベータ崩壊実験

終了

HDM実験(^{76}Ge)
現時点でのニュートリノ質量で世界最高感度
メンバーの一部が発見したとの報告　？？

稼働中

NEMO3(^{100}Mo) ⇒ SuperNEMO(^{82}Se)
電子の飛跡を観測　検出効率低い
CUORICINO(^{130}Te) ⇒ CUORE(^{130}Te)
ボロメータとして観測　次期計画に移行中

計画・建設中

国外
上記以外にMajorana(^{76}Ge), GERDA(^{76}Ge), COBRA(^{116}Cd), EXO(^{136}Xe), NEXT(^{136}Xe), SNO+(^{150}Nd)など
国内
CANDLES(^{48}Ca), MOON(^{100}Mo), KamLAND+(^{136}Xe), XMASS(^{136}Xe), DCBA(^{150}Nd)

重要開発項目
- 検出器の大型化
- バックグラウンドの低減

Overview of Experiments

Name	Nucleus	Mass*	Method	Location	Time line
Operational & recently completed experiments					
CUORICINO	Te-130	11 kg	bolometric	LNGS	2003-2008
NEMO-3	Mo-100/Se-82	6.9/0.9 kg	tracko-calo	LSM	until 2010
Construction funding					
CUORE	Te-130	200 kg	bolometric	LNGS	2012
EXO-200	Xe-136	160 kg	liquid TPC	WIPP	2009 (comiss.)
GERDA I/II	Ge-76	35 kg	ionization	LNGS	2009 (comiss.)
SNO+	Nd-150	56 kg	scintillation	SNOlab	2011
Substantial R&D funding / prototyping					
CANDLES	Ca-48	0.35 kg	scintillation	Kamioka	2009
Majorana	Ge-76	26 kg	ionization	SUSL	2012
NEXT	Xe-136	80 kg	gas TPC	Canfranc	2013
SuperNEMO	Se-82 or Nd-150	100 kg	tracko-calo	LSM	2012 (first mod.)
R&D and/or conceptual design					
CARVEL	Ca-48	tbd	scintillation	Solotvina	
COBRA	Cd-116, Te-130	tbd	ionization	LNGS	
DCBA	Nd-150	tbd	drift chamber	Kamioka	
EXO gas	Xe-136	tbd	gas TPC	SNOlab	
MOON	Mo-100	tbd	tracking	Oto	
Other decay modes					
TGV	Cd-106		ionization	LSM	operational

***: mass of DBD-isotopes; detector & analysis inefficiencies NOT included! Range: 18% to ~90%**

S. Schönert, TAUP 2009

Experimental figure of merit

Candles

$$F = \frac{\varepsilon\,\boxed{f_x G^{0\nu}\left|M^{0\nu}\right|^2}}{W}\sqrt{\frac{MT}{\boxed{b}\,\Delta E}}$$

ε : detection efficiency

f_x : isotopic abundance

W : molecular weight

$G^{0\nu}$: phase space factor

$M^{0\nu}$: nuclear matrix element

M : source mass

T : measuring time

b : background rate in c/(keV･kg･yr)

ΔE : energy resolution

二重ベータ崩壊核

Candles

- 二重ベータ崩壊のQ値
  - 自然放射能の影響（バックグラウンド）

$$E_{\gamma}^{\max} = 2.6\,\mathrm{MeV}\ (^{208}\mathrm{Tl}) \qquad E_{\beta}^{\max} = 3.27\,\mathrm{MeV}\ (^{214}\mathrm{Bi})$$

- 自然存在比
  - enrichment

isotope	Q (keV)	ab.(%)	isotope	Q (keV)	ab.(%)	isotope	Q (keV)	ab.(%)	isotope	Q (keV)	ab.(%)
46Ca	990.4	0.004	98Mo	112	24.13	130Te	2529	34.08	170Er	654	14.93
48Ca	4272	0.187	100Mo	3034	9.36	134Xe	830	10.44	176Yb	1087	12.76
70Zn	1001	0.62	104Ru	1300	18.62	136Xe	2468	8.87	186W	488	28.43
76Ge	2039	7.61	110Pd	2000	11.72	142Ce	1417	11.114	192Os	414	40.78
80Se	134	49.61	114Cd	537	28.73	146Nd	70	17.2	198Pt	1047	7.163
82Se	2995	8.73	116Cd	2805	7.49	148Nd	1929	5.7	204Hg	416	6.87
86Kr	1256	17.3	122Sn	366	4.63	150Nd	3368	5.6	232Th	842	100
94Zr	1144	17.4	124Sn	2287	5.79	154Sm	1251	22.75	238U	1145	99.28
96Zr	3350	2.8	128Te	867	31.74	160Gd	1730	21.86			

$Q > 3.3$ MeV ; $Q_{\beta}(^{214}\mathrm{Bi})=3.27$ MeV

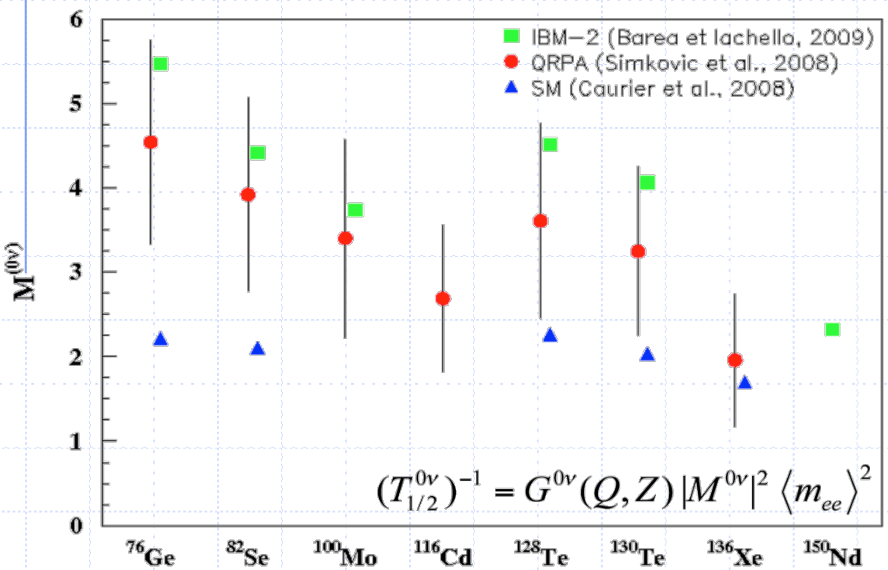
$Q > 2.0$ MeV

V.I. Tretyak and Y.G. Zdesenko 2002

核行列要素(1)

S. Schönert, TAUP 2009

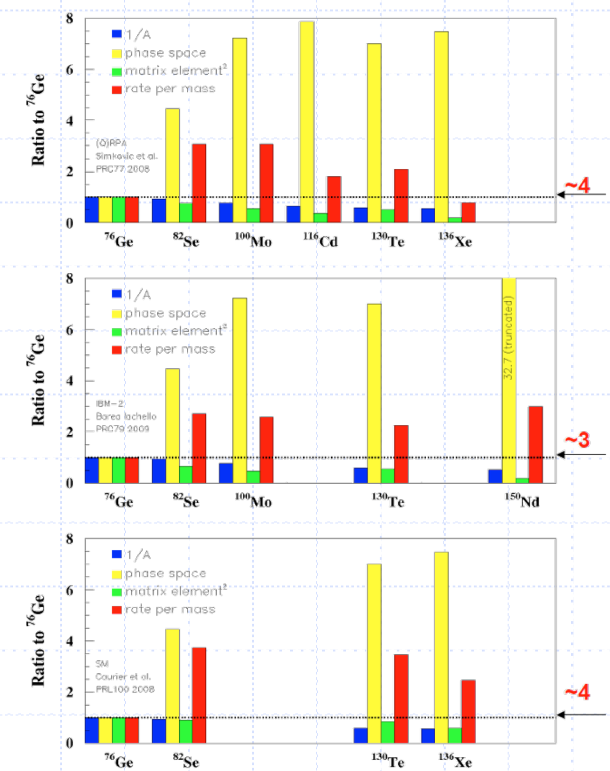
Comparison of DBD isotopes:
Recent calculations of nuclear matrix elemen



QRPA
(Simkovic et al.
PRC 77, 2008)

IBM2
(Barea and
Iachello, PRC
79, 2009)

SM
(Caurier et al.,
PRL 100, 2008)



核行列要素(2)

Interacting Shell Model　(Caurier et al., PRL 100, 2008)

	$M^{(0\nu)}$	$\langle m_\nu \rangle$
$^{48}Ca \rightarrow {}^{48}Ti$	0.59	1.07
$^{76}Ge \rightarrow {}^{76}Se$	2.22	0.91
$^{82}Se \rightarrow {}^{82}Kr$	2.11	0.46
$^{124}Sn \rightarrow {}^{124}Te$	2.02	0.48
$^{128}Te \rightarrow {}^{128}Xe$	2.26	1.68
$^{130}Te \rightarrow {}^{130}Xe$	2.04	0.37
$^{136}Xe \rightarrow {}^{136}Ba$	1.70	0.47

不定性あり
数種の原子核での測定が必要

Experimental figure of merit

Candles

$$F = \frac{\boxed{\varepsilon}\, f_x G^{0\nu} \left| M^{0\nu} \right|^2}{\boxed{W}} \sqrt{\frac{MT}{\boxed{b\Delta E}}}$$

f_x : isotopic abundance

ε : detection efficiency

W : molecular weight

$G^{0\nu}$: phase space factor

$M^{0\nu}$: nuclear matrix element

M : source mass

T : measuring time

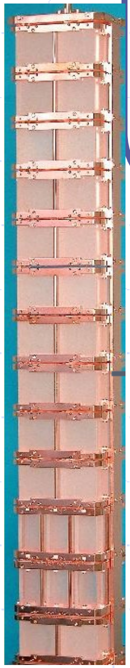
b : background rate in c/(keV･kg･yr)

ΔE : energy resolution

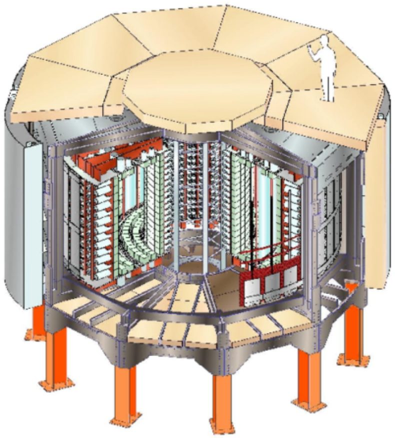
検出器のタイプによる分類

Candles

- Source = detector
  - Semiconductor ($\bigcirc \Delta E$)
    - COBRA
    - Majorana
    - GERDA
  - Bolometer ($\bigcirc \Delta E$)
    - CUORE/CUORICINO
  - Scintillator
    - CANDLES
    - KamLAND
    - SNO+



- Source ≒ detector
  - Time Projection, tracking & Drift Chambers ($\bigcirc\ b$, $\times\ \varepsilon$)
    - NEMO/Super-NEMO
    - DCBA
    - EXO



バックグラウンドの比較

Candles

- 検出器サイズあたりのBackground rate

$b\Delta E$ (counts/kg/year)

の比較

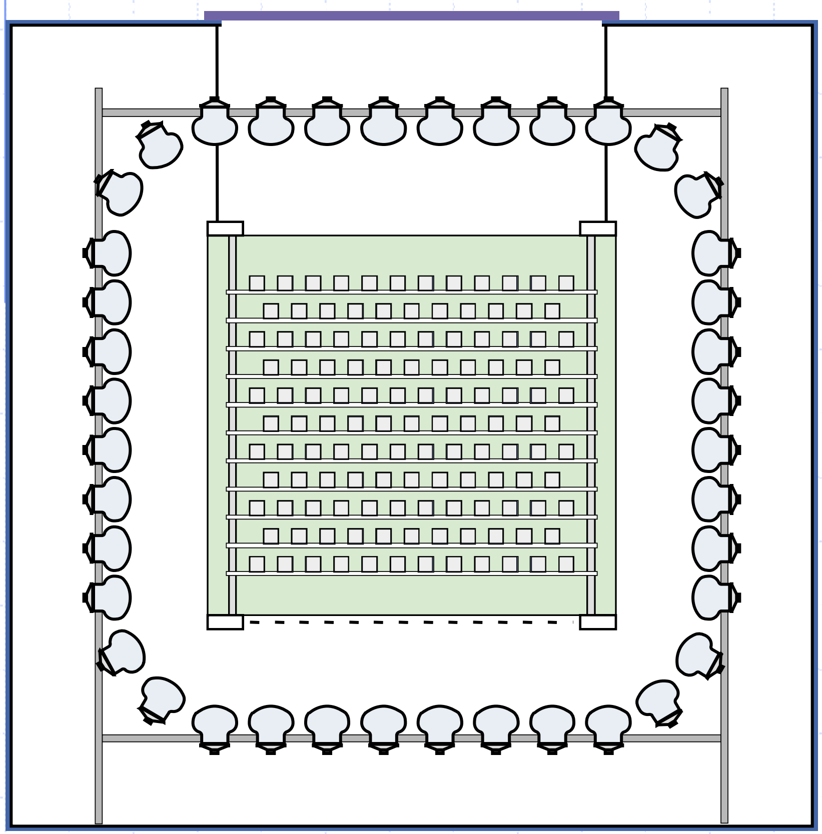
Target	Project	Status	Abund. (%)	Background rate (counts/kg/year)
^{48}Ca	ELEGANT VI	Finish	0.187	0 (measured) 0.075 (expected)
	CANDLES III	Constr.	0.187	5x10^{-4} (expec.)
^{76}Ge	HDM	Finish	~86	0.61 (meas.)
^{130}Te	CUORICINO	Finish	33.9	2.4 (meas.)
	CUORE	Const. R&D	33.9	0.8 (CUORE-0;expec.) 10^{-2}~10^{-3}(Goal)
^{136}Xe	EXO-200	Constr.	~80	0.1 (expec.)

CANDLES Project

CANDLES

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

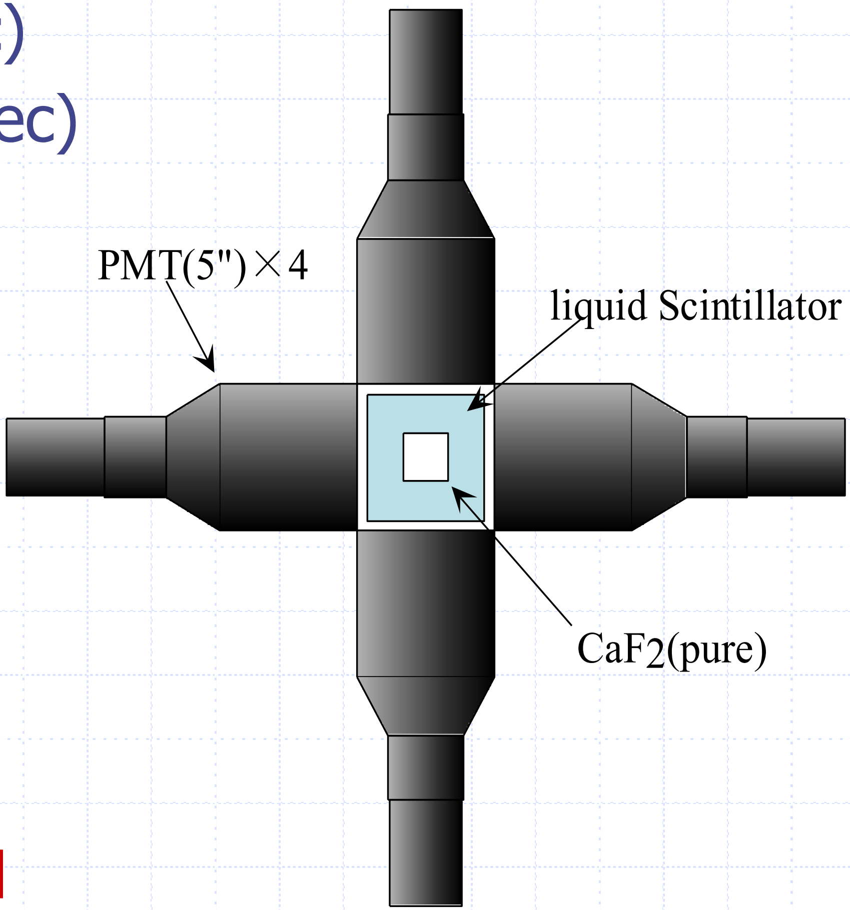
BG reduction / rejection — 4π active shield —

CANDLES I

- POP (Proof of Principle) Detector

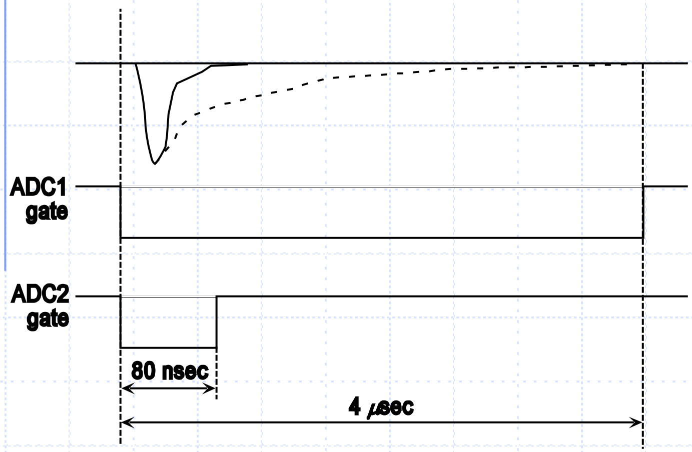
- CaF_2(pure) crystal (~1 μsec) in liquid scintillator (~10 nsec) (with w.l. shifter) viewed by 4 PMTs (5 inch)
- LS : mineral oil
  + DPO (3 g/l)
  + Bis-MSB (0.3 g/l)

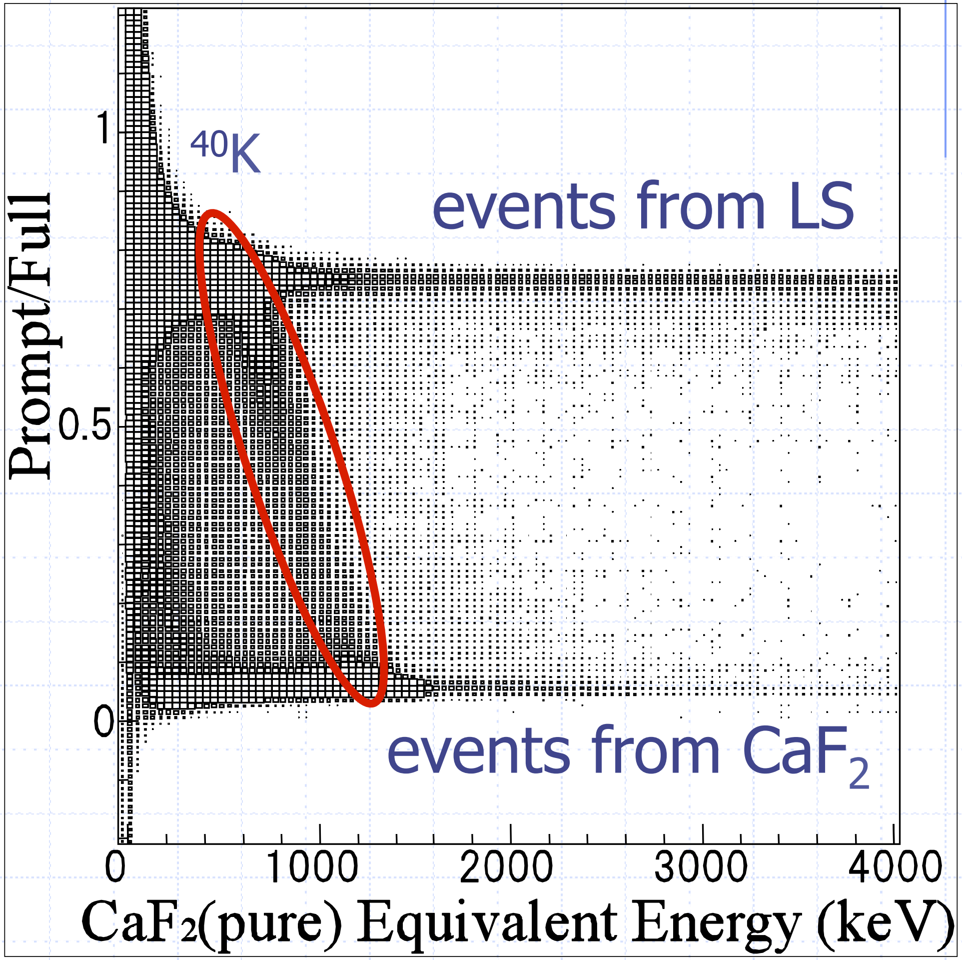
→ 4π active shield



Performance Test (4π active shield)

2 ADCs with
different gate width





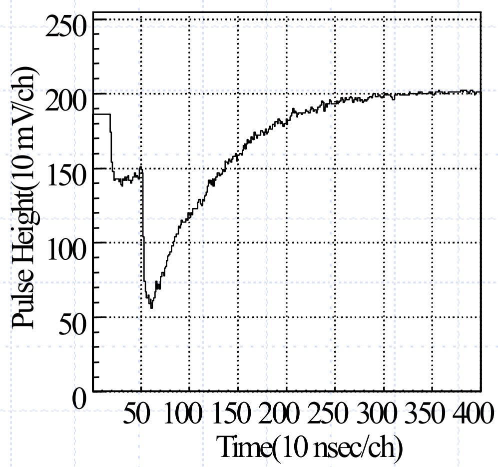
Clear separation
between CaF_2 and LS

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

Succesive decays in CaF_2 scintillator

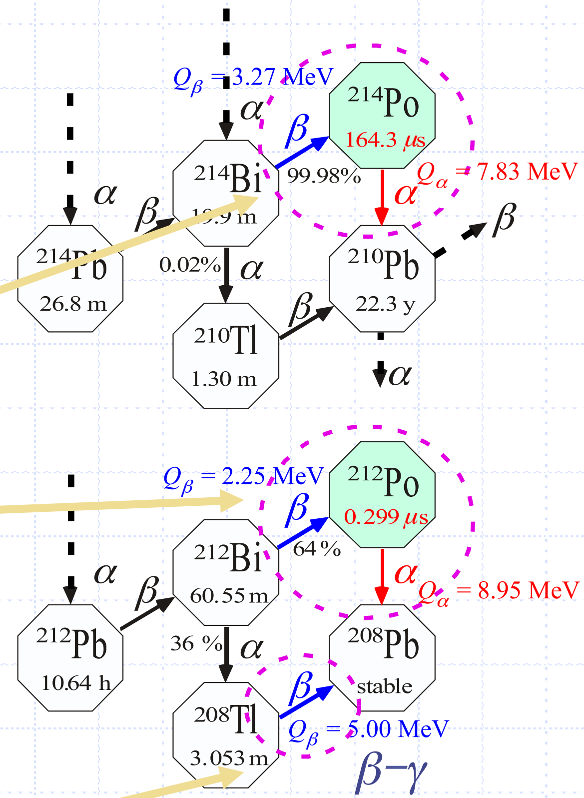
Candles

- 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

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)

Raw Materials $CaCO_3$, HF → **CaF_2 Powder** → **Fused CaF_2** → **CaF_2 Crystal**

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

↓ Powder selection

Crystal growing

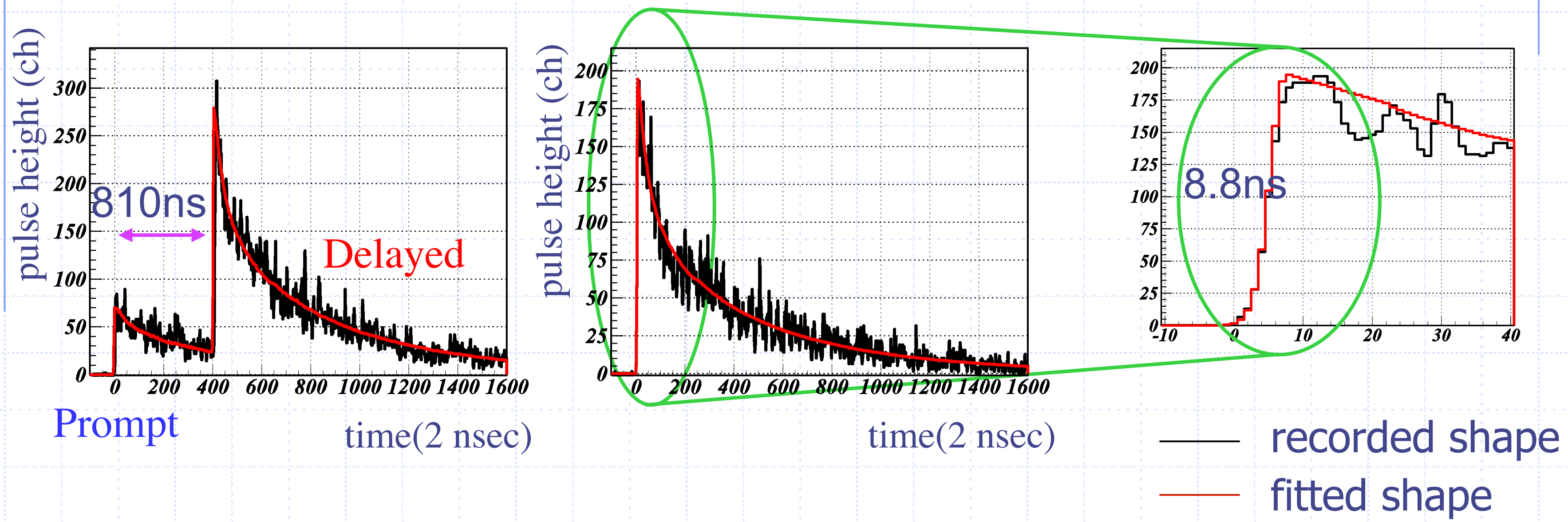
101 crystals

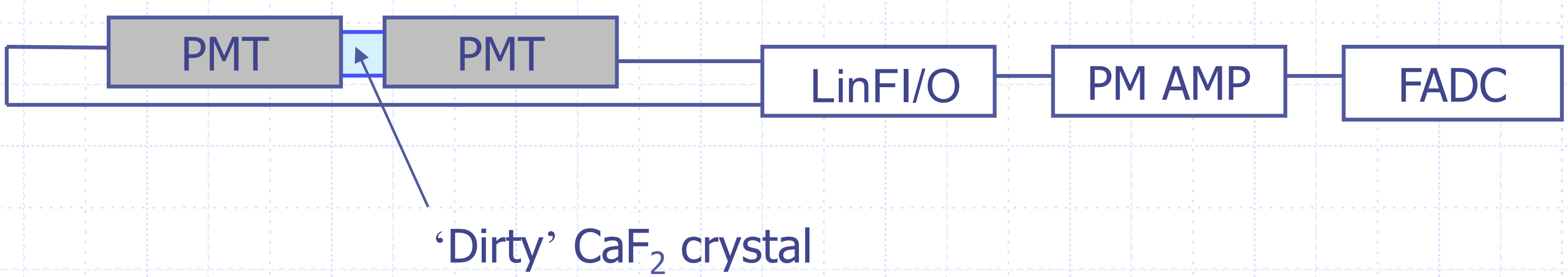
U-chain(^{214}Bi) ~36 μBq/kg …1/30 of Previous Crystals (14±5 μBq/kg ;Best)

Th-chain(^{220}Rn) ~28 μBq/kg …1/3 of Previous Crystals (6±1 μBq/kg ;Best)

Rejection of Double Pulse(DP)

Typical Pulse Shapes

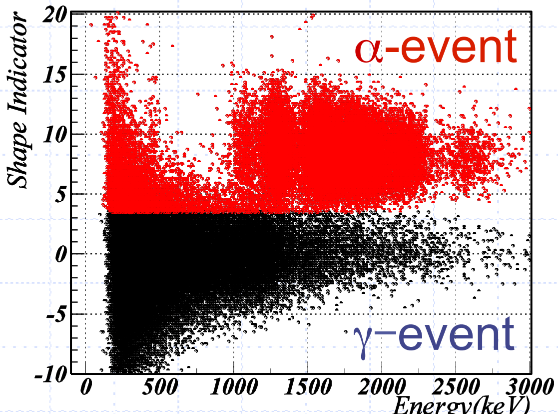


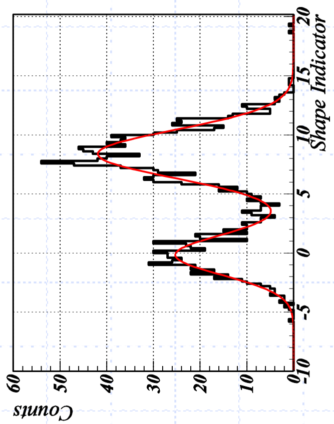


Pulse Shape Discrimination

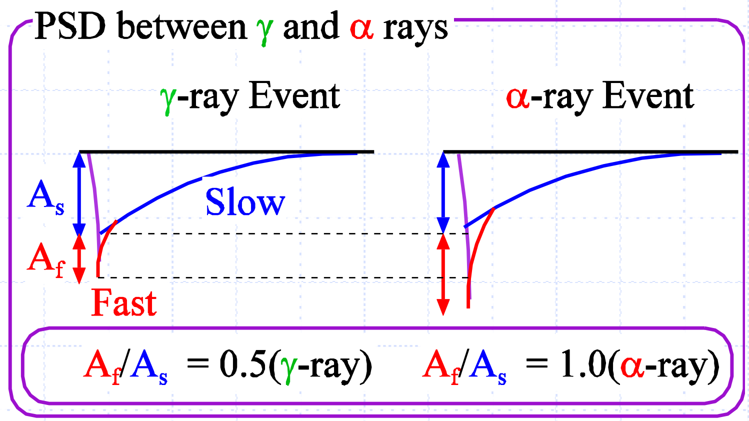
Candles

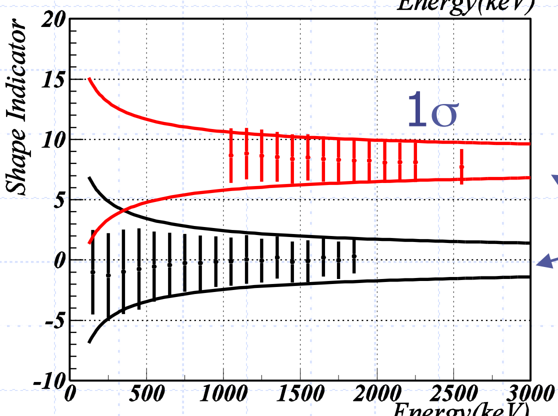
- Pulse Shape discrimination
  - Shape Indicator (PRC **67**(2003) 014310)





Difference in decay shape between α and γ rays





mean value:
no energy dependence (>1 MeV)

CANDLES III

CANDLES III (prototype)

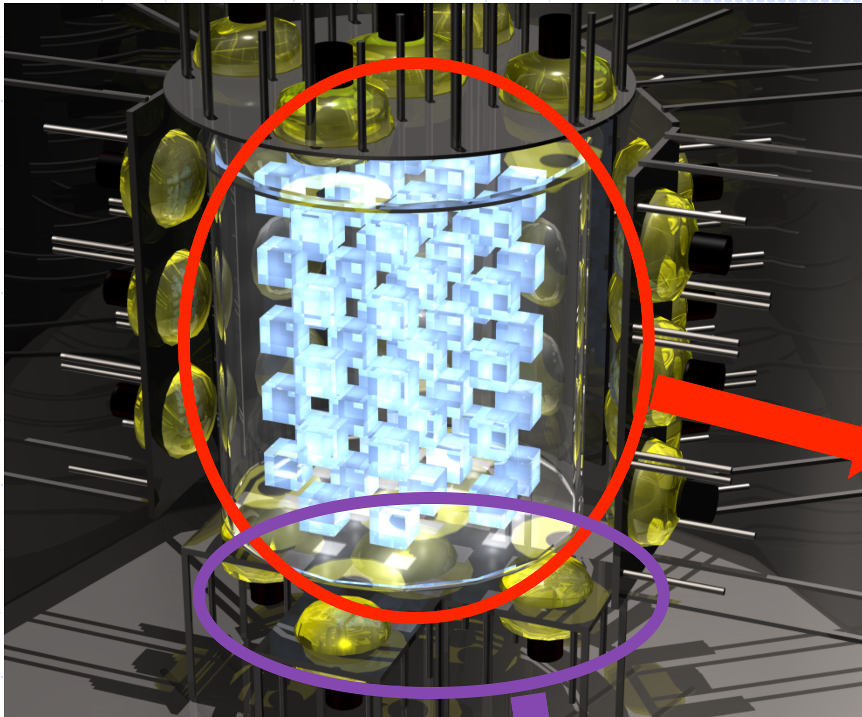
- Constructed at Osaka Univ. (sea level)
  - small version for R&D
  - check the performance of CANDLES
- CaF_2 modules
  - 10^3 cm^3 × 60 crystal; 191 kg
  - with conversion phase
- Liquid scintillator
  - $^{\phi}1000 \times {}^{h}1000$ acrylic container
- H_2O Buffer : passive shield
  - $^{\phi}2800 \times {}^{h}2600$
- PMTs
  - 15" PMT (× 8) : R2018
  - 13" PMT (×32) : R8055

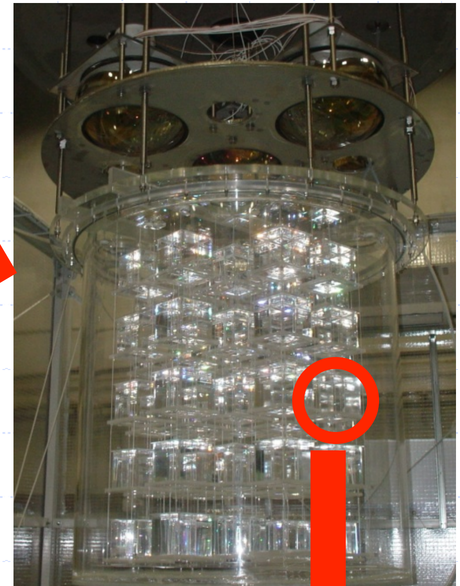
1 "calibration" crystal (#60)
(High Contamination in U, Th)
65 mBq/kg (U-chain),
28 mBq/kg (Th-chain)

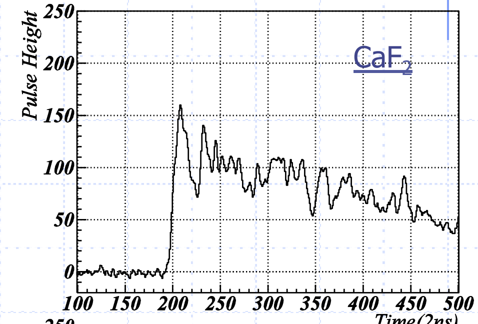
CANDLES III

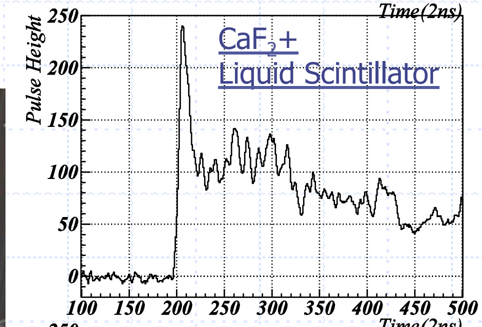
Candles

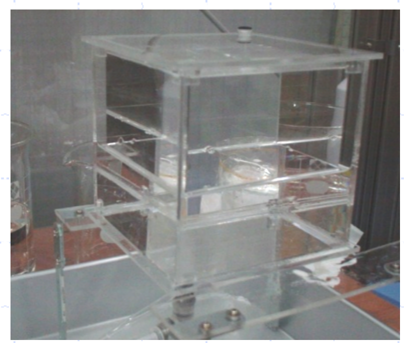
CaF_2: 191 kg
10^3 $cm^3 \times 60$

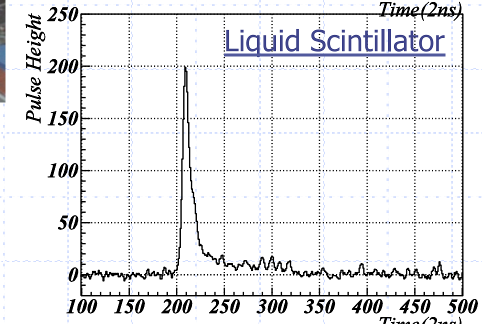












40 PMTs

Tank: $^{\Phi}2.8 \times {}^{h}2.6$ m

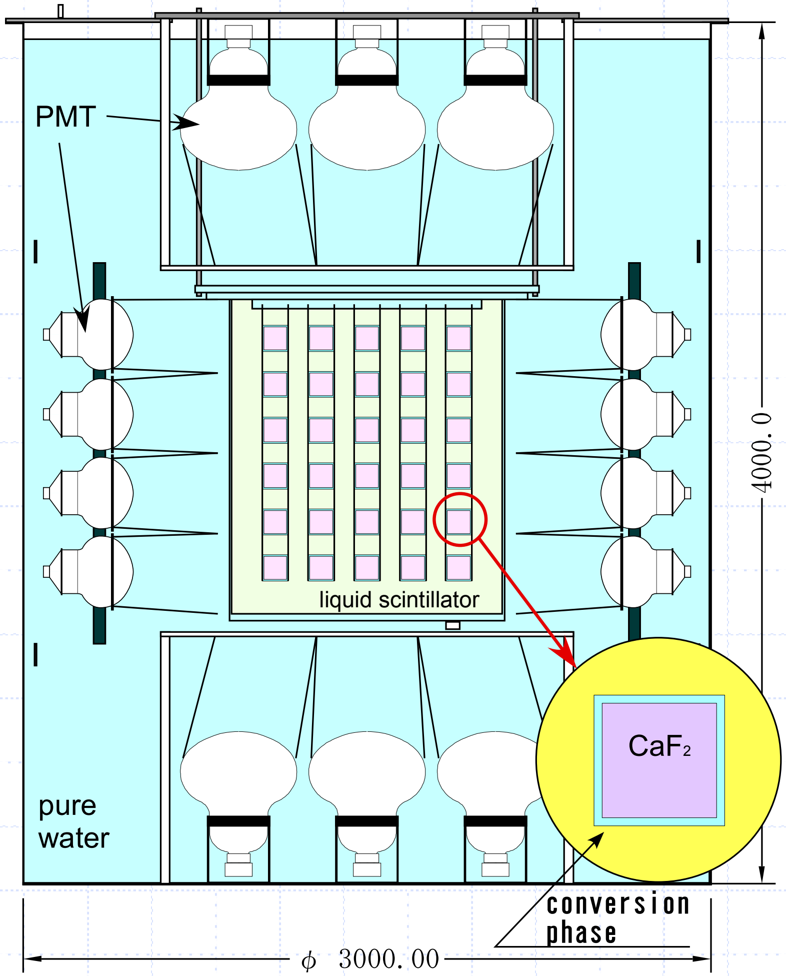
CANDLES III (U.G.) @Kamioka

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

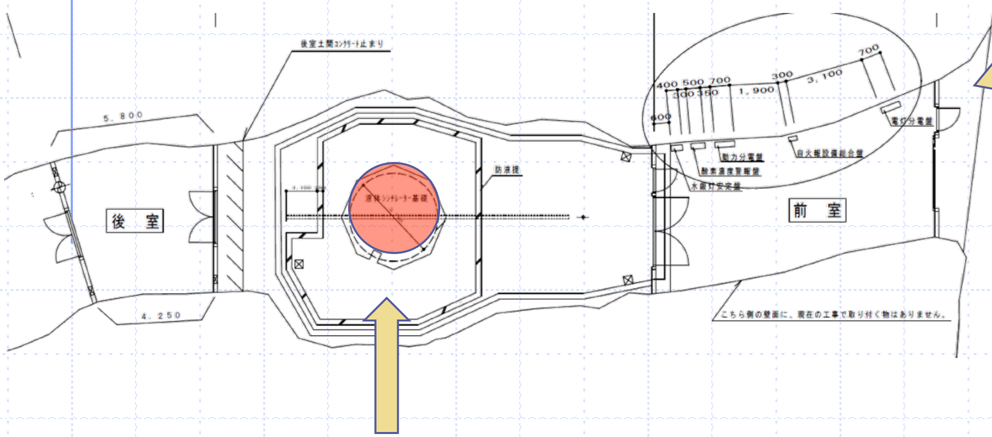
- photon trans. simulation
  ⇨ energy res. ~4.0 % @ $Q_{\beta\beta}$

- Kamioka underground lab.

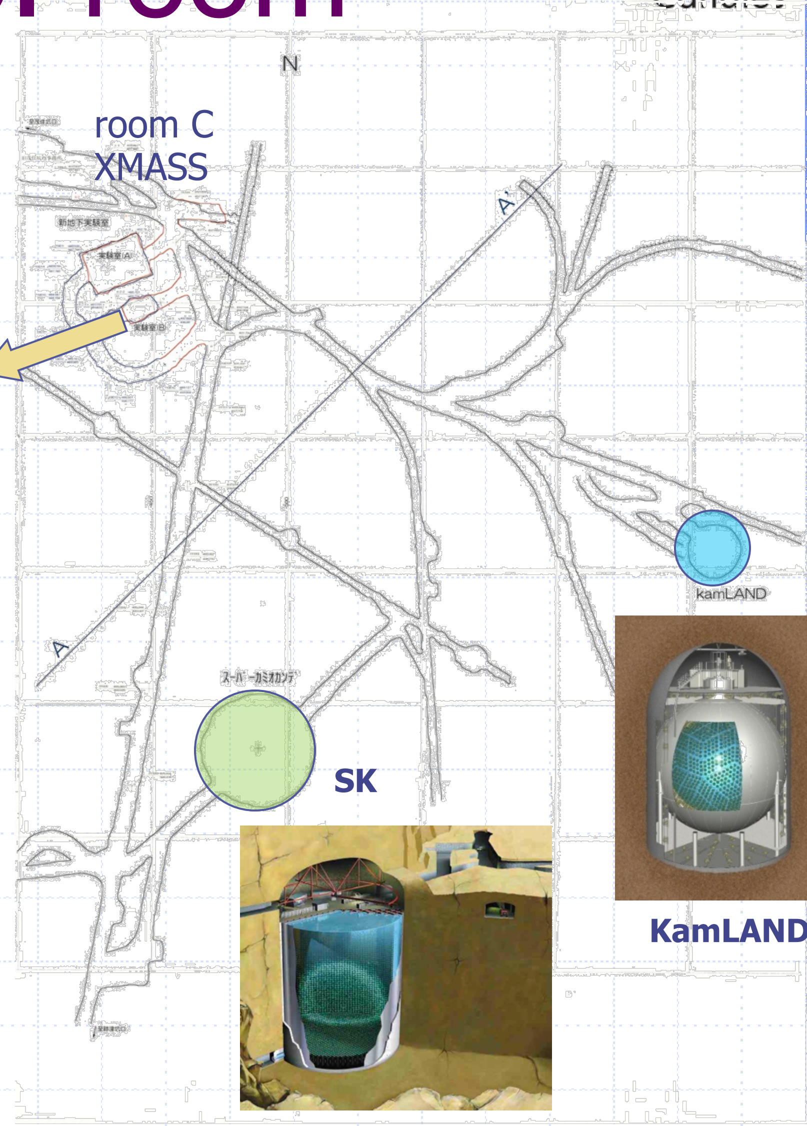


Kamioka new exp. room

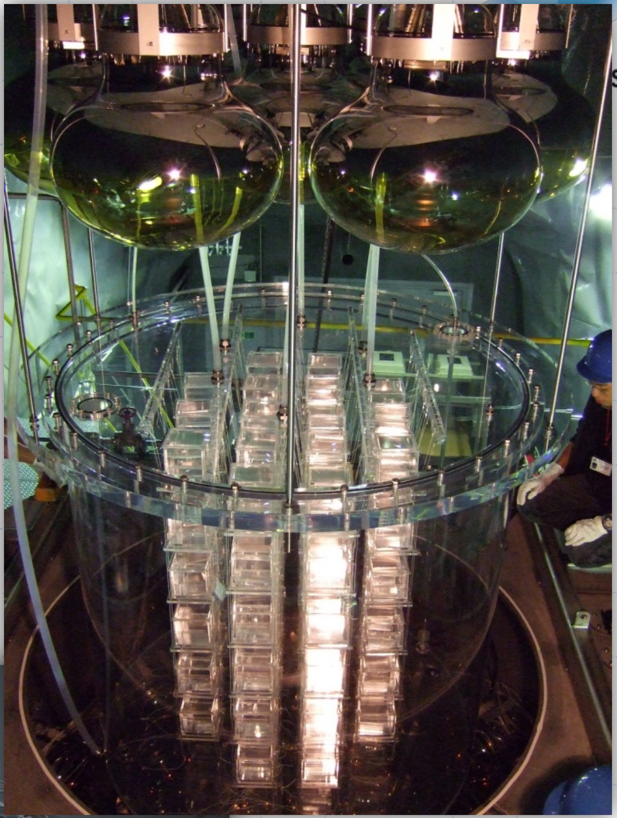
- experimental room D

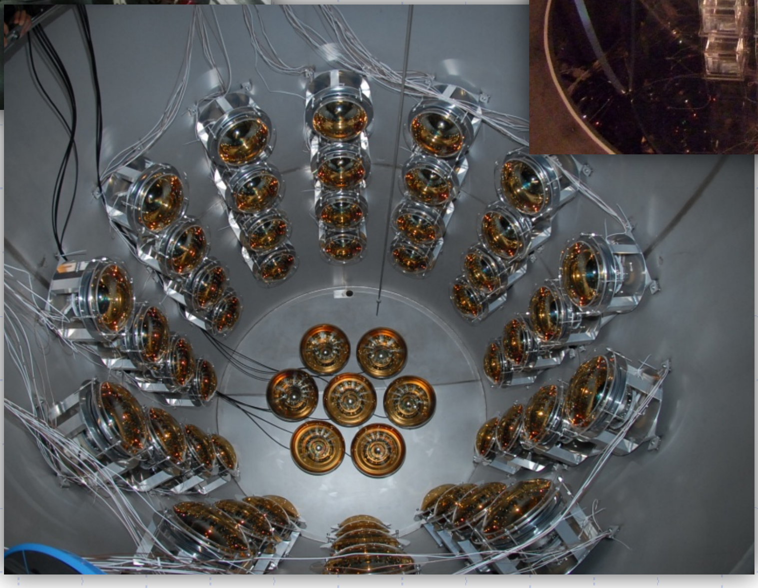


San-chika



CANDLES III (U.G.)





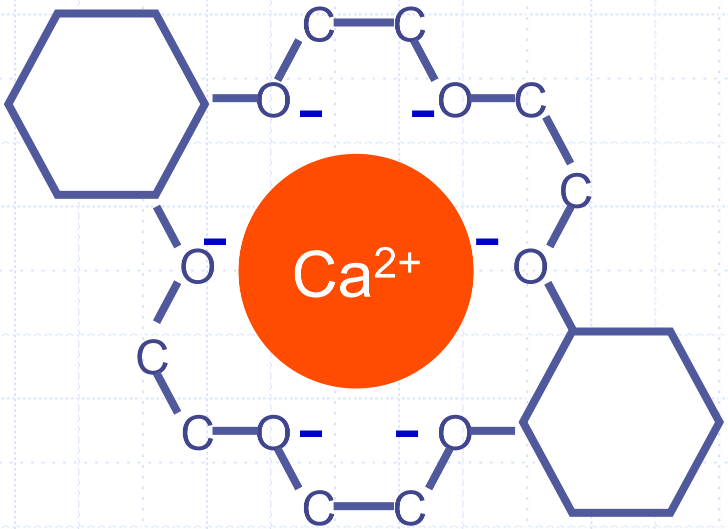
R&D
for future large detector

Candles

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

Crown Ether

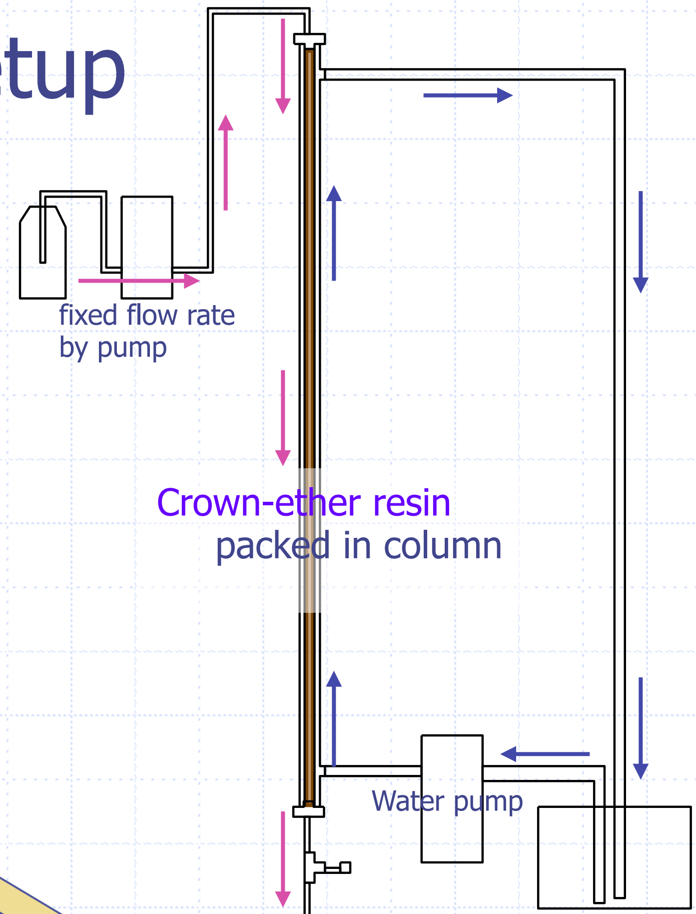


Dicyclohexano 18-crown-6

Chromatography

◆ Experimental Setup

Breakthrough method

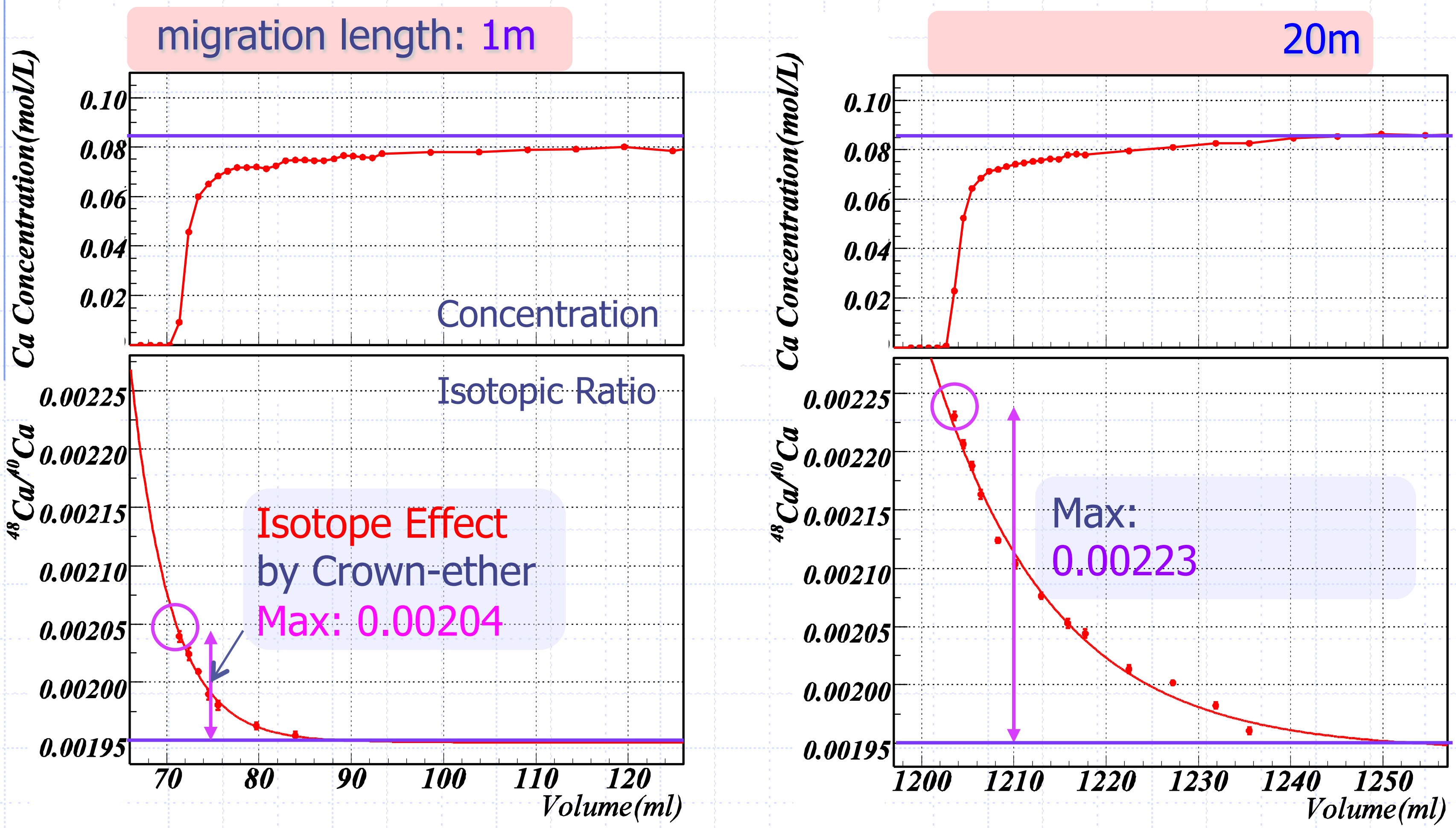


Measurement of

- Ca concentration
- isotopic ratio

^{48}Ca Enrichment by crown-ether

Candles



Further efforts for mass production

Summary & Outlook

現在まで　～2014　～2020

最近の実験
few10 kg・y
～eV

縮退領域
100 kg・y
100 meV

異なる原子核・テクニック
<m>の精密測定
NME

逆階層領域
数 t・y
few 10 meV

順階層領域
~100 t・y
few meV

CANDLES III地下

CANDLES IV（数トン nat.）

Enrichment技術の開発

Enriched $^{48}CaF_2$
CANDLES V

^{48}Caの生産