Double beta decay study of ^{48}Ca by ELEGANT VI and CANDLES project

特定・宇宙ニュートリノ第9回研究会　　8 May '02

- Introduction
- ELEGANT VI
- Present results
- Improvements
- CANDLES
- Summary

OGAWA Izumi (小川 泉)
Dept. of Phys., Osaka Univ.
(大阪大学 大学院理学研究科)

ELEGANT VI collaboration

ELEGANT VI collaboration

■ **Graduate school of science, Osaka University**

T. Kishimoto, R. Hazama, Ogawa, I.,
S. Ajimura, K. Matsuoka , S. Yoshida,
N. Suzuki, T. Nitta, H. Miyawaki, S. Shiomi,
Y. Tanaka, Y. Ishikawa, M. Itamura,
K. Kishimoto, A. Katsuki, H. Sakai,
D. Yokoyama, S. Umehara, S. Tomii
And K. Mukaida

■ **Research Center for Nuclear Physics, Osaka University**

H. Ejiri, N. Kudomi and K. Kume

■ **Faculty of Culture and Education, Saga University**

H. Ohsumi

■ **Faculty of Integrated Arts and Science, Tokushima University**

K. Fushimi

CaF_2 scintillation Detector

■ ^{19}F : Search for spin coupled Dark Matters

– large σ

– small ambiguity between the models

■ ^{48}Ca : Search for $0\nu\beta\beta$ decay

– highest Q-value

least BG expected

Isotope	^{48}Ca	^{76}Ge	^{82}Se	^{100}Mo	^{116}Cd	^{136}Xe	^{150}Nd
Q-value (MeV)	4.27	2.04	3.00	3.03	2.80	2.48	3.37

– Natural abundance 0.187%

$$\left[T_{1/2}^{0\nu}\right]^{-1} = C_{mm}^{(0)} \frac{\langle m_\nu \rangle^2}{m_e^2}$$: mass term only

$C_{mm}^{(0)}$ J. Suhonen and O. Civitrase, Phys. Rep. **300** (1998) 123.

» Shell model calculation

$$(1.55 - 4.91) \times 10^{-14}\ \text{year}^{-1}$$

» QRPA

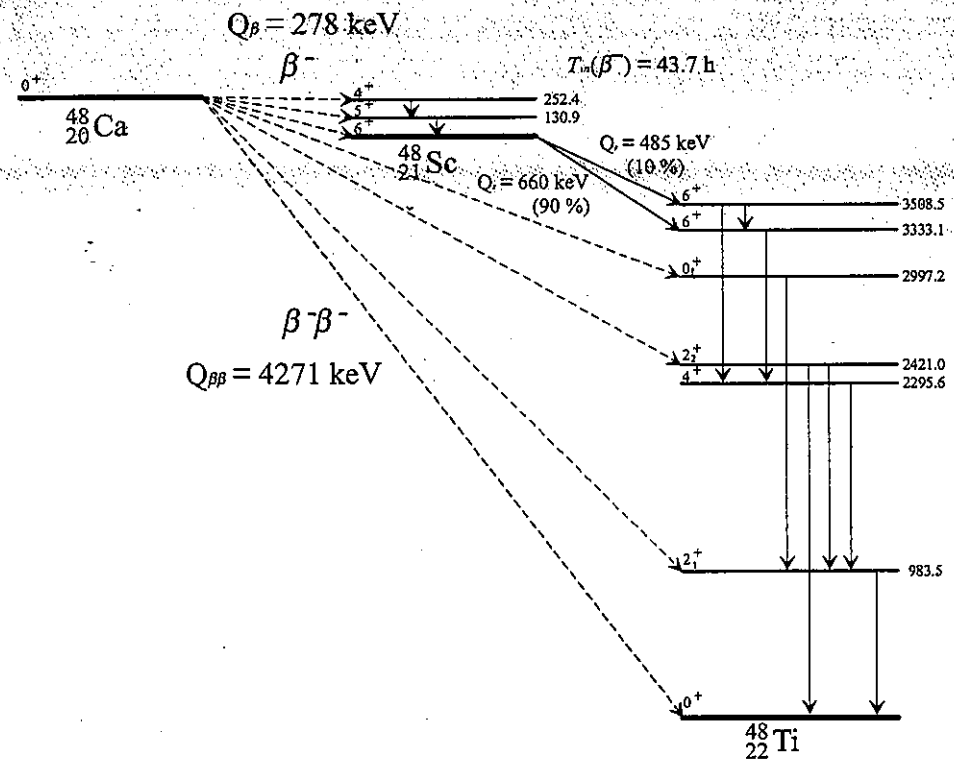
$$(0.935 - 36.3) \times 10^{-14}\ \text{year}^{-1}$$

^{48}Ca

Current status

- $2\nu\beta\beta$　$T_{1/2}^{2\nu} = \left(4.3^{+2.4}_{-1.1}[\text{stat}] \pm 1.4[\text{syst}]\right) \times 10^{19}$ yr　Balysh
  $= \left(4.2^{+3.3}_{-1.1}\right) \times 10^{19}$ yr　TGV
- $0\nu\beta\beta$

Experiment	Life-time (yr) Lower limit	$\langle m_\nu \rangle$ (eV) Upper limit	C.L. (%)
Goldhaber	2×10^{20}	59.5	
Wu	2×10^{21}	18.8	80
Beijing	9.5×10^{21}	8.3	76
TGV	1.5×10^{21}	20.9	90



ELEGANT VI

Detector System

– large mass

scintillator $45\times45\times45\ mm^3$ $\times25\ (23)$

$\sim3.5\ kg\ ^{19}F$

$\sim7.7\ g\ ^{48}Ca$

– low background

» high purity crystal

» least material : non hygroscopic

» **4π active shield**

* $CaF_2(Eu)+CaF_2(pure)$

roll-off ratio

* segmentation
* CsI(Tl) veto detector

$65\times65\times250\ mm^3$ $\times38$ modules

» passive shield

* OFHC Cu(t:5 cm), Pb(t:10 cm)
* air-tight box + N_2 gas purge

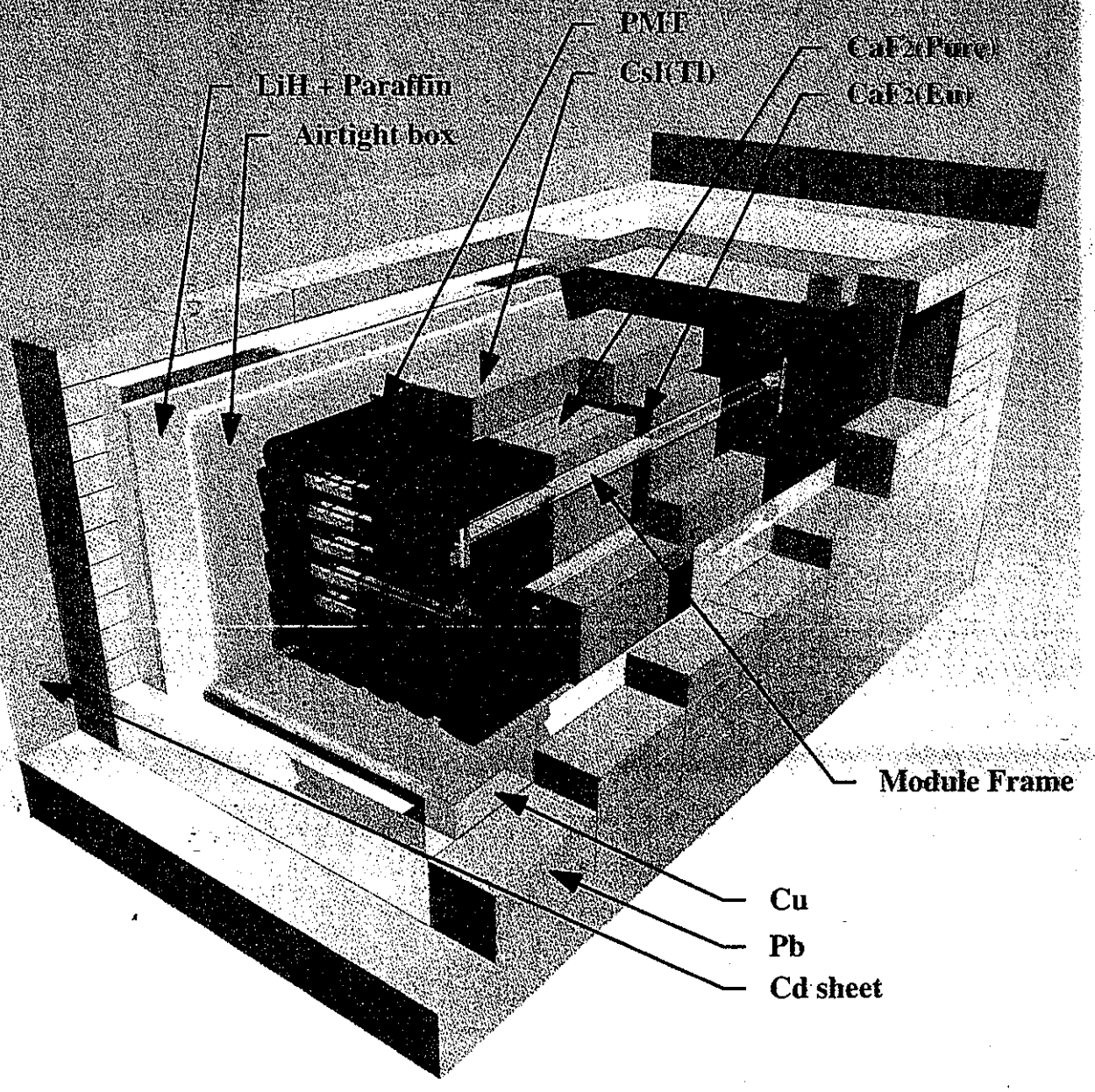
Rn in the air

* LiH + paraffin(t:15 mm), Cd sheet(t:0.6 mm)

$H_3BO_3+H_2O$ tank

neutron

ELEGANT VI

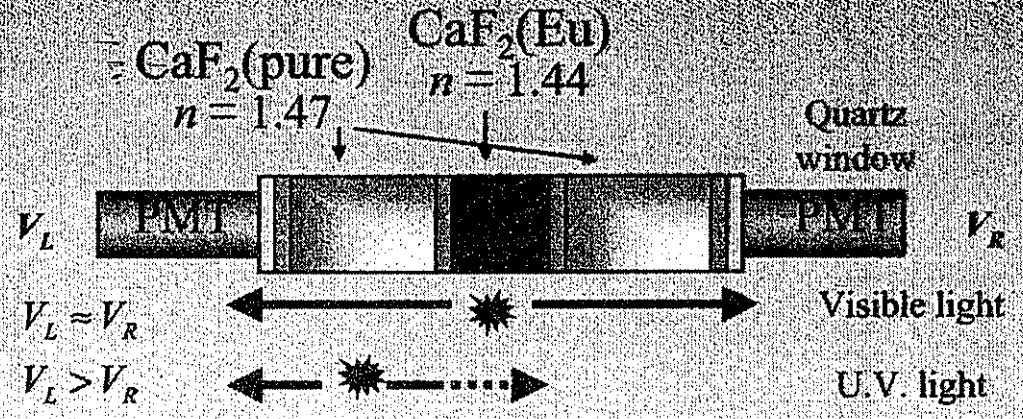


Surrounded by H_3BO_3 loaded-water tank

Roll-off ratio

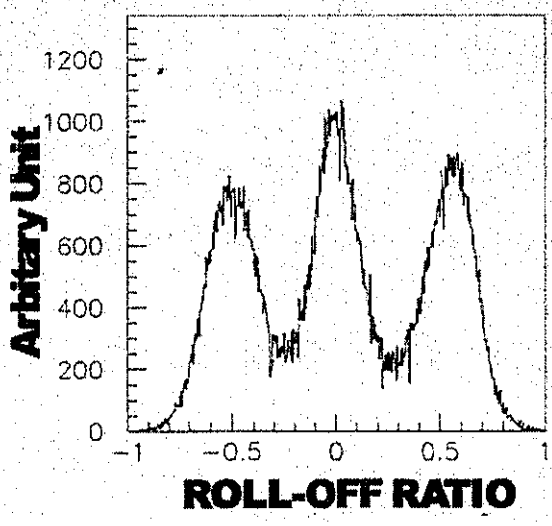
CaF_2(pure) as { light guide / active shield against PMT

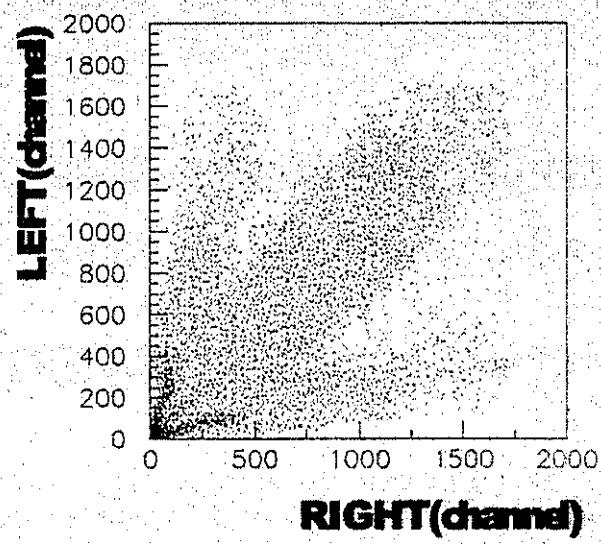
CaF_2(Eu) is not transparent for U.V. light



$$R = \frac{V_R - V_L}{V_R + V_L}$$

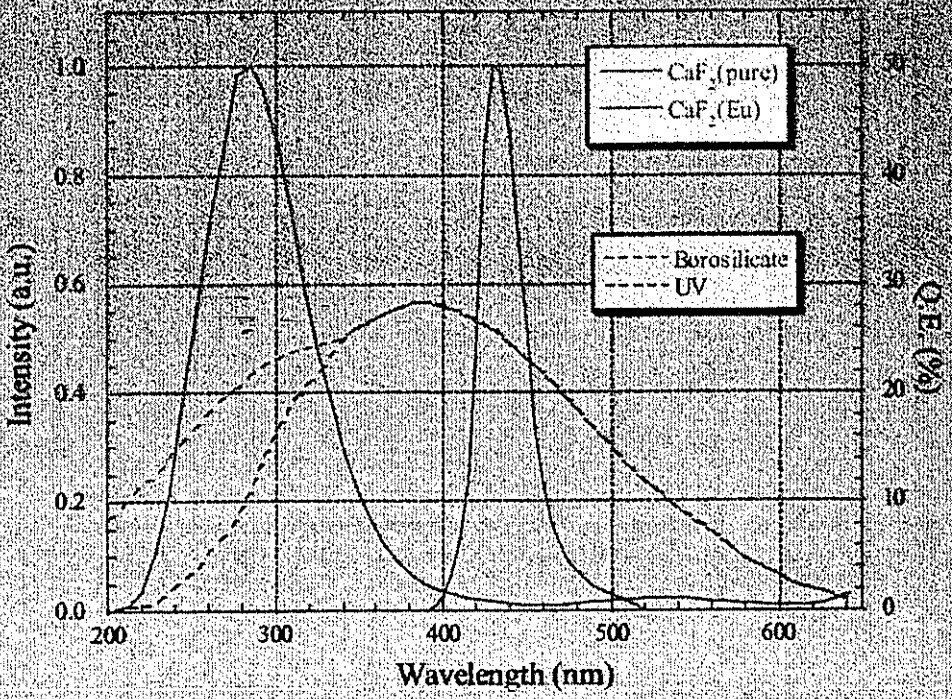
V_L, V_R : ADC channel from left & right PMT



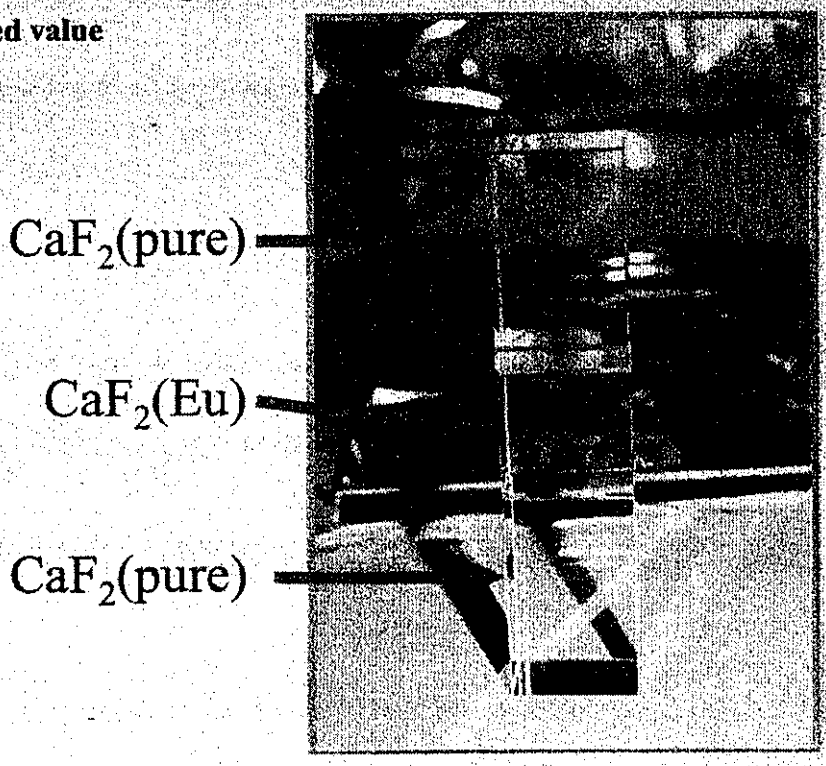


CaF_2(Eu) & CaF_2(pure)

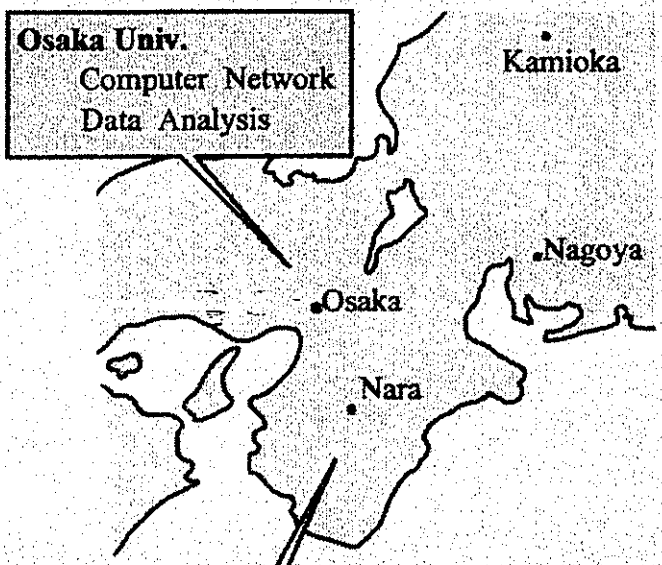
Scintillation emission spectra of CaF_2 crystal



- **CaF2(Eu) : from BICRON catalogue**
- **CaF2(pure) : measured value**



Oto Cosmo Observatory



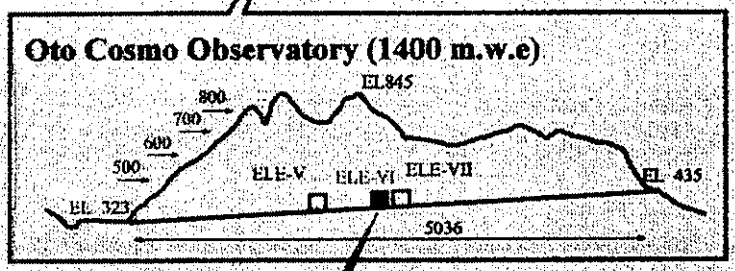
Underground laboratory (1400 m.w.e.)

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.

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

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

Rn concentration: 10 Bqm^{-3}



ELEGANT VI detector
CaF_2 scintillator array

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

Contamination measurement

■ U-series

– hardware (second) trigger

– time window : 9 – 499 μsec.

$$^{214}\mathrm{Bi} \xrightarrow{E_\beta=3270} {}^{214}\mathrm{Po} \xrightarrow[(164.3\,\mu\mathrm{sec})]{E_\alpha=7687} {}^{210}\mathrm{Pb}$$

■ Ac-series

$$^{219}\mathrm{Rn} \xrightarrow{E_\alpha=6819} {}^{215}\mathrm{Po} \xrightarrow[(1.781\,\mathrm{msec})]{E_\alpha=7386} {}^{211}\mathrm{Pb}$$

■ Th-series

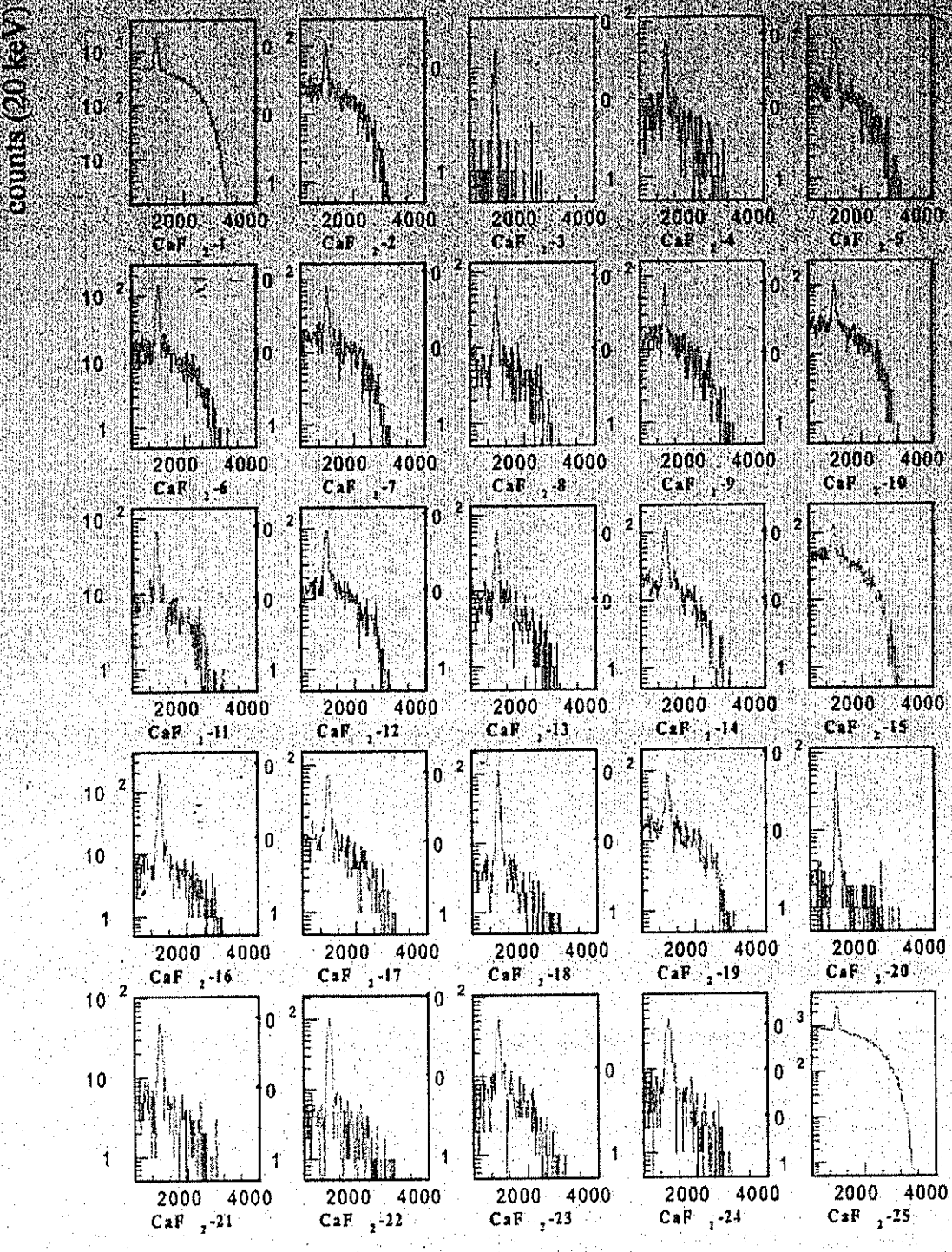
– software cut

– time window : 0.05 – 1.0 (0.5) sec.

$$^{220}\mathrm{Rn} \xrightarrow{E_\alpha=6288} {}^{216}\mathrm{Po} \xrightarrow[(0.145\,\mathrm{sec})]{E_\alpha=6779} {}^{208}\mathrm{Pb}$$

U- & Ac- series

$^{214}Bi \xrightarrow{\beta} {}^{214}Po$　　$^{219}Rn \xrightarrow{\alpha} {}^{215}Po$



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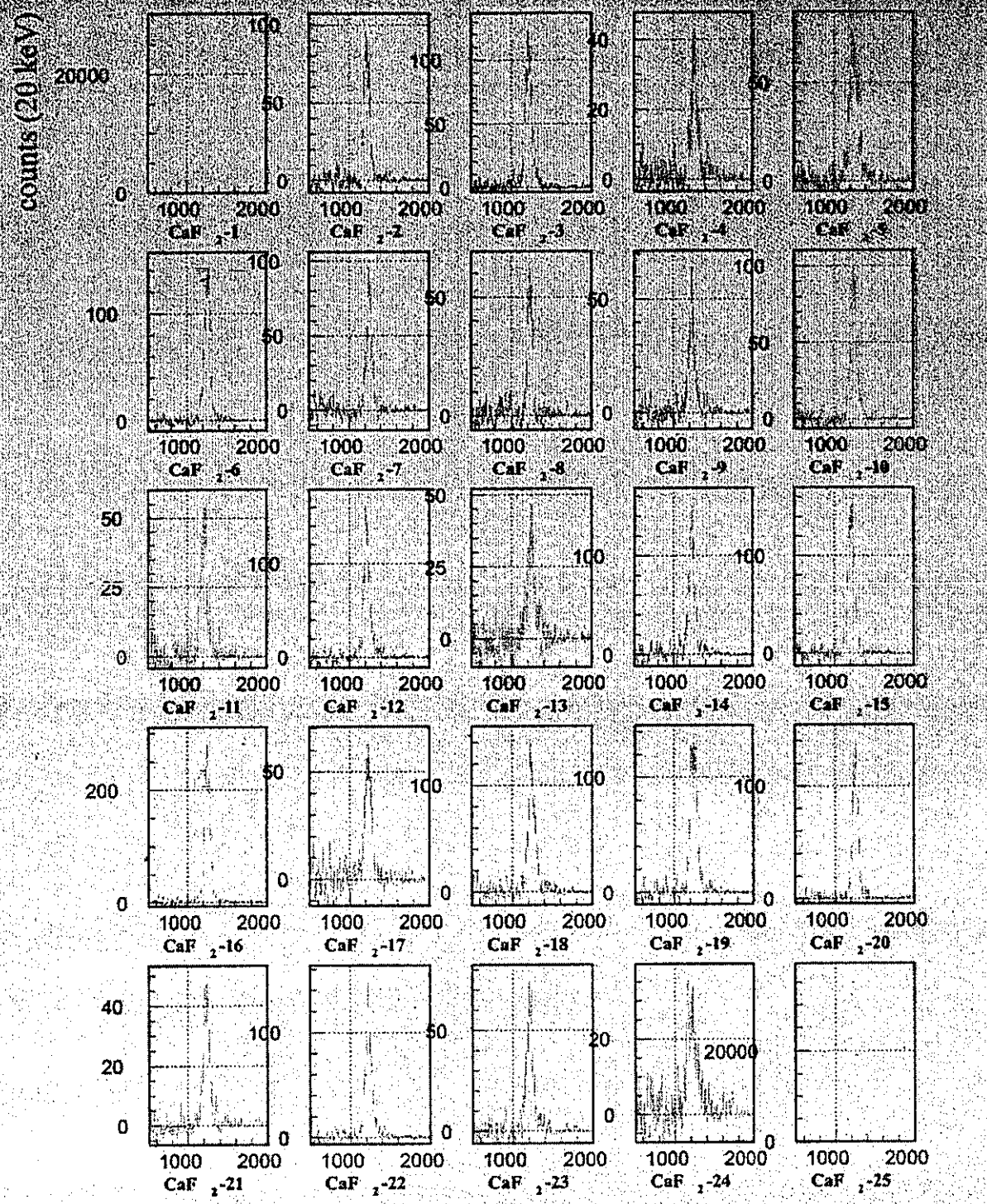
Th-series

$^{220}Rn \xrightarrow{\alpha} {}^{216}Po$　　time window : 0.05-1.0 sec



Contamination inside crystals

21	22	23	24	25
16	17	18	19	20
11	12	13	14	15
6	7	8	9	10
1	2	3	4	5

CaF_2 #1 & #25

high contamination

Average contamination

(#2 – #24)

U – series

1.11×10^{-3} Bq/kg

Ac – series

3.84×10^{-4} Bq/kg

Th – series

1.09×10^{-4} Bq/kg

(mBq/kg)

CaF_2 #	U-series	Ac-series	Th-series
1	4.6E+4	6.9E+3	3.2E+4
2	2.1E+3	4.E+2	9.4E+1
3	5.2E+1	5.5E+1	1.3E+2
4	6.E+2	2.4E+2	4.1E+1
5	1.6E+3	5.9E+2	1.1E+2
6	1.5E+3	6.E+2	1.5E+2
7	1.5E+3	2.6E+2	8.6E+1
8	6.2E+2	2.8E+2	5.1E+1
9	1.4E+3	2.5E+2	5.4E+1
10	2.4E+3	3.7E+2	1.1E+2
11	6.8E+2	2.9E+2	5.E+1
12	1.6E+3	4.7E+2	1.5E+2
13	7.E+2	2.8E+2	4.6E+1
14	1.6E+3	6.5E+2	1.5E+2
15	4.E+3	4.8E+2	1.8E+2
16	6.E+2	8.8E+2	2.7E+2
17	9.8E+2	3.3E+2	6.9E+1
18	4.E+2	4.8E+2	1.5E+2
19	1.5E+3	4.3E+2	1.7E+2
20	1.6E+2	2.1E+2	1.3E+2
21	3.7E+2	2.5E+2	5.E+1
22	3.3E+2	5.1E+2	1.4E+2
23	5.5E+2	2.7E+2	7.6E+1
24	4.2E+2	2.6E+2	4.9E+1
25	7.6E+4	9.6E+3	4.4E+4

Present Results

Run #2 series (98/06/18 — 99/11/04)

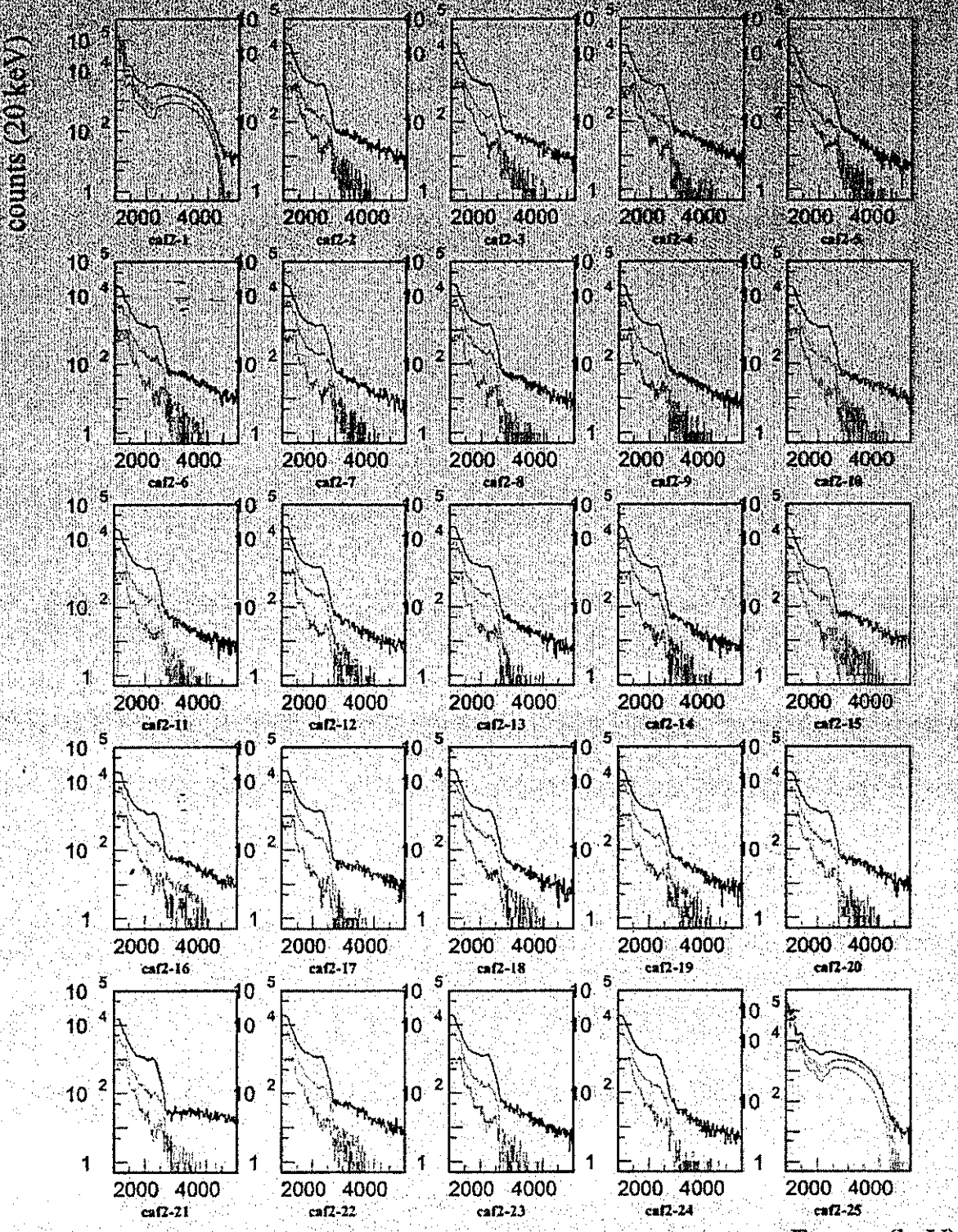
- **CaF_2 : 23 crystals　　M=6.66 kg**
  - $^{48}Ca : 9.61 \times 10^{22}$ atoms
- **Total live time :　　5567 hours**
- **Total acquired events:　　297256278**
- **Energy resolution**

$$R(\%) = \frac{200.7 \pm 1.827}{\sqrt{E(\mathrm{keV})}} \Rightarrow R = 3.07(\%) \quad @4271\ \mathrm{keV}$$

- **Analysis**
  - Raw data　　:black
  - CaF_2 multiplicity=1　　:green
  - CsI veto
  - Delayed-α cut　　:blue
  - Roll-off cut　　:red
- **Efficiency**
  - $\pm 3\sigma$ energy window :　57.71 %

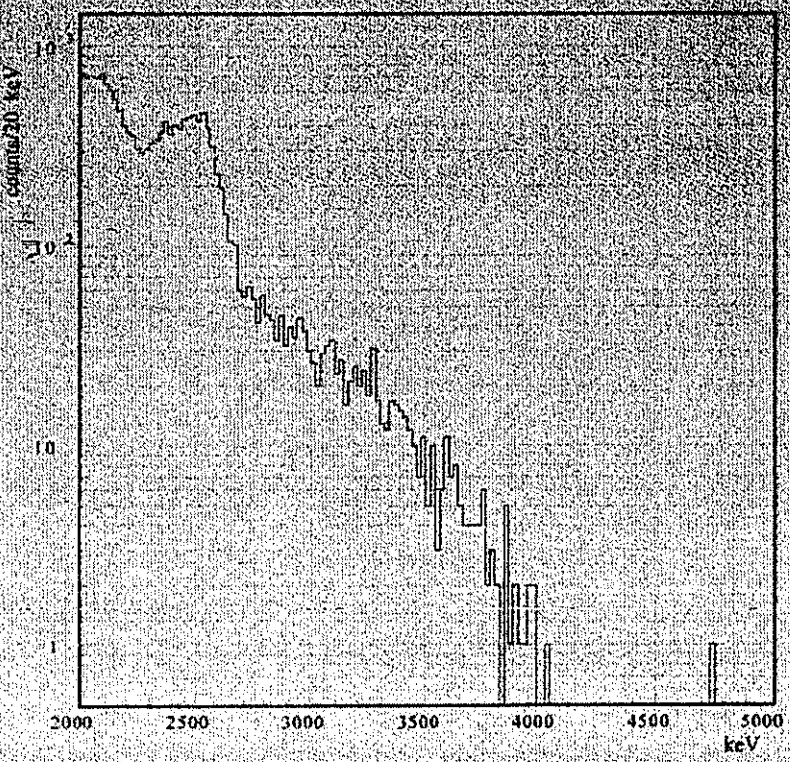
(for $0\nu\beta\beta$ decay)

Energy spectra



Measurement at Oto

Summed spectrum (crystal #2 – #24)



Assumed 0 BG expected

0 events in $0\nu\beta\beta$ energy window

$$T_{1/2}^{0\nu\beta\beta} > 1.9\times10^{22}\ \text{year}\quad (68\%\ \text{C.L.})$$
$$> 1.0\times10^{22}\ \text{year}\quad (90\%\ \text{C.L.})$$

$$\langle m_\nu \rangle < 5.9\,\text{eV}\quad (68\%\,\text{C.L.})$$
$$< 8.1\,\text{eV}\quad (90\%\,\text{C.L.})$$

Improvements

Double beta decay study

Main BG source around 3-4.5 MeV

2ν : $^{212}\mathrm{Bi} \xrightarrow{\beta} {}^{212}\mathrm{Po} \xrightarrow{\alpha} {}^{208}\mathrm{Pb}$

$(0.299\,\mu\mathrm{sec})$

$(Q=2254.0)$ $(Q=8954.1)$

0ν : $^{214}\mathrm{Bi} \xrightarrow{\beta} {}^{214}\mathrm{Po} \xrightarrow{\alpha} {}^{210}\mathrm{Pb}$

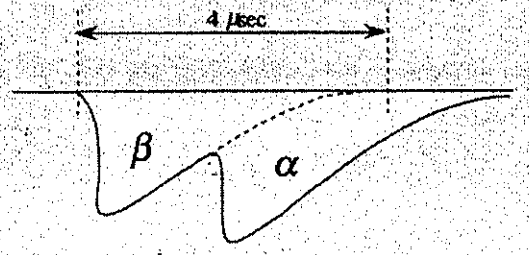
$(164.3\,\mu\mathrm{sec})$ $f \approx 1/4$

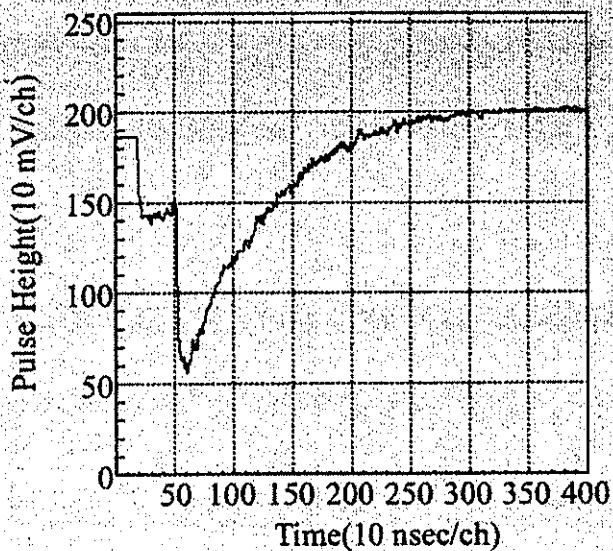
$(Q=3272.0)$ $(Q=7833.5)$

ADC gate : 4 μsec.

Flash-ADC

to discriminate β+α events





At least 80 % of the events can be reject (3 – 4.5 MeV)

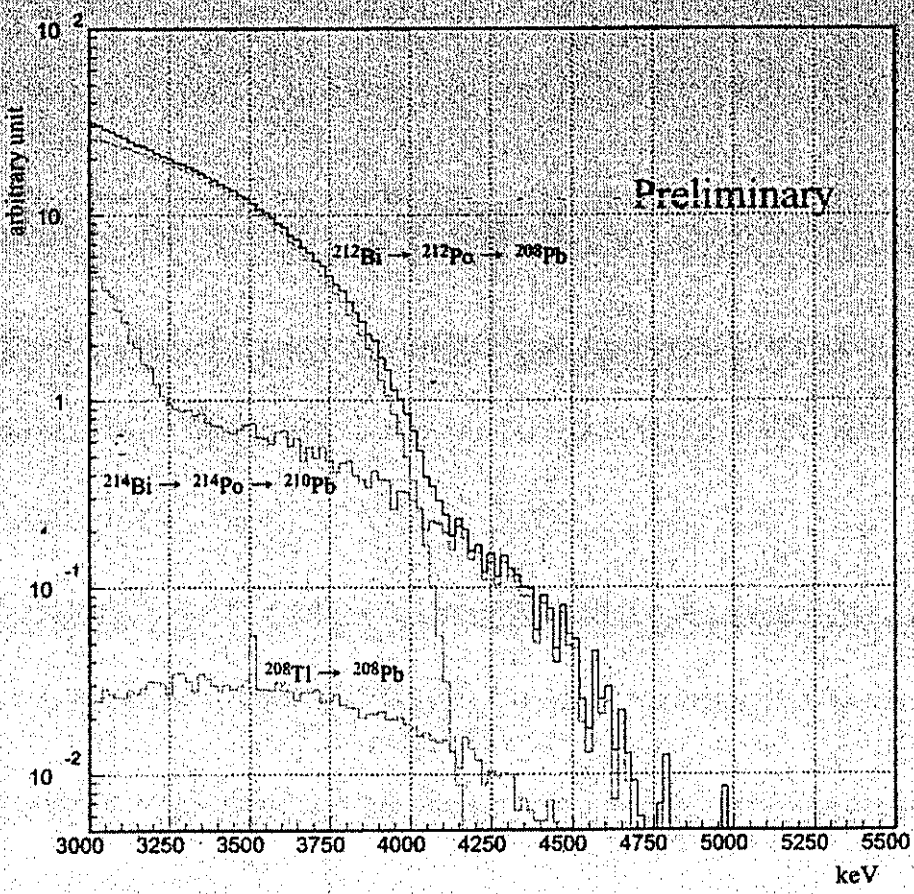
More efficient analysis:

under study

$^{208}\mathrm{Tl} \xrightarrow{\beta} {}^{208}\mathrm{Pb}$ $(Q=5000.9)$

BG simulation

- **blue:** $^{212}\mathrm{Bi} \xrightarrow{\beta} {}^{212}\mathrm{Po} \xrightarrow{\alpha} {}^{208}\mathrm{Pb}$ (0.299μsec)
- **purple:** $^{214}\mathrm{Bi} \xrightarrow{\beta} {}^{214}\mathrm{Po} \xrightarrow{\alpha} {}^{210}\mathrm{Pb}$ (164.3μsec)
- **red:** $^{208}\mathrm{Tl} \xrightarrow{\beta} {}^{208}\mathrm{Pb}$



CANDLES project

■ Increase the number of nuclei (^{48}Ca)

– Enrichment of ^{48}Ca

under study

– Large volume detector

7.7 g (ELE VI) ⇒ O(10kg)

9.6×10^{22} atoms　　$\sim10^{26}$ - 10^{27} atoms

■ CANDLES

(CAlcium fluoride for studies of Neutrino and Dark matters by Low Energy Spectrometers)

Basic concepts of CANDLES

CaF_2(pure) crystal cube immersed in Liquid Scintillator

- **Liquid scintillator**
  - 4π active shield
    - decay time of the signal
      - » ~1 μsec　　CaF_2
      - » a few – 10 nsec　liquid scintillator
  - passive shield
    - » Large volume in low cost
  - Low radio active impurity
    - » U/Th/K　~0.1ppt
    - » purification system (U,Th,K,Rn,…)
      (KamLAND, BOREXINO, etc.)
  - n/γ, α/γ discrimination property
    - Monitoring
      - neutron flux
      - Rn concentration

CaF_2(pure) crystal

- **High purity (Development for excima laser)**

Crystal	manufacturer	U series(^{214}Bi)	Th series(^{208}Tl)
CaF_2(Eu)	BICRON	1110 μBq/kg	109 μBq/kg
CaF_2(pure)	BICRON	56.7 μBq/kg	29.7 μBq/kg
CaF_2(pure)	OKEN (1)	2130 μBq/kg	406 μBq/kg
CaF_2(pure)	OKEN (2)	1110 μBq/kg	<380 μBq/kg

commercially available crystals

high purity CaF_2(pure) ⟹ under study

- **Long attenuation length**
  - CaF_2(Eu) ~13 cm
  - CaF_2(pure) > 1 m ⟹ **large detector**
- **PSD property**
  - α/γ discrimination
- **Low cost**
- **Low light emission**
  - 1/3 ~ 1/4 of CaF_2(Eu)
    - » peak emission U.V. region (275 nm)

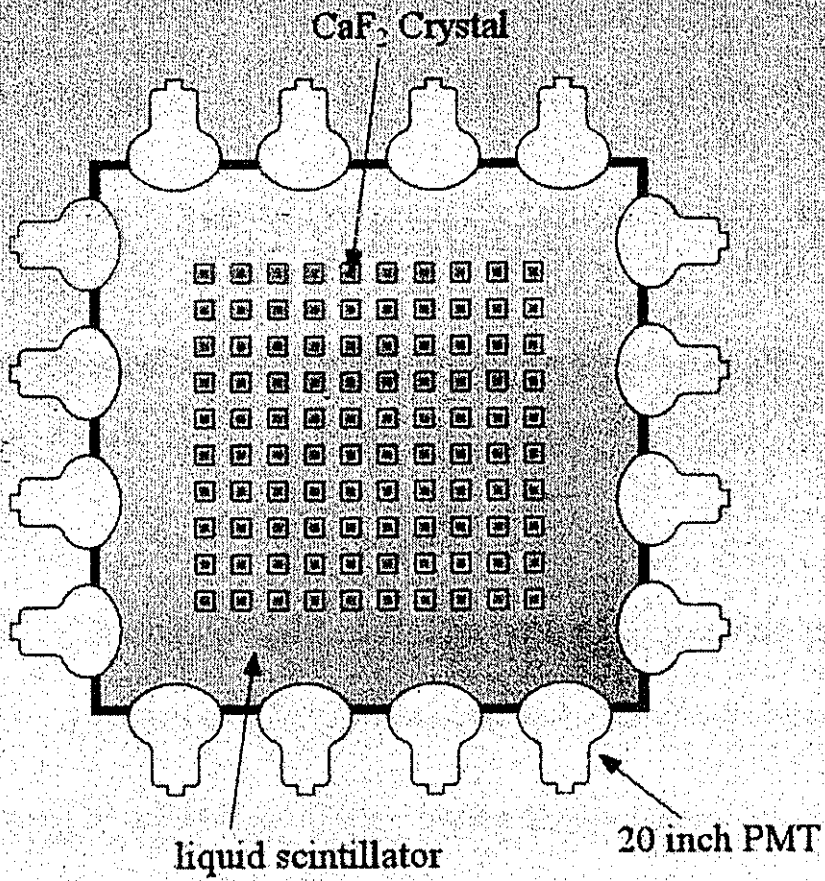
⇓

wavelength shifter in liquid scintillator

Concept drawing of CANDLES

$10^3 \times 10^3$ cm^3 CaF_2 crystals
in $3 \times 3 \times 3$ m^3 Vessel

→ 3.2 t CaF_2
→ 3.1 kg ^{48}Ca (natural)
→ 33 kg (2% enriched)



Schedule

- **CANDLES I**
  ~2001
  - Demonstration
  - 1 – 2 crystal(s)
- **CANDLES II**
  2002 ~ 2003
  - Design study model
  - Multiple crystals in x,y,z-axis　~10 kg of CaF_2
  - Dark Matter (Spin coupled WIMPs) search

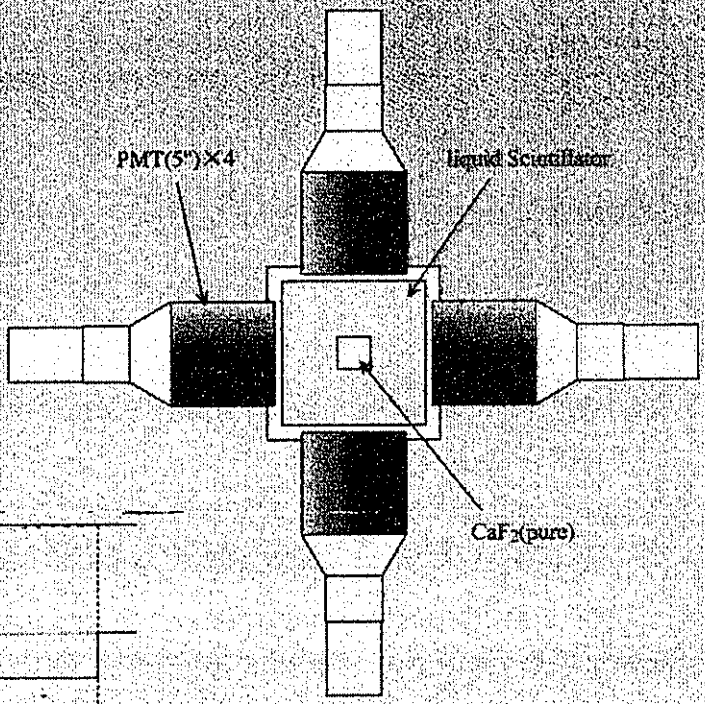
  Material selection
  - Crystal, liquid scintillator, etc.
- **CANDLES III**
  2003 — 2005 construction & test run @ Osaka
  2005 —　　move to underground lab.
  - a few × 100 kg of CaF_2

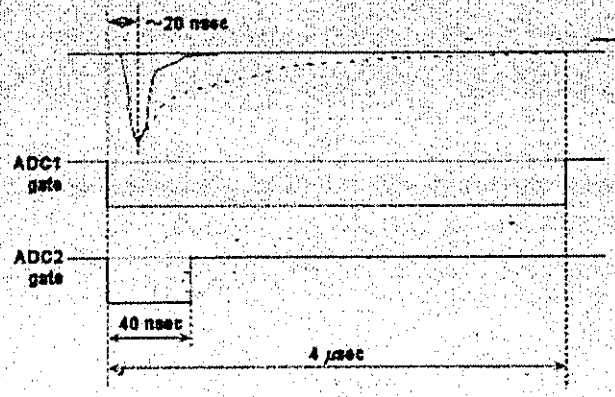
    $\Longrightarrow \langle m_\nu \rangle \approx O(0.1\text{eV})$
- **Goal**
  - a few tons of CaF_2
  - Enrichment of ^{48}Ca

    $\Longrightarrow \langle m_\nu \rangle \approx O(0.01\text{eV})$

Prototype detector (CANDLES I)

1~2 CaF_2(pure) crystal(s)
in liquid scintillator (with w.l. shifter)
viewed by 4 PMTs (5 inch)





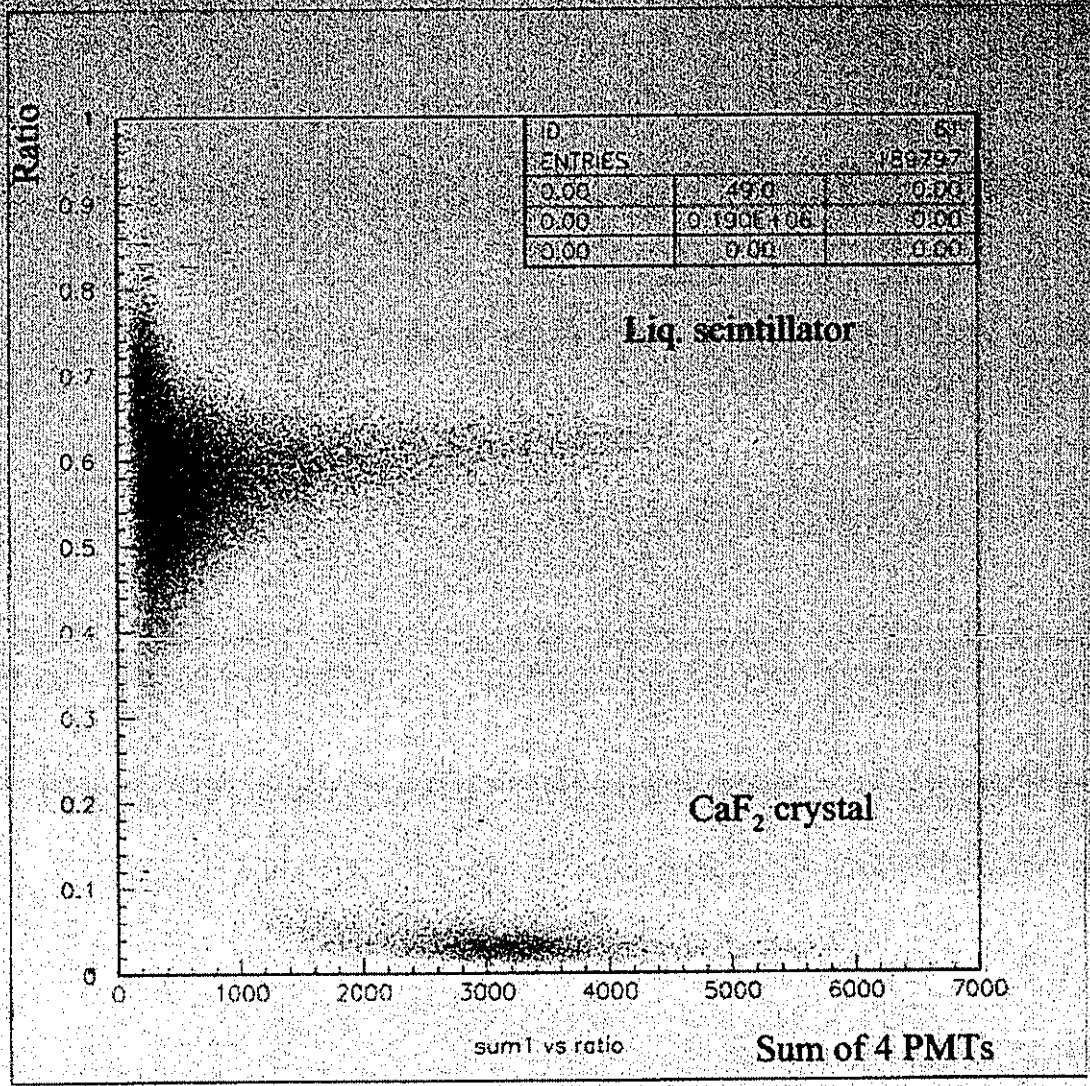
Signal discrimination ratio (ADC2/ADC1)

liq. scint. : mineral oil + DPO + Bis-MSB

(0.15 g/*l*) (0.015 g/*l*)

Signal discrimination

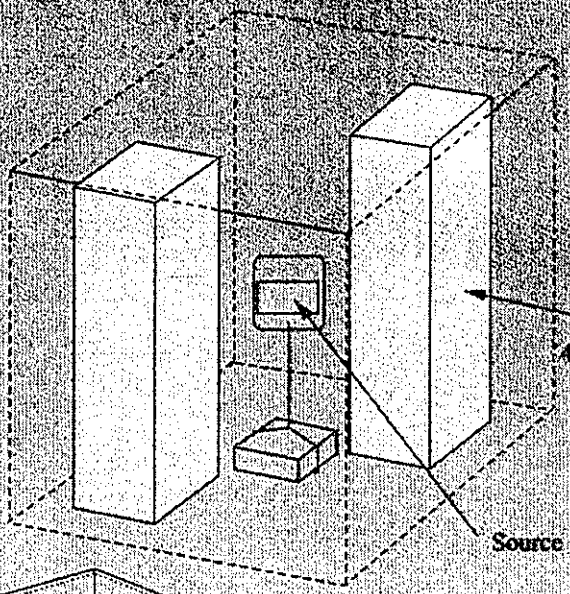
^{57}Co source

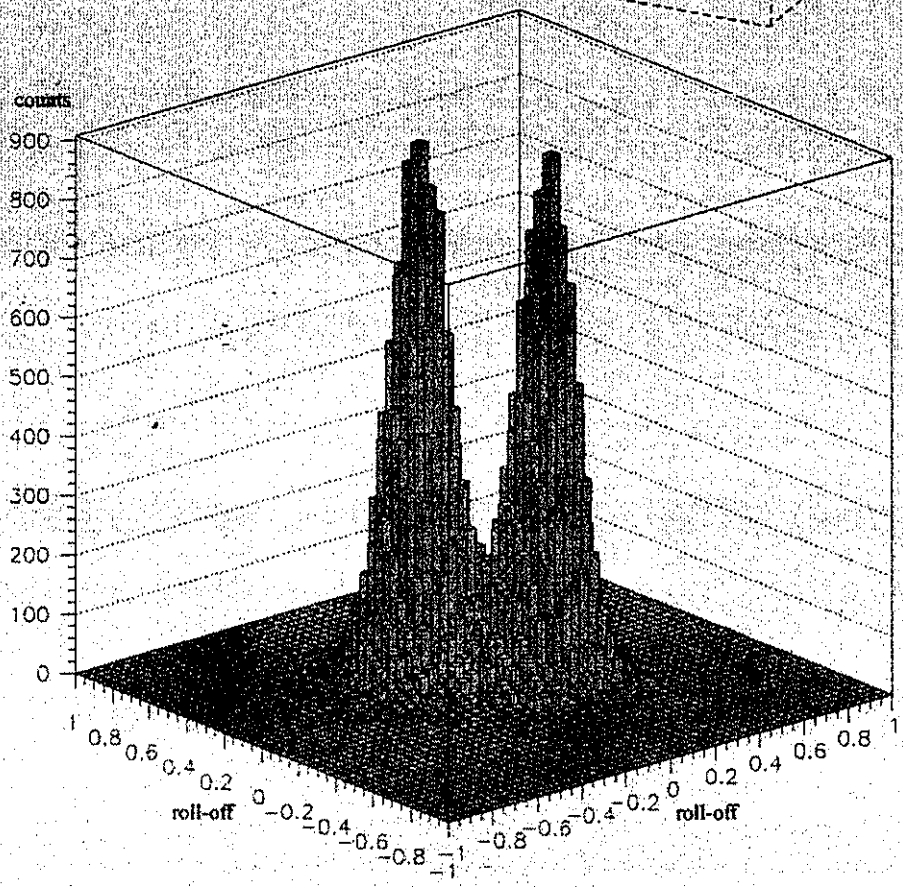


2 crystals test

2 crystals inside detector

^{137}Cs source





After
Ratio cut

Summary

- **We are operating ELEGANT VI detector system at Oto Cosmo Observatory to study...**
  - Dark matter (WIMPs) search
  - Double beta decay of ^{48}Ca
- **Measured the contamination inside the CaF_2 crystal**
  - U – series (^{214}Bi) 1.11×10^{-3} Bq/kg
  - Ac – series (^{219}Rn) 3.84×10^{-4} Bq/kg
  - Th – series (^{220}Rn) 1.09×10^{-4} Bq/kg
- **Analyzed 5567 hours (live time) data...**
  - Obtained lower limit (preliminary)

$$T_{1/2}^{0\nu\beta\beta} > 1.9\times10^{22} \text{ year} \quad (68\%\ \text{C.L.})$$

$$> 1.0\times10^{22} \text{ year} \quad (90\%\ \text{C.L.})$$

- **Prospects**
  - Analyze more 1.5 years data
  - Simulate B.G. events arround 3 – 4.5 MeV
  - Flash ADC analysis
- **CANDLES**
  - Signal discrimination study using prototype detector (CANDLES I)
  - Constructing CANDLES II detector
  - Goal $\Longrightarrow$ $\langle m_\nu \rangle \approx O(10^{-2}\text{eV})$