Background Rejection for CANDLES System

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CANDLES Collaboration

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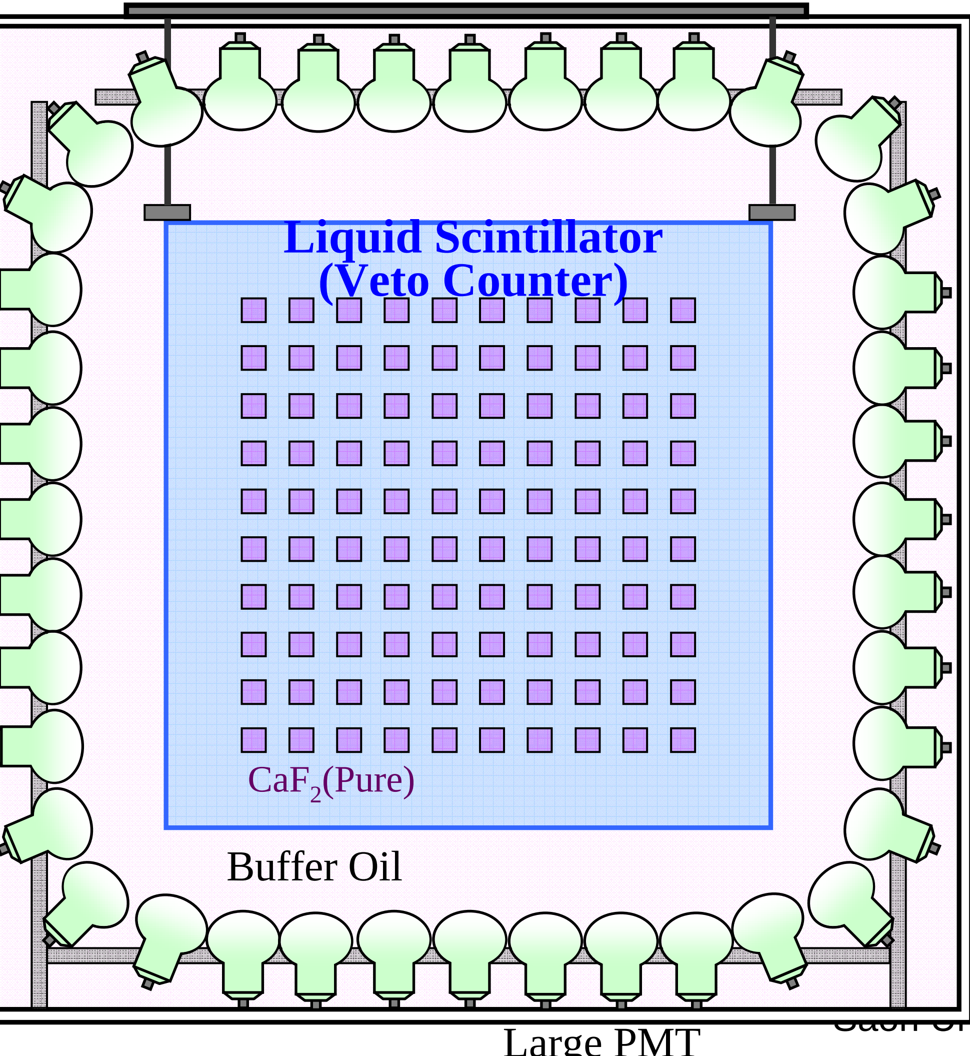
Outline

CANDLES for Double Beta Decay of ^{48}Ca

- Design Concept of CANDLES for Background Rejection
  - 4π Active Shield
- Expected Background
  - Internal Background
- Background Rejection & Reduction
  - High Purity CaF_2 Crystal
  - Sequential Pulse Rejection
  - Pulse Shape Discrimination between α and γ rays
  - Position Correlated Background Rejection
- Summary

Design Concepts of CANDLES

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



- **Undoped CaF_2 Scintillator** **(CaF_2(Pure**
  Double Beta Decay Source ^{48}Ca
  ($Q_{\beta\beta}$=4.27MeV
  Peak Emission at UV Region (280nm)
  ↓
  Wave Length Shifter
- **Liquid Scintillator**
  Wave Length Shifter
  4 π Active Shield
- **Large Photomultiplier Tube**
  Signals from both scintillators are detected simultaneously

⇓

Active Shielding Technique

Different Time Constants

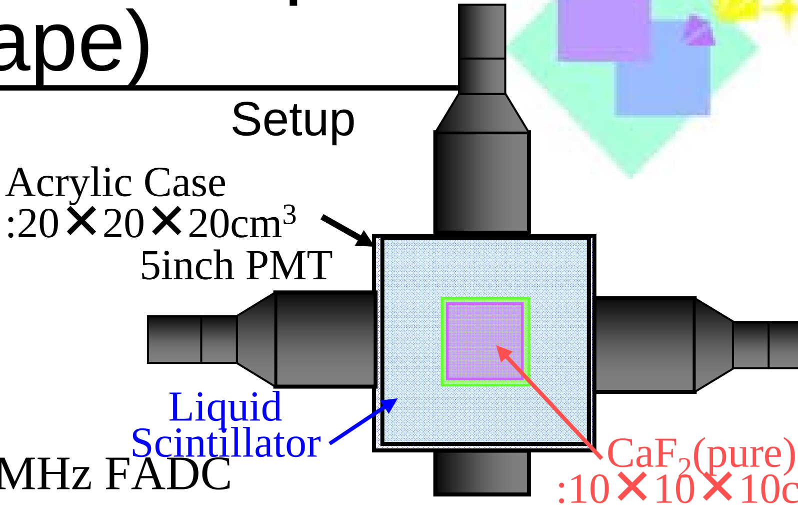
CaF_2(pure)	: ~1μsec
Liquid Scintillator	: a few 10 nsec

Active Shielding Technique (Pulse Shape)

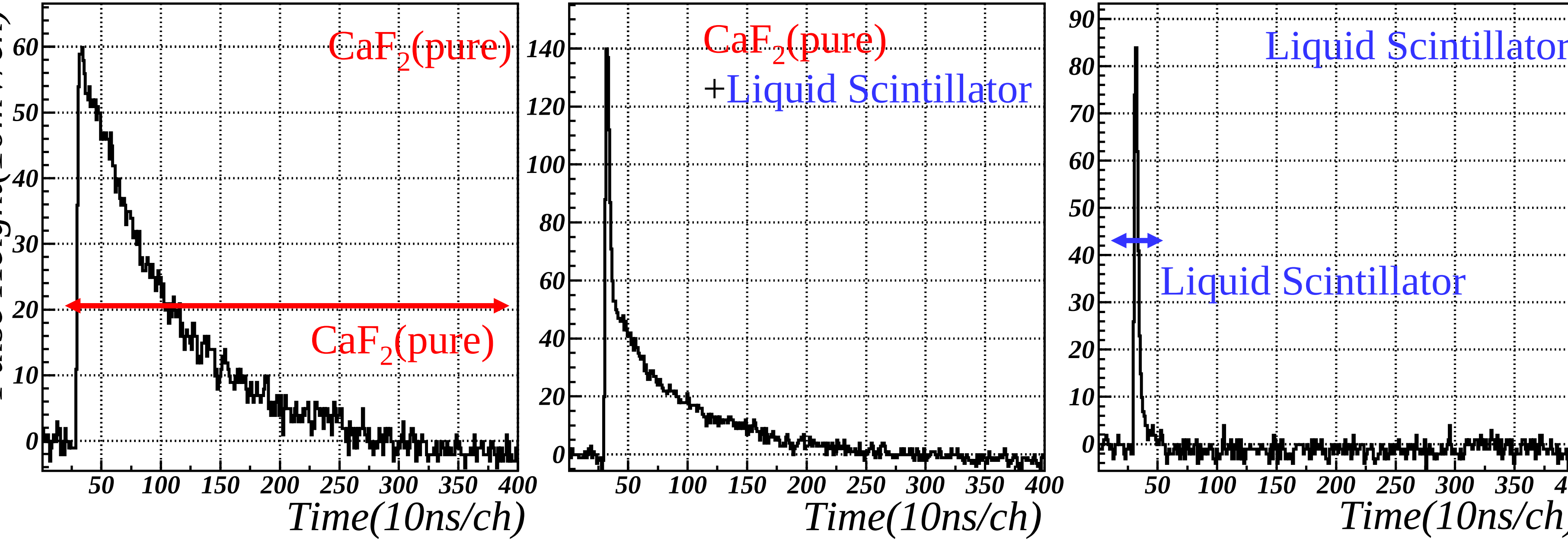
Concept of 4π Active Shield and Performance Test

- Pulse Shape of Signals from CaF_2 and Liquid Scintillators

Setup



Typical Pulse Shape of Each Scintillators by 100MHz FADC

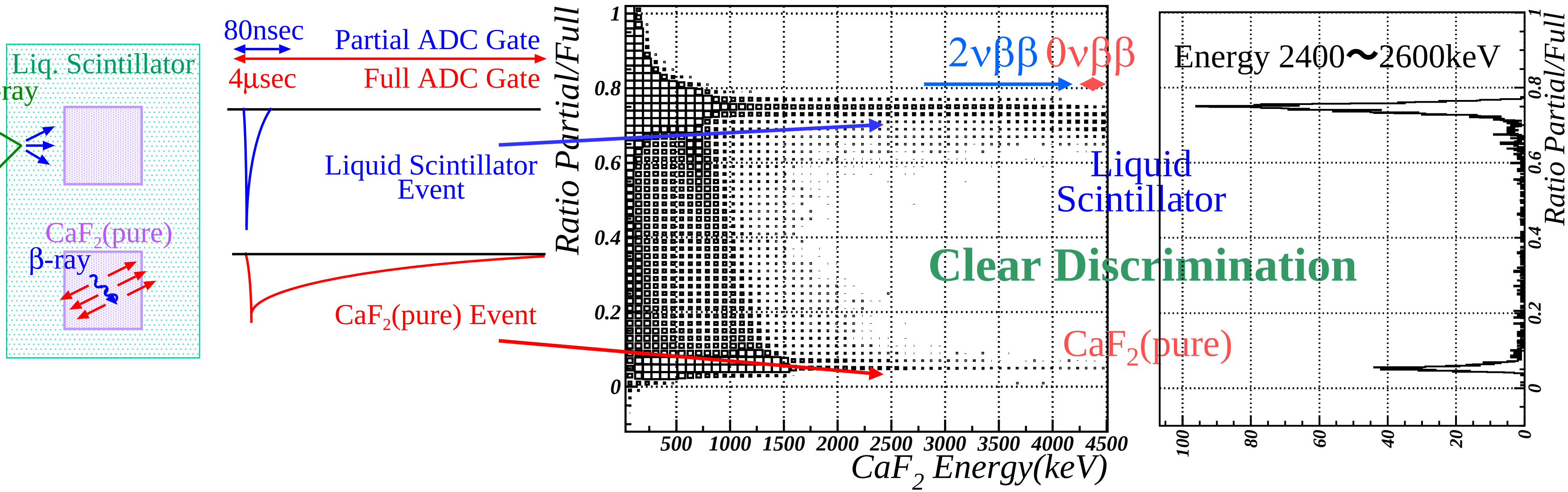


Active Shielding Technique

Concept of 4π Active Shield and Performance Test

Dual Gate Technique

$$\text{Ratio} = \frac{\text{Charge of Partial ADC Gate}}{\text{Charge of Full ADC Gate}}$$



Clear Discrimination between CaF_2 and Liquid Scintillators

. . .Well Act as Veto Counter

Expected Background in CANDLES

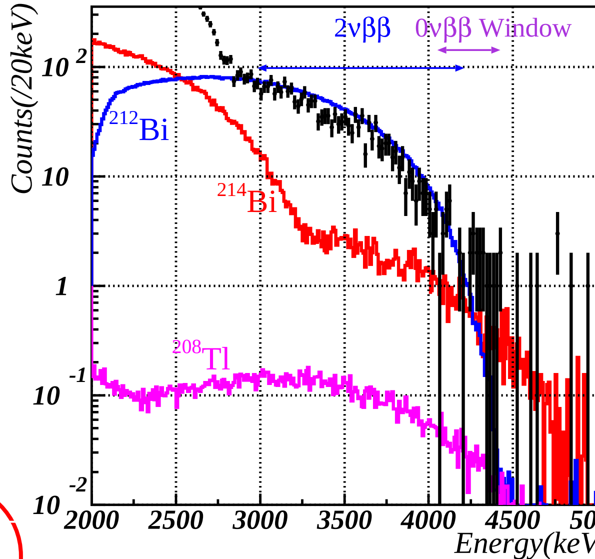
External Background

⇒ Strongly Suppressed

Because of High $Q_{\beta\beta}$ of ^{48}Ca(4.27MeV)

4π Active Shielding System

Background Studies with $CaF_2(Eu)$ System (ELEGANT VI)



Simulation

^{212}Bi, ^{214}Bi and ^{208}Tl ;
Natural Radioactivities in $CaF_2(Eu)$ Crystal

→ Serious Background

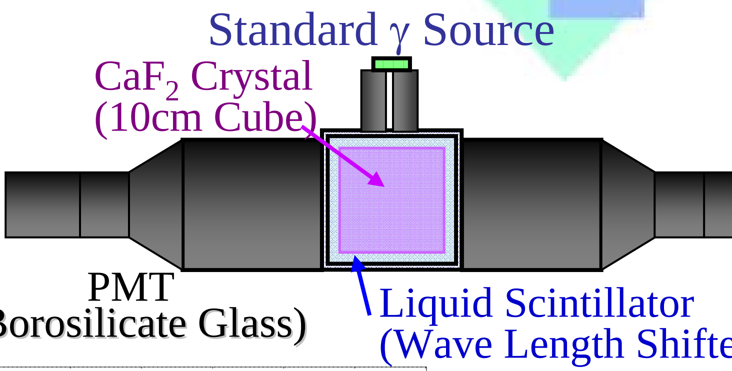
Remaining Background . . .The Only Decays

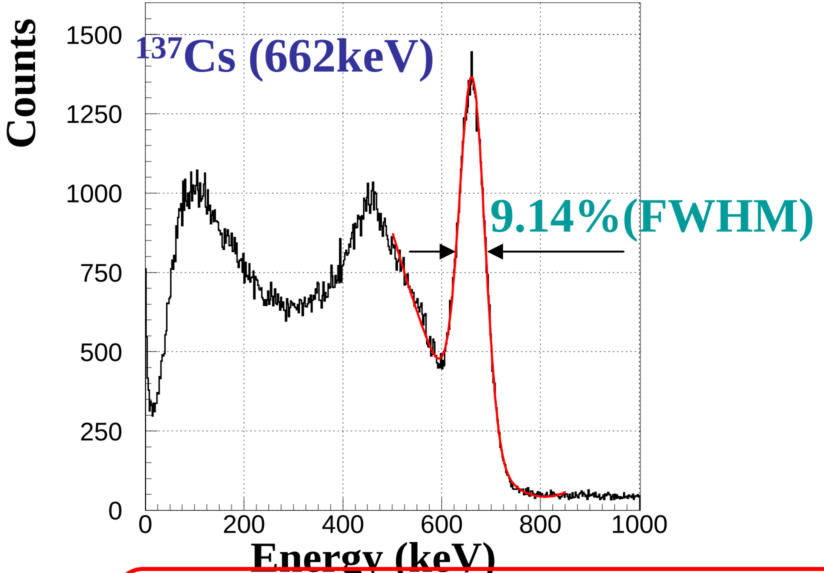
- $2\nu\beta\beta$ Decay Event
  - Improve Energy Resolution
- Natural Radioactivities in CaF_2(pure) Crystal
  - Improve Purity of CaF_2
  - Rejection by Offline Analyses

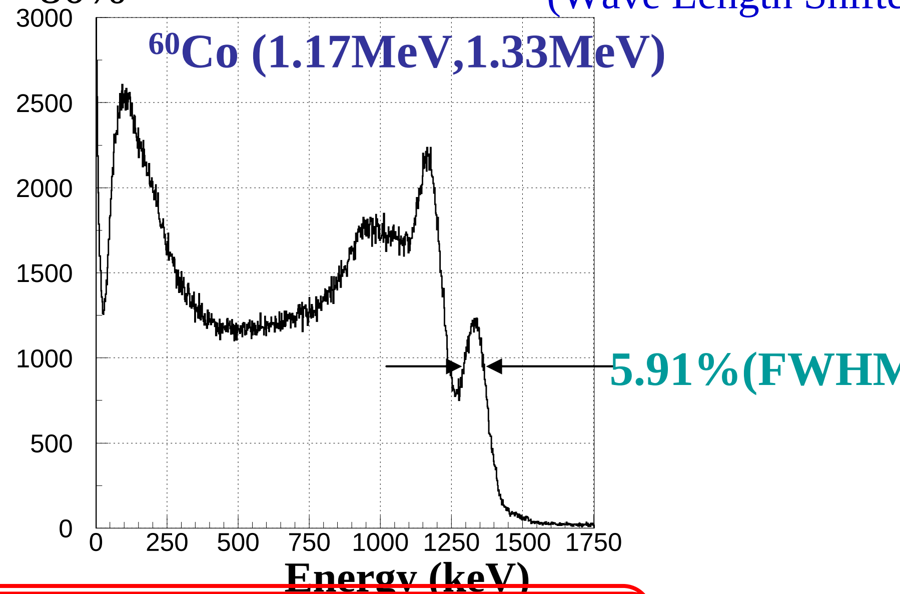
Light Propagation in CANDLES

Energy Resolution with Prototype Detector (CANDLES I)

- CaF_2(pure) (280nm Peak Emission)
- Liquid Scintillator ; Wave Length Shifter
- PMT ; 5inch × 4 modules
- PTFE Reflector → Light Collection : ~80%







Energy Resolution: 9.1%(FWHM) at 662keV

=3.4% (FWHM) at 4.27MeV($Q_{\beta\beta}$ of ^{48}Ca)

Req. for CANDLES III ; 4.0%

Backgrounds from Natural Radioactivities in Crystals

Sequential Pulse

U-Chain

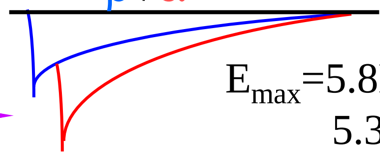
^{238}U ‥ ^{214}Bi (Q_β = 3.27MeV) —β→ ^{214}Po ($T_{1/2}$ = 164μsec, Q_α = 7.83MeV) —α→ ^{210}Pb

Th-Chain

^{232}Th ‥ ^{212}Bi (Q_β = 2.25MeV) —β 64%→ ^{212}Po ($T_{1/2}$ = 0.299μsec, Q_α = 8.95MeV) —α→ ^{208}Pb stable

Sequential Pulse

β+α



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

Because . . .
CaF_2(pure) Decay Constant
: 900ns

^{208}Tl Event

Th-Chain

^{232}Th ‥ ^{212}Bi (Q_α = 6.09MeV) —α 36%→ ^{208}Tl ($T_{1/2}$ = 3.05min, Q_β = 4.99MeV) —β→ ^{208}Pb stable

E_{max}=5.0MeV

^{212}Bi and ^{208}Tl($T_{1/2}$=3min) . . .
Space-Time Correlation Cut

For Rejection . . .

- Development of High Purity CaF_2(pure) Crystal
- Sequential Pulse Rejection by FADC
- Pulse Shape Discrimination between α and γ rays
- Space-Time Correlation Cut . . . For ^{208}Tl Rejection

Development of High Purity CaF_2(pure) Crystals

Selection of CaF_2 Powder

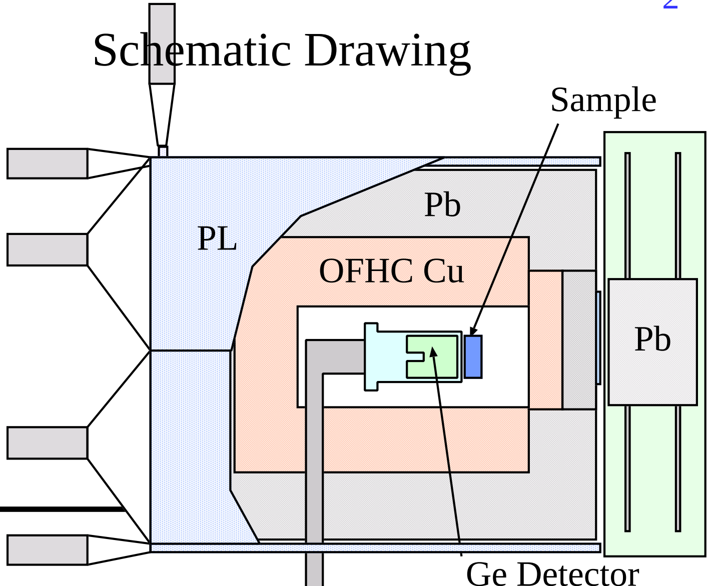
Growing Process of CaF_2(pure) Crystals

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 by delayed coincidence)

HPGe Measurement . . . For Measurement in CaF_2 Powder

Schematic Drawing



For Measurement of CaF_2 Powder : HPGe Detector Sensitivity:〜3mBq/kg

Delayed Coincidence Measurement

Delayed Coincidence Measurement . . . Radioactivities in Crystals

U-Chain: ^{238}U ∘ ∘ ^{214}Bi —β→ ^{214}Po ($T_{1/2}$ = 164μsec) —α→ ^{210}Pb

Q_β = 3.27MeV Q_α = 7.83MeV

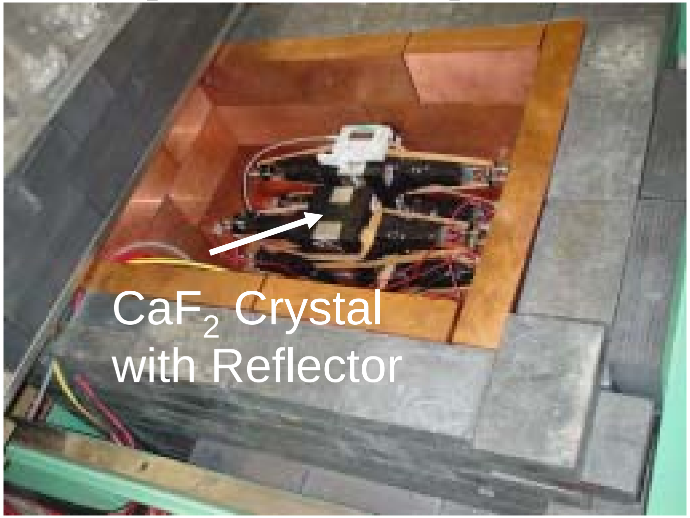
Th-Chain: ^{232}Th ∘ ∘ ^{220}Rn —α→ ^{216}Po ($T_{1/2}$ = 145msec) —α→ ^{212}Pb

Q_β = 2.25MeV Q_α = 8.95MeV

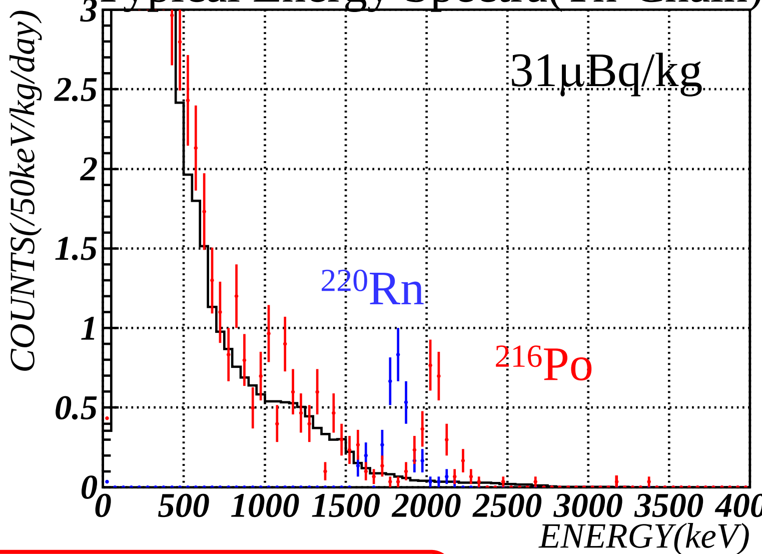
Delayed Coincidence =
Measurement of
2 Correlated Event in the Chains
Prompt Decay + Delayed Decay

CaF_2 Crystal

Experimental Setup



Typical Energy Spectra(Th-Chain)



For Measurement of CaF_2 Crystal
: Delayed Coincidence Measurement . . . Sensitivity:〜5μBq/kg

Development of High Purity CaF_2(pure) Crystals

Relation between Radioactivities in Powder and Crystal

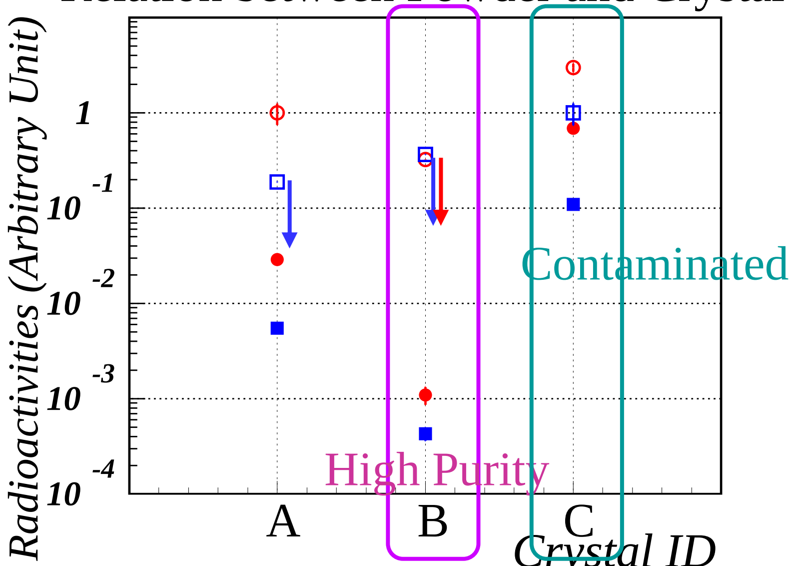
Check of Radioactivities
in many kinds of Powder and Crystals

- ○ Powder Radioactivity (U-chain)
- ● Crystal Radioactivity (U-chain)
- □ Powder Radioactivity (Th-chain)
- ■ Crystal Radioactivity (Th-chain)

High Purity Powder
⟶ High Purity Crystal

⇨ Selection of Powder

Relation between Powder and Crystal

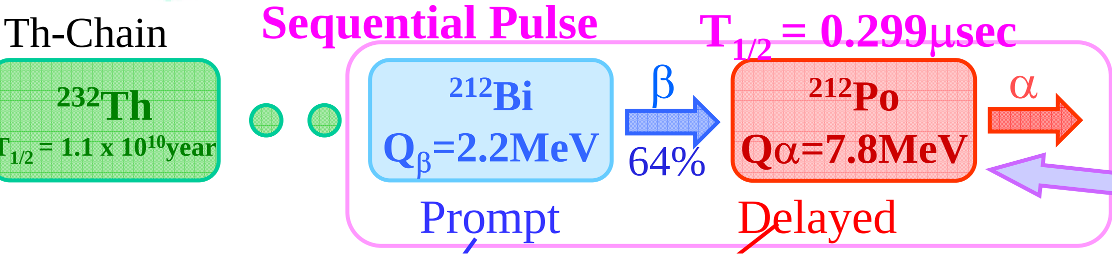


So far . . .CaF_2(Eu) in ELEGANT VI System
U-chain(^{214}Bi) :1100μBq/kg
Th-chain(^{220}Rn) :98μBq/kg

U-chain(^{214}Bi) : 41μBq/kg (Averaged 42) . . . 1/25 of Previous Crystals
Th-chain(^{220}Rn) : 21μBq/kg (Averaged 42) . . . 1/5 of Previous Crystals
in Progress . . .

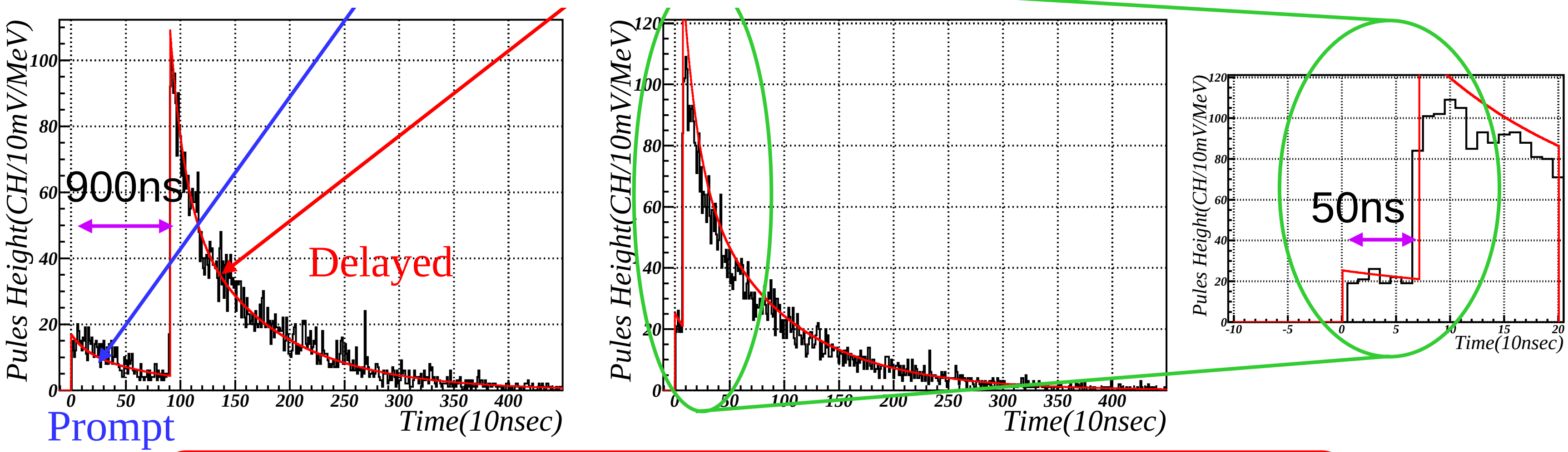
Rejection of Sequential Pulse

Sequential Pulse



Decay Constant of CaF_2(pure)
: 0.9μsec

Typical Pulse Shape(100MHz FADC)



Background Rejection Efficiency by 100MHz FADC

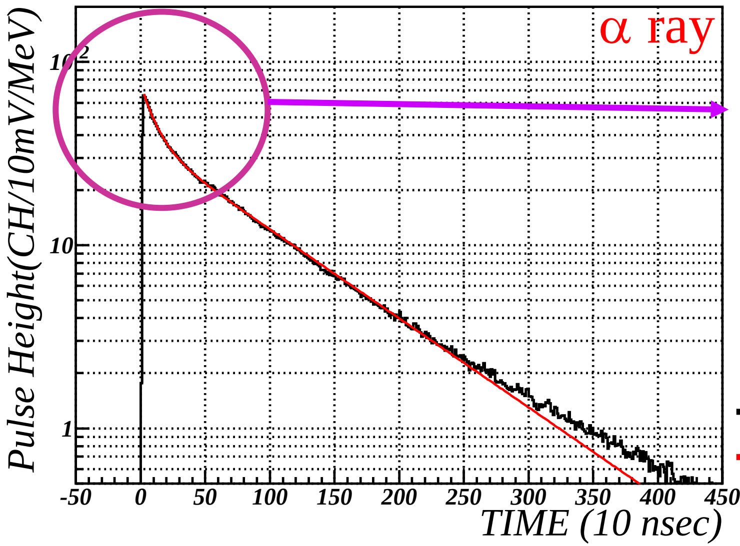
ΔT > 30ns(3ch)

If Fast Sampling FADC . . . ΔT > 5ns ; Rejection Effi. = 99%

Pulse Shape Discrimination

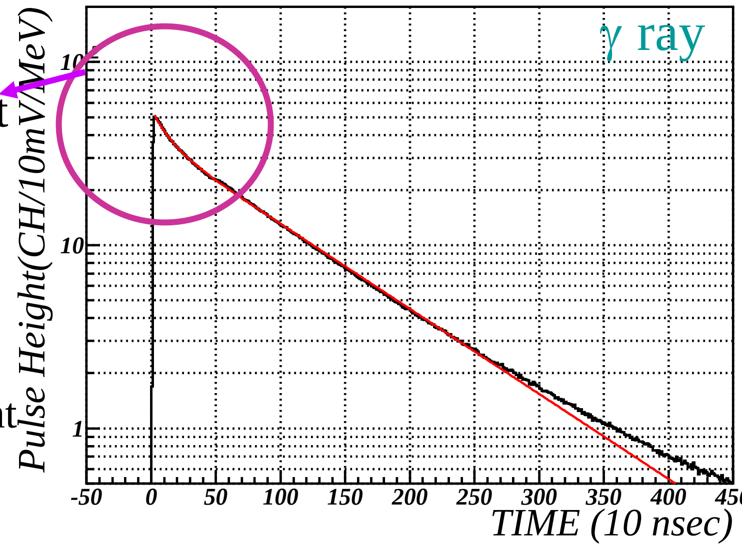
between α and γ rays

Reference Pulse



Fast Component

Measurement
Best Fit



CaF2 Pulse = 2 Exponential Components

α ray Fast	α ray Slow		γ ray Fast	γ ray Slow
111±6ns	894±15ns	Decay Constants	128±13ns	936±13ns
38.4±0.2	37.3±0.7	Intensity	17.3±0.1	38.1±0.7

Intensity of Fast Component

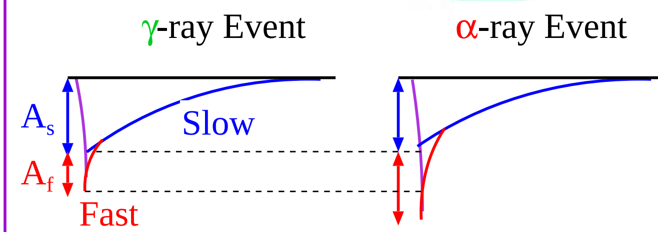
α ray > γ ray . . .Apply to PSD

Pulse Shape Discrimination

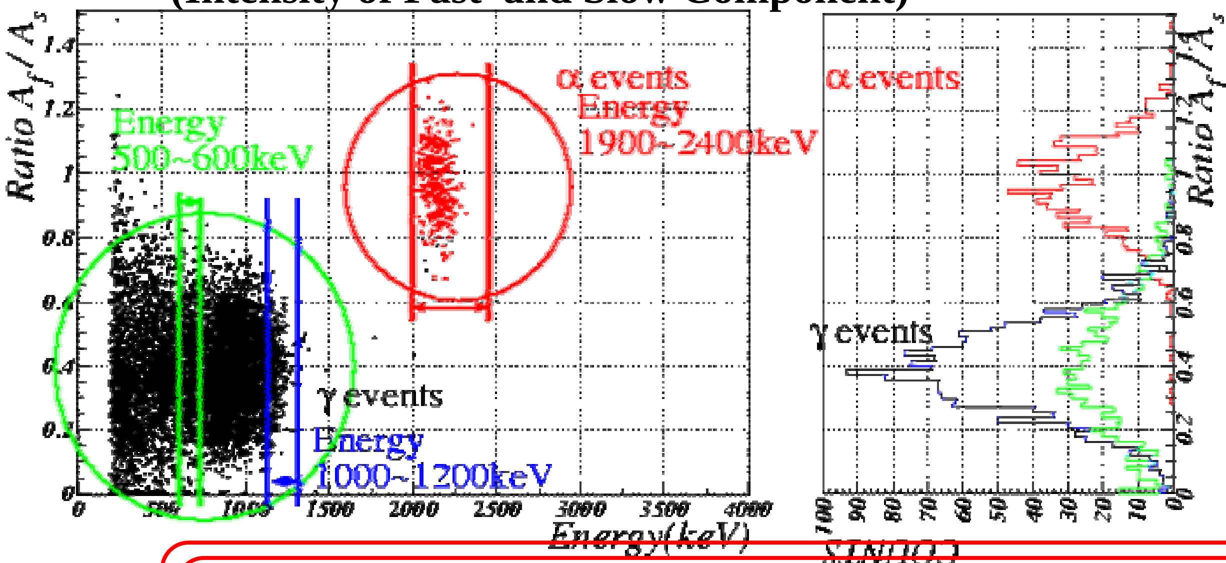
between α and γ rays

- **PSD (Event by Event Analysis)**
  - **FADC (100MHz)**
  - **Fit with Two Exponential Function (fixed time constants)**
  - **Ratio ; A_{fast}/A_{slow} (Intensity of Fast and Slow Component)**

PSD between γ and α rays



A_f/A_s = 0.5(γ-ray) A_f/A_s = 1.0(α-ray)



Clear Discrimination between α and γ(β) Events

Background Rejection Efficiency > 99.7%

Position Correlated Background Rejection

^{208}Tl Events

Th-Chain

^{232}Th ($T_{1/2}$ = 1.1 x 10^{10}year) ● ● ^{208}Tl Event: ^{212}Bi —α 36%→ ^{208}Tl ($T_{1/2}$ = 3.05min) —β→

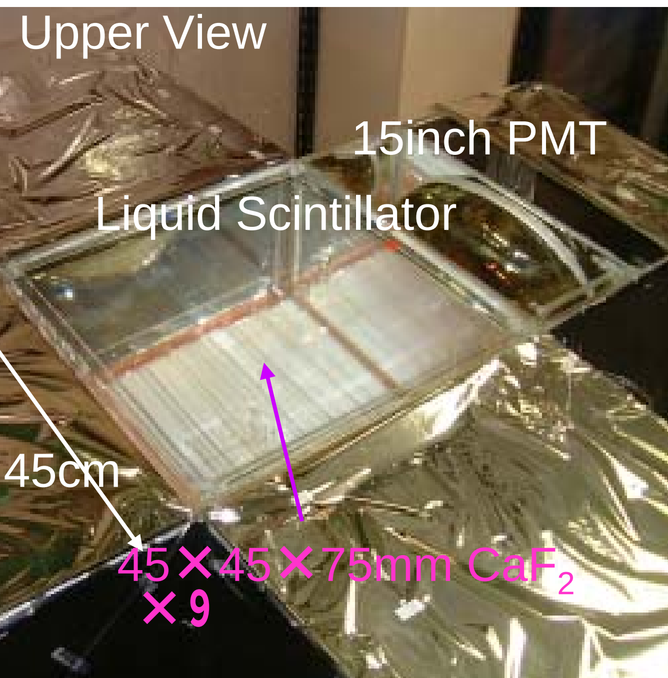
Q_β = 4.99MeV

Prompt α-ray Delayed β-ray

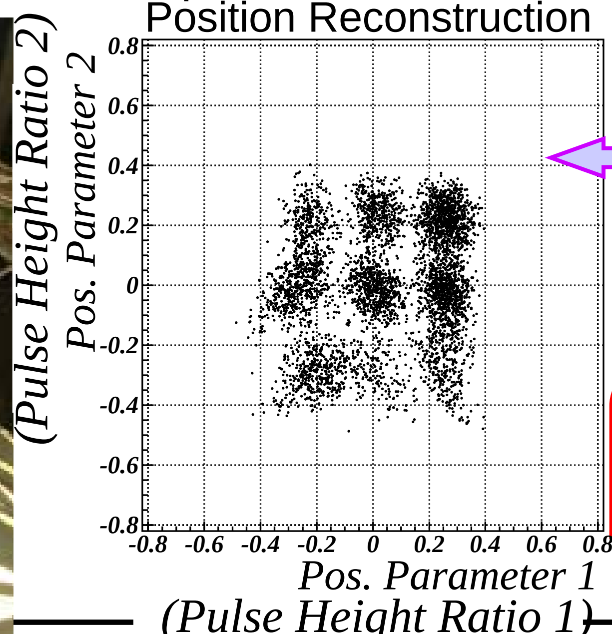
For ^{208}Tl Event Rejection . . .
Space-Time Correlation Cut
The Same Crystal (α and β-rays
$T_{1/2}$=3min

Check for Space Correlation Cut (Position Reconstruction)

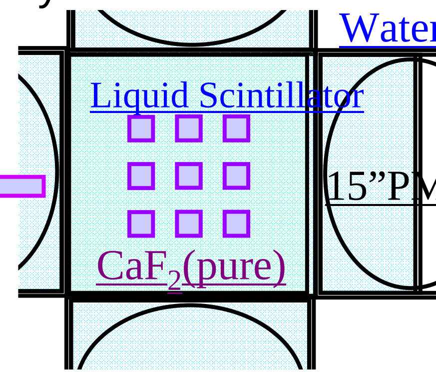
Experimental Setup (CANDLES II)



Experimental Result



Crystal Position



Reconstruction of Event Position
⇩
Rejection of ^{208}Tl Events

Background Rate of CANDLES Series

CANDLES Series

	CANDLES III	CANDLES IV	CANDLES V
Crystal	3.2kg×60 crystals		
Total Mass	191kg	6.4 ton	100 ton
Energy Resolution	4.0%(Req.)	3.5%(Req.)	3.2%(Req.)
^{4}Bi(μBq/kg) in Crystal	50	10	1
^{2}Bi(μBq/kg) in Crystal	20	1	0.1
2νββ	0.01	0.10	1.33
^{214}Bi	0.01	0.03	0.05
^{212}Bi	0.07	0.10	0.15
^{208}Tl	0.04	0.06	0.10
Expected BG	0.14/year	0.29/year	1.63/year
Measuring Time	5 years	6	7
<mν>	0.56 eV	0.10	0.03

Summary

- Background Rejection & Reduction
  - CANDLES System
    - 4π Active Sheild by Liquid Scintillator
  - Energy Resolution . . . for 2νββ Reduction
    - 4.0% (FWHM)@4.27MeV for CANDLES-III
      : PMT coverage ~60%(PMT ×60)
  - Radioactivities in CaF_2 **(averaged 42)**
    - U- and Th-Chain activity ; 41μBq/kg,21μBq/kg
  - BG Rejection Factor
    - Sequential Pulse Rejection ×10^{-2} (min. time lag : 5 nsec)
    - PSD efficiency ×10^{-3} at 4MeV (Energy dep.)
    - Space-Time Correlation (for ^{208}Tl) ×10^{-4}

⇨ CANDLES III Sensitivity : 0.56eV