Status of the search for ^{48}Ca double beta decay with CANDLES

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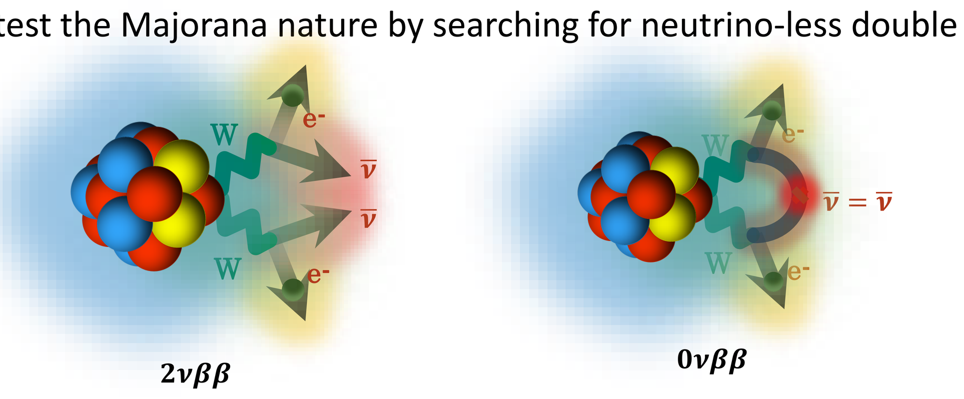
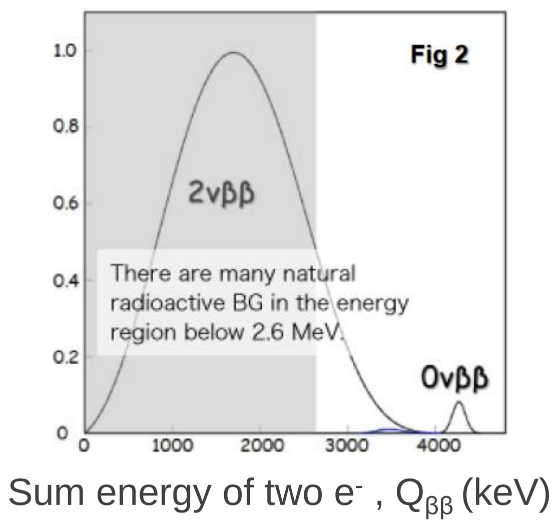
I. Introduction

Neutrino less double beta decay

- The origin of neutrino masses is one of the unsolved puzzles in particle physics
- One possibility is that neutrinos have Majorana masses
- We can test the Majorana nature by searching for neutrino-less double beta decay ($0\nu\beta\beta$)



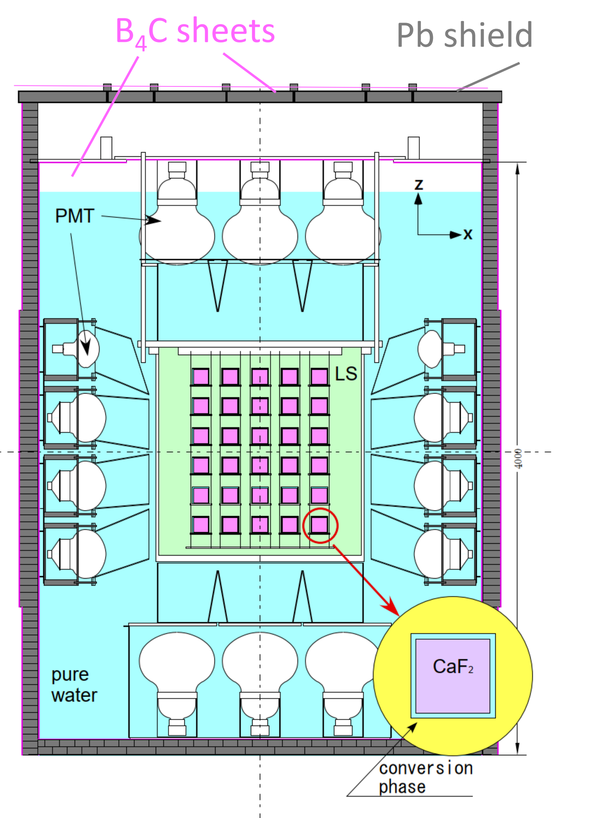


Double beta decay of ^{48}Ca

- Our target is the double beta decay of 48Ca
  - Largest $Q_{\beta\beta}$-value of 4.27 MeV among known $0\nu\beta\beta$ nuclei
  - The lightest double beta decay nucleus

II. CANDLES-III system

- CANDLES-III system is installed underground in Kamioka observatory
- CaF2 scintillator
  - 3.2 kg × 96 natural CaF2 crystals (350 g of 48Ca)
  - ^{48}Ca: $0\nu\beta\beta$events have high $Q_{\beta\beta}$ =4.27 MeV
- Liquid scintillator (LS): 1.8 m3
  - 4π active shield
- Photo multiplier tubes (PMTs): 62 PMTs
  - 10, 13, and 20 inch PMTs
- Shielding background radiation
  - Pb: 10-12 cm
    - Reduce gamma events by ~1/100
  - B4C sheets: 0.5 cm
    - Reduce thermal neutron by ~1/1200

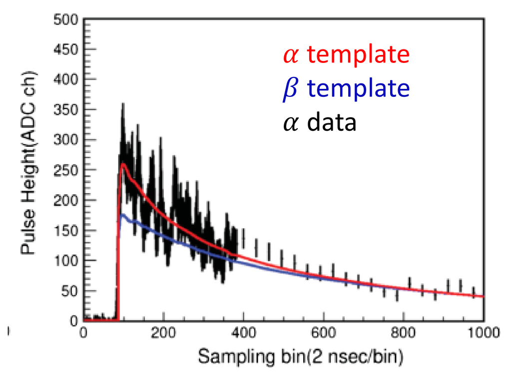


III. Review of Previous analysis

Background (BG)s and their reduction

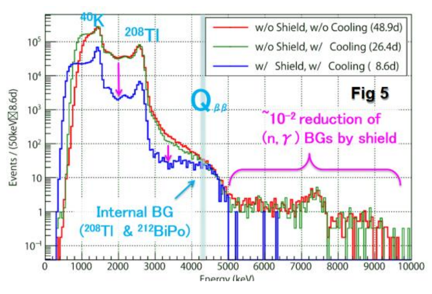
Pulse shape discrimination technique:

- To distinguish α backgrounds and β signals, we use pulse shape discrimination (PSD) technique, which use the information of pulse shape
  - External γ backgrounds, which deposit energy in surrounding LS, are also discriminated by using PSD



(n, γ) backgrounds:

- Reduced by Pb and B_4C shields and its number of events was estimated with Monte Carlo(MC) simulations (K. Nakajima et al. 2018)



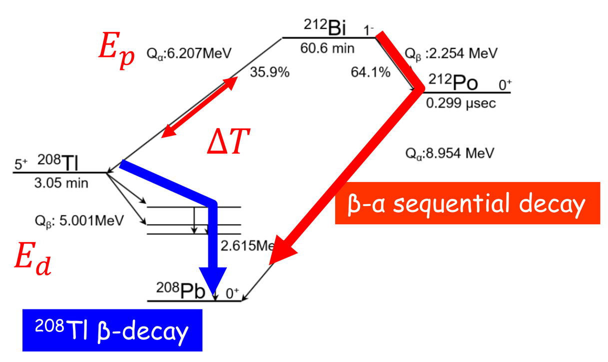
S. Ajimura et. al. (2021)

^{212}Bi-^{212}Po backgrounds:

- ^{212}Bi-^{212}Po sequential decay's energy cannot be separated and measured to be up to 5.1 MeV
  - Sequential decay can be identified using rising shape of pulses
  - We are working on reducing this BGs using machine learning
  - We expect to reduce this BGs almost 100%

^{208}Tl backgrounds:

- β decay produces γ ray
  - total energy is up to 5.0 MeV
- We can veto this background using delayed coincidence method by tagging parent ^{212}Bi
  - α events with 1.63 MeV (quenched energy of 6.027 MeV)



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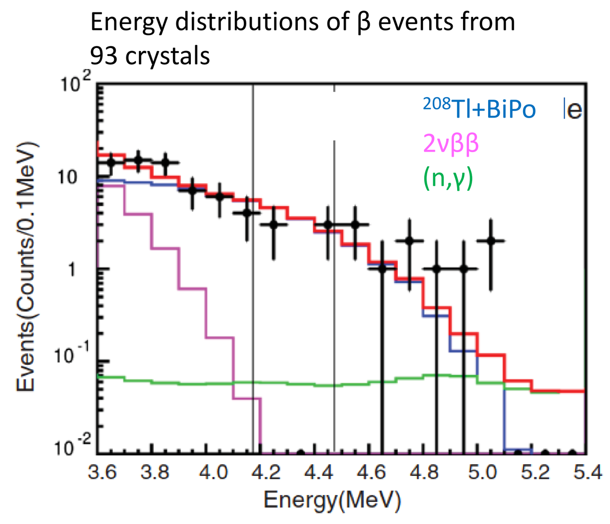
Dominant background events in Run9

- We made 130.4 days of observation in previous run (Run9) [2]
- The dominant background event is by 208Tl background
  - To reduce this BG, we lost live-time in Run9
  - In Run10 with 652.0 days of events, we want to increase the live time

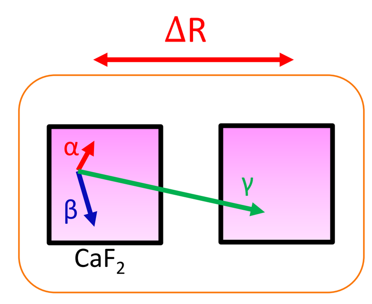


With selected 21 crystals	
Live-time	130.4 days
0νββ efficiency	37.5%
Events in ROI	0
Expected BGs	1.0
Limit	>5.6 × 10^{22} yr
Sensitivity	2.7 × 10^{22} yr

[2] S. Ajimura et. al., Phys. Rev. D. 103 092008 (2021)

We want to reduce the veto time

- We used some variables to veto ^{212}Bi->^{208}Tl->^{208}Pb events in Run009
  - E_d (delayed energy): energy deposit of β from ^{208}Tl decay: 3.5 MeV < E_d
    - 0νββ signal region
  - E_p (prompt energy): energy deposit of α from ^{212}Bi decay: 1.50 < E_p < 1.89 MeV
  - ΔT :time difference between ^{212}Bi decay and ^{208}Tl decay: ΔT < 1080 s



- In Run009, we lost 27.3% of events by this Run9 veto

To increase live-time

- We try to include position difference between prompt event and delayed event
  - Since $\beta+\gamma$ events can deposit energy in different crystals, this helps to identify the sequential decays
  - ΔR : position difference between energy deposited position between ^{212}Bi α event and ^{208}Tl $\beta+\gamma$ event
  - We also introduce "likelihood analysis" to effectively veto signal like (^{212}Bi→^{208}Tl) events

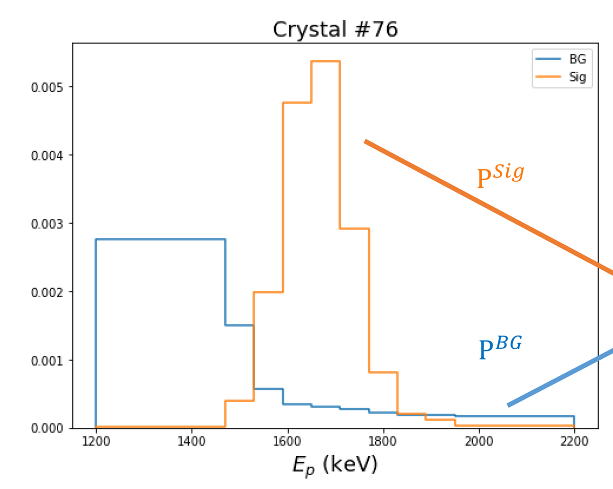
IV. Likelihood analysis

How to construct Likelihood?

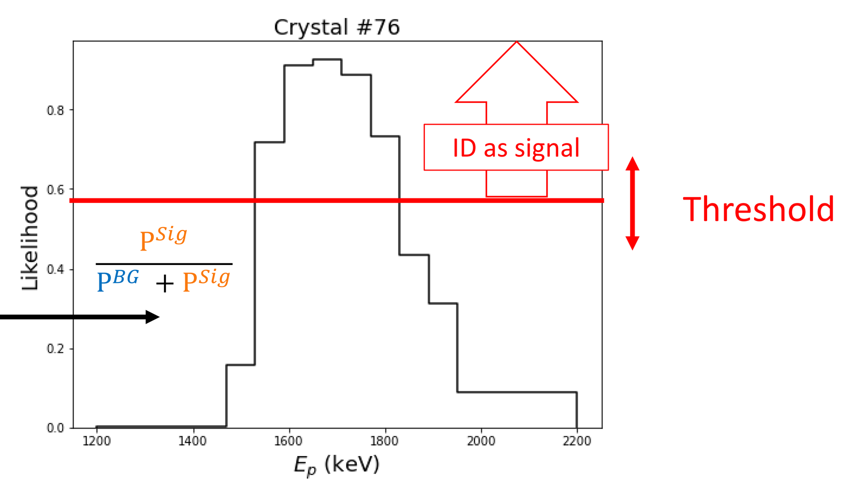
- From Monte Carlo simulations (MC), generated signal (^{212}Bi→^{208}Tl) probability function, P^{Sig}
- From MC and data, generated BG probability function, P^{BG}
- Construct a likelihood function by

$$\mathcal{L} = \frac{P^{Sig}}{P^{BG} + P^{Sig}}$$

- Identify all the events which excess likelihood threshold as signal events

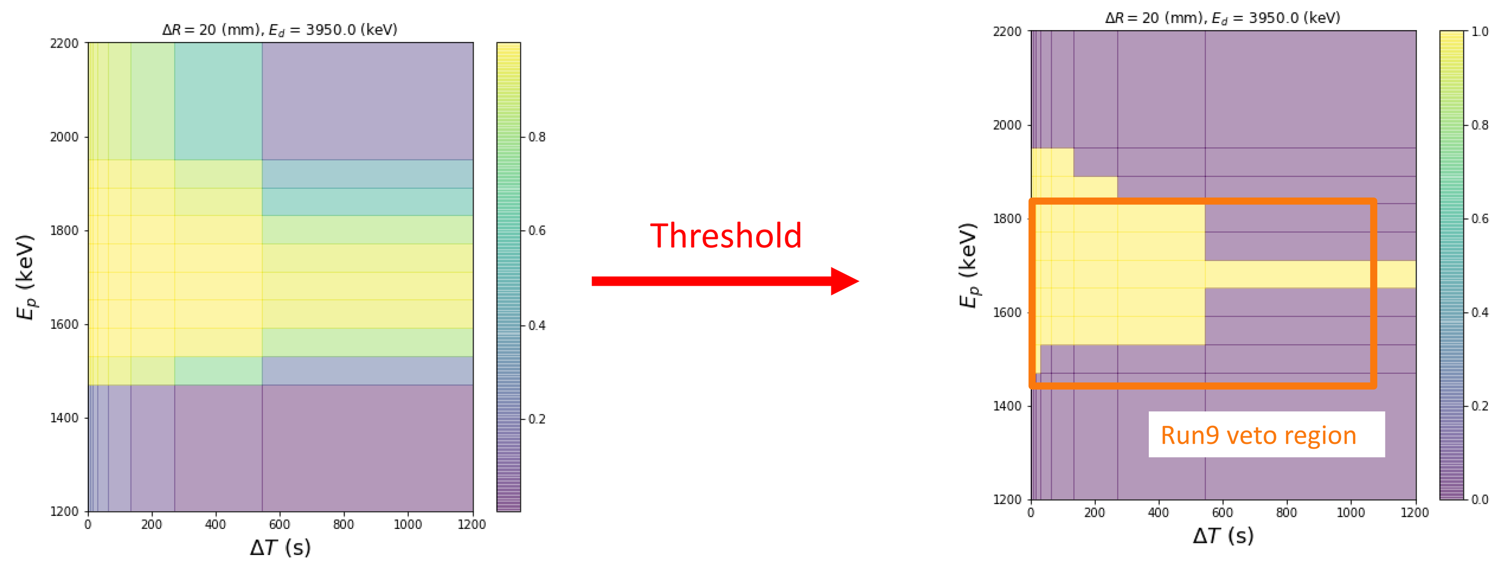


Probability function



Likelihood function

- We construct a likelihood function with 4-dimensions from the four variables ($E_d, E_p, \Delta T, \Delta R$)
- We define the likelihood threshold to realize the similar signal efficiency with Run9 veto



Example 2D Likelihood function

likelihood region which excess threshold

We can reduce veto region thanks to the likelihood analysis

V. Results

- We apply the old-style veto and the new veto to all Run010 event whose live-time is ~ 652.0 days (with 21 crystals)
  - Without ^{212}Bi-^{212}Po cut
- We compare the live-time after the veto
  - Since the veto ΔT depends on E_d and ΔR, we use the maximum ΔT against any E_d and ΔR bins

Preliminary	Live-time with veto/Total live-time (with 23 pure crystals)
Run9 veto	66.5%
New veto	77.3%

We can increase the live-time by 16.4% in Run010 data.

- Including Run009 data, we can have 130.4+652.0 days of live-time
- We increase the live-time efficiency by 16.4%
- Thus, we expect to set limit of half-life for $0\nu\beta\beta$ as 1.6 × 10^{23} yr with $T^{1/2} \propto \frac{T^{obs}}{\sqrt{N_{obs}}}$
  - (With Run009 data, 5.6 × 10^{22} yr)
  - Improvement of a factor of three

VI. Future prospects

- We plan to include PSD in the likelihood analysis
  - Because α decay of ^{122}Bi also emits γ, pulse shape information can help to distinguish ^{122}Bi decay events from other events
- We are making study of enrichment of ^{48}Ca with Lase Isotope Separation technique
  - We found that we can collect ^{48}Ca with deflection method [TAUP2019, SPLG2021, UGAP2022]
- We also plan to develop scintillating bolometers with superconducting detectors to realize high energy-resolution