Status of ^{48}Ca double beta decay search and its future prospect in CANDLES

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Abstract. CANDLES(CAlcium fluoride for the study of Neutrinos and Dark matters by Low Energy Spectrometer) is the experiment to search for the neutrino-less double beta decay($0\nu\beta\beta$) of ^{48}Ca with CaF_2 scintillator. ^{48}Ca has the highest $Q_{\beta\beta}$-value (4.3 MeV) among all isotope candidates for $0\nu\beta\beta$. It enables us to measure signals with very low background condition. After rejection analysis with 131 days $\times$ 86 kg data for background events from radioactive contaminations in the CaF_2 scintillators, no events are observed in the $Q_{\beta\beta}$-value region. As a result, the $0\nu\beta\beta$ half-life of ^{48}Ca is greater than 6.2×10^{22} yr (90% confidence level). For further high sensitive measurement of ^{48}Ca $0\nu\beta\beta$ search, we have been developing the ^{48}Ca enrichment and CaF_2 scintillating bolometer techniques. In this paper, the latest result for CANDLES and the status of scintillating bolometer development are described.

1. CANDLES experiment

1.1. The CANDLES detector

The CANDLES detector is installed at Kamioka underground observatory(2700 m.w.e.), Japan.

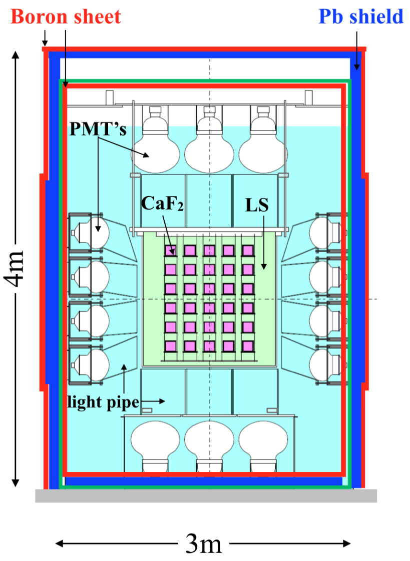

Figure 1. A schematic view of the CANDLES detector. The detector consists of 96 CaF_2(pure) scintillators with total mass of 305 kg. These scintillators are immersed in the liquid scintillator. The liquid scintillator with total volume of 2 m^3 is used as an 4π active shield to veto external backgrounds. Scintillation lights from the CaF_2(pure) and the liquid scintillator are corrected by the light pipes and measured by 62 large photomultiplier tubes. Boron sheet, Pb shield and pure water are used for passive shield against external backgrounds.

1.2. Background of the CANDLES experiment

Although backgrounds can be strongly limited due to the 4 π active shield and the highest Q-value of ^{48}Ca, the remaining backgrounds are following processes.
(a) $^{212}\mathrm{Bi} \rightarrow {}^{212}\mathrm{Po} \rightarrow {}^{208}\mathrm{Pb}$ (Th-chain)
(b) $^{208}\mathrm{Tl} \rightarrow {}^{208}\mathrm{Pb}$ (Th-chain)
(c) γ-rays from neutron capture
The backgrounds form (a) and (b)processes can be rejected by analysis[1]. The backgrounds form (c) process are reduced by the shielding system with boron sheet and Pb shield.

1.3. Half-life

By using the background rate and experimental event rate, we present a lower $0\nu\beta\beta$ half-life limit of 6.2×10^{22} yr (90% confidence level). The limit is compatible to the result for more than 2 years by the previous detector ELEGANT VI[2].

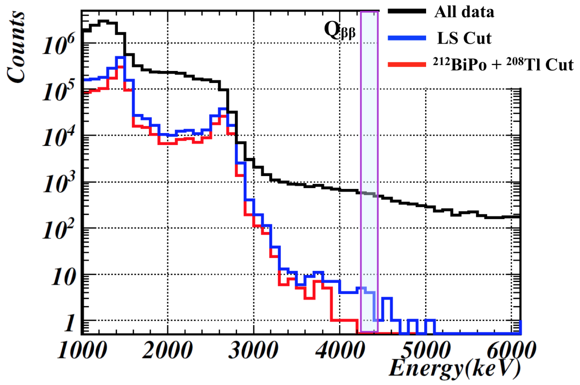

Figure 2. Obtained energy spectra by using high-purity 27 CaF_2(pure) scintillators. Black spectra represents all data. Blue one is the spectra after rejecting the external backgrounds. Red one is the spectra after rejecting the internal backgrounds. Measurement time is 131 days. After the event selections, there are no events in the $Q_{\beta\beta}$-value region.

2. CaF_2 Scintillating Bolometer

CANDELS develop two strategic plans to improve the detection sensitivity in the ^{48}Ca $0\nu\beta\beta$ search. One is the technology development of ^{48}Ca enrichment. The other is the development of scintillating bolometers using CaF_2 crystals. We report here our recent progress on the low temperate detector development. Scintillating bolometers can provide a high energy resolution and an efficient particle identification (PID). Both are crucial detector parameters to search for $0\nu\beta\beta$ of ^{48}Ca. A high resolution detection minimizes the interference at the energy region of interest (ROI) from $2\nu\beta\beta$ signals which are an inevitable source of backgrounds. Moreover, a PID capability discriminates the alpha signals appearing in the ROI. We develop CaF_2 scintillating bolometers having the two features based on metallic magnetic calorimeter (MMC) technology [3].

2.1. The CaF_2 Scintillating Bolometer detector

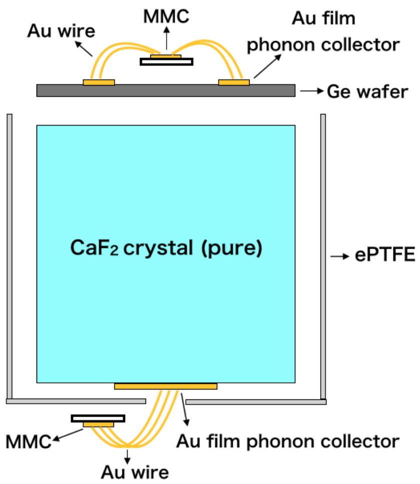

Figure 3. A schematic view of a CaF_2 scintillating bolometer for heat and light detection. A CaF_2(pure) of 5cm diameter and 5cm height was used as the absorber crystal. A 2 cm diameter gold film on the CaF_2 surface transfers the heat to an MMC phonon sensor via gold wires. This heat channel measures the major energy deposit to the crystal. Scintillation photons absorbed in the 2 inch Ge wafer are measured with another MMC photon sensor.

2.2. Particle identification

Alpha signals can be discriminated by relative amplitude ratios of heat and light signals in a simultaneous detection for heat and light signals at low temperatures. Figure 4 shows a 2D scatter plot of PSD parameters of the heat and light signals measured in an above-ground laboratory. A clear PID was shown with 5.4 σ discrimination power.

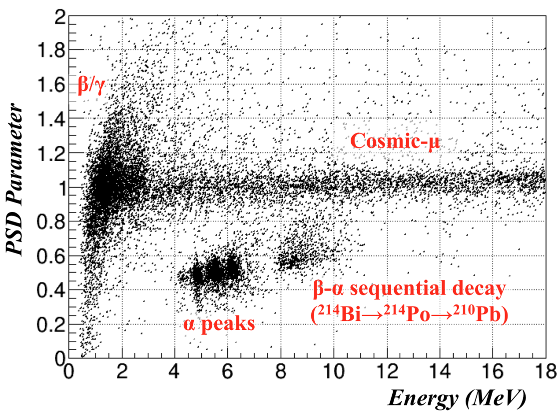

Figure 4. PSD parameter distribution. The energy is measured with the heat channel. The PSD parameter is found from the light/heat ratio and the rise time of photon signals. The alpha signals originate from internal impurity contamination intentionally added during crystal fabrication.

2.3. Energy resolution

Figure 5. represents the energy spectrum of the alpha events around 5 MeV. The energy resolution is 1.8%(σ) at 4.89 MeV which is much worse than the baseline resolution found from the signal to noise ratio. Position dependence of photon and phonon signals are responsible for the excess energy resolution. Alpha events from ^{222}Rn $\rightarrow$ ^{218}Po $\rightarrow$ ^{214}Pb are used for the position dependence study. As the half life of ^{218}Po is 3.1 minutes, a consecutive alpha decays of ^{222}Rn and ^{218}Po pairs are selected with 3-minute cut. As shown in Figure 6, ^{222}Rn and ^{218}Po events have a strong correlation. The amplitude ratio of the two events is the same as the energy ratio, 1.09. After correction of this effect, the energy resolution becomes 0.18% (σ) at 5 MeV.

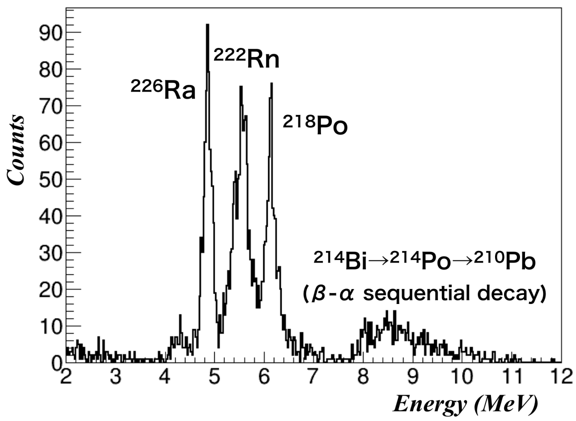

Figure 5. Energy spectrum of alpha events.

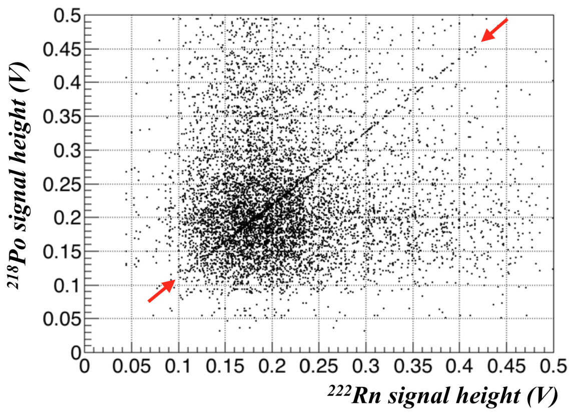

Figure 6. Amplitude correlation between ^{222}Rn and ^{218}Po events in the heat channel.

3. Conclusion

CANDLES is the experiment to search for the $0\nu\beta\beta$ of ^{48}Ca with CaF_2 scintillator. After rejection analysis with 131 days $\times$ 86 kg data for background events from radioactive contaminations in the CaF_2 scintillators, the $0\nu\beta\beta$ half-life of ^{48}Ca is greater than 6.2 $\times$ 10^{22} yr (90% confidence level). For further improvement, we started developing CaF_2 scintillating bolometers with the Korean group. A low temperature measurement was carried out using a CaF_2(pure). A clear PID was demonstrated with a 5.4 σ discrimination power around the Q-value. An energy resolution of 1.8% was obtained at 4.89 MeV. With corrected position dependence, it became 0.18%. This R&D demonstrates CaF_2 crystals can be used in heat and light detection at low temperatures to search for $0\nu\beta\beta$ of ^{48}Ca. Further research on position dependance is ongoing to improve the energy resolution.

Acknowledgments

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References

[1] Umehara *et al.* 2016 *Proceedings of Science (INPC2016)* 246
[2] Umehara S *et al.* 2008 *Phys. Rev. C* **78** 058501
[3] Kim I *et al.* 2017 *Supercond. Sci. Technol.* **30** 094005