PROCEEDINGS OF SCIENCE

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

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The origin of neutrino masses remains shrouded in mystery. One of the possible scenarios is that neutrinos have Majorana masses, which leads to neutrinoless double-beta decay ($0\nu\beta\beta$). CANDLES is a project to search for the $0\nu\beta\beta$ events from ^{48}Ca, which has a relatively high $Q_{\beta\beta}$-value of 4.27 MeV among the known double beta decay nuclei. We developed a CANDLES-III system with 96 CaF_2 scintillation crystals with natural Ca isotope, which corresponds to 350 g of ^{48}Ca, and took data with about 652 days of observation from 2016. We are preparing a method to reduce β-decay background events to increase the sensitivity to the signal. In this contribution, a development of the method for background reduction and the latest status of the search for the $0\nu\beta\beta$ will be reported.

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1. Introduction

The origin of neutrino masses remains shrouded in mystery. One of the possible scenarios is that neutrinos have Majorana masses [1], which leads to neutrinoless double-beta decay ($0\nu\beta\beta$) events [2]. CANDLES (CAlcium fluoride for the study of Neutrinos and Dark matters by Low Energy Spectrometer) is a project searching for $0\nu\beta\beta$ events from ^{48}Ca which has high $\mathrm{Q}_{\beta\beta} = 4.27\,\mathrm{MeV}$ [3]. We developed a CANDLES-III system with 96 CaF_2 scintillation crystals of natural Ca isotope, which is effectively 350 g of ^{48}Ca [4]. In searching for $0\nu\beta\beta$ events with the CANDLES-III system, we need to tag and veto the γ-rays from external sources and β-rays from the decays of the impurities in the CaF_2 crystals.

In Ref. [5], they searched for $0\nu\beta\beta$ events with 130.4 days of live-time ("Run009"). The most dominant background events in Run009 is β decay events from ^{208}Tl with Q_β-value of 5.0 MeV. We can tag the ^{208}Tl events by searching for its prompt event, α event from the decay of ^{212}Bi, whose lifetime is 3.05 min and quenched energy is 1.63 MeV. To reduce the ^{208}Tl's β events, they vetoed 18 min of events after the tagged prompt events in the same crystal. This reduced a lot of un-vetoed live-time.

To increase the un-vetoed live-time, we have been developing a new likelihood method to effectively veto the β decay backgrounds [6]. In Ref. [6], we used prompt event energy (E_p) for α-ray energy of α event from the decay of ^{212}Bi, delayed event energy (E_d) for β/γ-ray energy in the decay of ^{208}Tl, and time difference (ΔT) between the two events in the same crystal as variables of the likelihood.

However, γ-ray emitted in the decay of ^{208}Tl can deposits energy in the different crystals. With a rough estimation, the ratio of the number of events which deposits energy in the same crystal is about 78% and in the different crystals is about 22%. In this contribution, we introduce a new variable which consider neighboring crystals to the likelihood. Following the Run009, we have taken data with 652.0 days of live-time ("Run010"). We show the results in the application of the new likelihood method to the Run010 data.

The rest of this contribution is organized as follows. In Sect. 2, we introduce the new likelihood method and show the performance of the new method in Sect. 3. In Sect. 4, we conclude and discuss.

2. Likelihood method with a new variable

We firstly review the methodology of Ref. [6]. In the construction of the likelihood, we refer to the sequential decays of ^{212}Bi and ^{208}Tl as "signal" events and the other background evens as "background" events. To construct a likelihood, with variables $\vec{x}$, we need a Probability Distribution Function (PDF) of the signal events, $P^{\mathrm{S}}(\vec{x})$, and of the background events, $P^{\mathrm{B}}(\vec{x})$. Then we can have a likelihood as,

$$L(\vec{x}) = \frac{P^{\mathrm{S}}(\vec{x})}{P^{\mathrm{S}}(\vec{x}) + P^{\mathrm{B}}(\vec{x})}. \tag{1}$$

In Ref. [6], we used E_p, E_d, and ΔT for the elements of $\vec{x}$.

In this contribution, we introduce a new variable which stands for a position difference between the prompt α event in the i-th crystal and the delayed β/γ event in the j-th crystal, ΔR^{ij}. To include crystal number, we redefine the previous variables as $E_p \rightarrow E_p^i$, $E_d \rightarrow E_d^j$, and $\Delta T \rightarrow \Delta T^{ij}$.

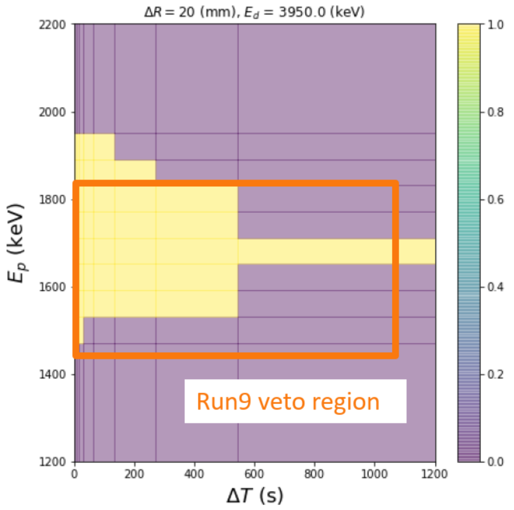

Figure 1: E_p vs ΔT region which excess likelihood threshold ℓ with $E_d = 3950.0$ keV and $\Delta R = 20$ mm.

Note that, we have to consider the correlation between E_d^j and ΔR^{ij} for signal events, because high energy γ can propagate to far crystals.

We construct signal PDFs of the E_p^i and of the E_d^j vs ΔR^{ij} with Monte Carlo (MC) simulations and that of the ΔT form the analytical exponential function with the lifetime of ^{212}Bi decay. We obtain the final $P^{\mathrm{S}}(\vec{x})$ by the product of these PDFs.

We construct background PDFs of the E_p^i and E_d^j from all the candidate events in the data. For the background PDF of ΔR^{ij}, we take position differences of all the candidate of prompt and delayed events in the data. We construct the background PDF of ΔT from the analytical flat distribution. We obtain the final $P^{\mathrm{B}}(\vec{x})$ by the product of these PDFs. With these constructed $P^{\mathrm{S}}(\vec{x})$ and $P^{\mathrm{B}}(\vec{x})$, we can construct a likelihood as Eq. (1).

In the next section, we will compare this new likelihood with the old Run009-like veto.

3. Results

To assess the performance of the new likelihood with ΔR, we apply the new likelihood and the old Run009-like veto to the all Run010 data and calculated the live-time efficiency which is the ratio of un-vetoed live-time against total live-time. For the fare comparison, we define the likelihood thresholds with which likelihood based cut realize the ^{208}Tl event selection efficiency similar to Run009-like veto. We show the example region where likelihood values excess the threshold in Figure 1. We can see that we can reduce ΔT based cut compared to the rectangular Run009-like veto thanks to the likelihood method.

We find that the live-time efficiency with the new likelihood is 77.3%, whereas that with old Run090-like veto is 66.5%. This leads to the increase of live-time by 16.4%.

4. Conclusions and discussions

In this contribution, we have targeted to reduce the ^{208}Tl's β-decay background events in the CANDLES-III system, which was the dominant background events in the Run009 analysis. We have been working on a development of a likelihood method to efficiently reduce the background event. In this contribution, we introduced a new variable, position difference ΔR, to the likelihood method in addition to the variables of energy and time. With the new likelihood method, we show that we can increase the live-time efficiency by 16.4% compare to the Run009-like veto.

Let us discuss a future prospect on the half-life limit, $T^{1/2}$, on $0\nu\beta\beta$ decay, which is related to $T^{1/2} \propto \frac{T^{\mathrm{obs}}}{\sqrt{N_{\mathrm{BG}}}}$, where T^{obs} is the observation time and N_{BG} is the number of background events. We can increase the T^{obs} by 16.4% thanks to the new likelihood method and the N_{BG} by a factor of six when we add Run010 data to the Run009 data. Therefore, we expect that we can give a limit as $T^{1/2} > 1.6 \times 10^{23}$ yr, which is a factor of 3 improvement from the Run009 result [5].

We still have room to improve the efficiency of the likelihood method by introducing some other variables. For example, we plan to include the pulse-shape related variables to the likelihood analysis to improve the ^{208}Tl BG reduction and we may improve the limit on $T^{1/2}$.

For future upgrade of CANDLES system, we are making study the enrichment of ^{48}Ca with Laser Isotope Separation technique and plan to develop scintillating bolometers with superconducting detectors for high energy-resolution.

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