CANDLES for double beta decay of $^{48}$Ca

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Abstract. CANDLES is the project to search for neutrinoless double beta($0\nu\beta\beta$) decay of $^{48}$Ca by using CaF$_2$ scintillators. The observation of $0\nu\beta\beta$ decay will prove existence of a massive Majorana neutrino. The expected performances of the CANDLES system for light-signal detection and background rejection are presented here. The current status of development for the detector system is also described.

1. Double Beta Decay of $^{48}$Ca

The existence of neutrino mass is indicated by observing atmospheric and solar neutrino oscillations. Neutrino oscillation experiments can determine mass differences by observing transformation from one type to another type of neutrino. However, the absolute scale of neutrino mass and the characterization of neutrino (Majorana or Dirac particle) are still unknown. Observation of neutrinoless double beta ($0\nu\beta\beta$) decay is the very sensitive study to investigate the properties of neutrino [1].

We have been studying the double beta decay of $^{48}$Ca [2]. $^{48}$Ca has the highest $Q_{\beta\beta}$-value (4.27 MeV) among $\beta\beta$ decay isotopes, where low background rate from natural radioactivities is expected. The large $Q_{\beta\beta}$-value also means a large phase space factor which enlarges $0\nu\beta\beta$ decay rate for a given Majorana mass. We have developed and operated the CaF$_2$(Eu) scintillator system ELEGANT VI at the underground laboratory. The first results were obtained by CaF$_2$(Eu) crystals with the total weight of 6.7 kg. We obtained the most stringent limit on the $0\nu\beta\beta$ decay of $^{48}$Ca [2]. In this measurement, the result is not limited by background events because no events were observed in the energy region of $0\nu\beta\beta$ decay. The limiting parameter is a small amount of $^{48}$Ca in the system. Therefore we proposed the large scale detector system CANDLES (CAlcium fluoride for the study of Neutrinos and Dark matters by Low Energy Spectrometer) [3].

2. CANDLES

The design of CANDLES III is schematically shown in figure 1. In the CANDLES III system, CaF$_2$(pure) scintillators with a dimension of 10 cm cube are immersed in liquid scintillator(LS). The LS acts as a $4\pi$ active shield to veto backgrounds as well as a passive shield. Scintillation lights from both scintillators are viewed by large photomultiplier tubes (PMTs; 15 and 13 inches in diameter). The CaF$_2$(pure) scintillator has a decay time of 1 $\mu$s which although the LS has a width of around a few tens nsec. Thus the signals from the CaF$_2$(pure) can be discriminated from signals of LS by observing pulse shape [3, 4]. Thus the external backgrounds can be rejected effectively. The remaining backgrounds are the events from $2\nu\beta\beta$ decay, which can be
The design of the CANDLES III system.

Figure 1. The design of the CANDLES III system.

Figure 2. Energy spectrum obtained by CaF$_2$(pure)+WLS system of $^{137}$Cs source. Energy resolution at 662 keV is 9.1% (FWHM).

Reduced by the good energy resolution, and the events due to radioactive contaminations within CaF$_2$(pure) detector.

3. Light Collection

As mentioned above we need the good light collection to reduce backgrounds from 2$\nu$\textit{\textbeta\beta} decay. The emission spectrum of CaF$_2$(pure) scintillator has a peak at the ultraviolet (UV) region at the maximum of 285 nm. Thus the LS must act as not only an active shield but also a wave length shifter (WLS) to convert the UV light emitted by CaF$_2$(pure) to the visible where the quantum efficiency of the large PMT is quite large (maximum at ~ 400 nm).

In order to achieve the good energy resolution and effective active shield, we apply “Two Phase System” of LS [5]. As shown in figure 1, “Two Phase System” consists of the thin layer of LS as WLS and the large volume luminous LS as veto phase. From the performance point of view as WLS, we selected the paraffin oil (Paral250:P250), which is more transparent for UV light than others [6], as a base solvent and bis-MSB (0.1g/l) as WLS. The performance of the WLS phase in “Two Phase System” was demonstrated with $^{137}$Cs $\gamma$ source as shown in figure 2. For a LS as the veto phase, we need large light output in addition to good transparency. Thus we found the LS mixture of P250(80%) / Pseudocumene(20%) / PPO(WLS:1.0g/l) / bis-MSB(0.1g/l) to be suitable. The attenuation length without purification of LS was evaluated to be 9.5 m. As the result, the expected energy resolution at Q$_{\beta\beta}$ value is 4% which satisfied the requirement for the CANDLES system [7].

4. Background

As mentioned above, backgrounds can be strongly limited in the CANDLES system because of the 4$\pi$ active shield and the good energy resolution. The remaining backgrounds are the events due to radioactive contaminations within CaF$_2$(pure) detector.

The candidate of the radioactive contaminations, which suffer the backgrounds in Q$_{\beta\beta}$ value window, are mostly composed of the following decays, (a) $^{214}$Bi $\beta^{-}$$^{214}$Po ($T_{1/2} = 164\mu$sec) $\alpha$$^{210}$Pb (U-chain) and (b) $^{212}$Bi $\beta^{-}$$^{212}$Po ($T_{1/2} = 0.299\mu$sec) $\alpha$$^{208}$Pb (Th-chain). Two kinds of Po nuclei have short half-lives while CaF$_2$(pure) has long decay constant. Thus radiations emitted by two sequential decays are measured as one event for CaF$_2$(pure) scintillator. As the result, the events are serious backgrounds in interesting energy window for the 0$\nu$\textit{\textbeta\beta} decay [7].

In order to reduce these backgrounds, we studied the development of the high purity crystal.
First we checked the growing process of CaF$_2$(pure) crystal. In the process, we turned attention to CaF$_2$ powder which is raw material of CaF$_2$(pure) crystal. We measured the radioactivities in the powder by using HPGe detector and the ones in the crystals by delayed coincidence method ($\alpha$-ray measurement). We found the radioactivities in the crystal largely depend on those in the powder. By selecting the high purity powder, we could obtain the high purity crystals, whose radioactivities (42 crystals average) are 41(21) $\mu$Bq/kg for U(Th)-chain.

Second we investigated the analysis for rejections of the events. We measured the pulse shape of the sequential events by using 100 MHz flash ADC (FADC). Figure 3 shows a typical pulse shape of the events. We can discriminate the events in which time lags between prompt and delayed events are more than 2 channels ($\sim$25nsec). Since the time lag which can be identified as the sequential pulse largely depends on the time resolution of the detector system, we are developing the fast sampling ($\sim$500MHz) FADC. The backgrounds will be reduced by two orders of magnitude by improvement of the sampling time [7].

In addition, we studied pulse shape discrimination (PSD) between $\alpha$- and $\gamma$-events in order to reject the sequential decays whose time lag is shorter than 5 nsec [7]. The demonstration of PSD is shown in figure 4. $A_f(A_s)$ in figure 4 is an intensity of an exponential fast(slow) component of the scintillation pulse. The details of PSD are given in reference [7]. Including the reduction with time lag analysis, the backgrounds from the sequential events will be reduced by 4 orders of magnitude. As the results, the background rate in the CANDLES III system is expected to be negligible at $Q_{\beta\beta}$ value region.

5. CANDLES III
We are now constructing the CANDLES III system in our laboratory at sea level, which consists of 60 CaF$_2$(pure) crystals with the total mass of 191 kg. Considering the expected energy resolution and background rate, the sensitivity of CANDLES III is $\sim$0.5 eV for neutrino mass. Based on experiences in CANDLES III, the CANDLES project will be scaled up to several tons of calcium to have the sensitivity to the mass region of interest.

References
[1] Doi M, Kotani T and Takasugi E 1985 Prog. Theor. Phys. Suppl. 83 1
[2] Ogawa I et al 2004 Nucl. Phys. A 730 215-23
[3] Kishimoto T et al 2003 Proc. of 4th Int. Workshop on Neutrino Oscillations and their Origin (Kanazawa) (Singapore : World Scientific) pp 338-49
[4] Ogawa I et al 2004 Proc. of 5th Int. Workshop on Neutrino Oscillations and their Origin (Tokyo) (Singapore : World Scientific) pp 260-5
[5] Yoshida S et al 2005 Nucl. Phys. B (Proc. Suppl.) 138 214-6
[6] Iwamoto T and Suekane F 1998 KamLAND-NOTE 98-16
[7] Umehara S et al 2003 Proc. of Symp. on Neutrino and Dark Matters in Nuclear Physics (Nara) (Osaka : Yamada Science Foundation) pp XII3-33