Development of CANDLES Low Background HPGe Detector and Half-life Measurement of ^{180}Ta^m

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Abstract. A low background HPGe detector system was developed at CANDLES Experimental Hall for multipurpose use. Various low background techniques were employed, including hermatic shield design, radon gas suppression, and background reduction analysis. A new pulse shape discrimination (PSD) method was specially created for coaxial Ge detector. Using this PSD method, microphonics noise and background event at low energy region less than 200 keV can be rejected effectively. Monte Carlo simulation by GEANT4 was performed to acquire the detection efficiency and study the interaction of gamma-rays with detector system. For rare decay measurement, the detector was utilized to detect the nature's most stable isomer tantalum-180m (^{180}Ta^m) decay. Two phases of tantalum physics run were completed with total livetime of 358.2 days, which Phase II has upgraded shield configuration. The world most stringent half-life limit of ^{180}Ta^m has been successfully achieved.

INTRODUCTION

The low background HPGe detector is widely used as a high energy resolution γ-ray spectrometer for radioactivity assessment. To improve the sensitivity of the detector, optimization of detection efficiency and minimization of the background level are essential. This requirement become necessary if the measurement sample has long half-life ($T_{1/2}$), extremely low isotopic abundance or emitted γ-ray energy lay within majority of the natural radioactivity. Common low background techniques for HPGe detector including purification of detector material, graded shields, airtight system for radon suppression, underground site and off-line background reduction analysis.

CANDLES is a ^{48}Ca neutrino-less double beta decay experiment using CaF$_2$ scintillators [1]. Low background techniques is required to observe this very rare neutrino-less double beta decay event. Hence, each component used to construct CANDLES must has low radioactivity and background evaluation. A HPGe detector was constructed at CANDLES Experimental Hall, which located at Kamioka Underground Observatory (2700 m. w. e.) [2]. This HPGe detector is used for material screening, rare decay measurement like tantalum-180m (^{180}Ta^m) and other multipurpose. Underground cite at Kamioka provides advantages of muon flux with 5 order magnitude lower than the Earth's surface ($3 \times 10^{-3} m^{-2} s^{-1}$) and easy handling of samples from CANDLES.

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HPGE DETECTOR SYSTEM OF CANDLES

The HPGe detector was equipped with passive shields, liquid nitrogen supply line, data acquisition (DAQ) system and environmental condition monitors, as shown in Figure 1. This HPGe detector is a standard electrode closed coaxial Ge detector (Model GC5019) made by CANBERRA Industries Inc. The Ge crystal size is 65 mm in diameter and 64 mm in length. The relative efficiency is 50 % and energy resolution, FWHM is 1.9 keV at 1.33 MeV. A liquid nitrogen tank is piped to the dewar and refill weekly. Surrounding conditions such as liquid nitrogen level and radon concentration are continuously monitored. Boil-off nitrogen gas is channelled into the detector chamber, which is a very effective background reduction method to suppress radon gas.

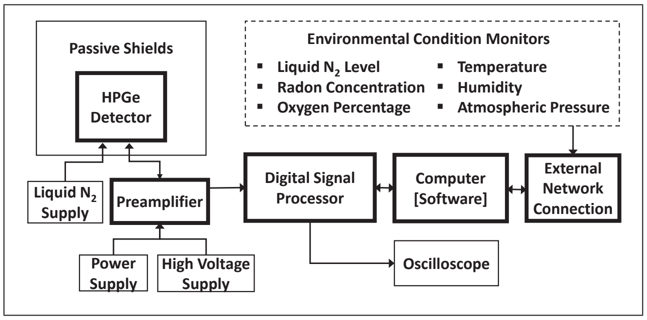

FIGURE 1. Schematic diagram of CANDLES Low Background HPGe detector system.

DAQ system of the detector was indicated by bold line boxes in Figure 1. The digital signal processor (DSP, Model APU8002 by Techno AP Inc.) is capable to perform signal amplification, digitization and pulse shaping. ADC sampling rate is 100 MHz and resolution is 14 bit. Pulse shape of the preamplifier signal can be recorded event-by-event with time range of 640 ns and resolution of 2 ns. This pulse shape information was important to create pulse shape discrimination for background reduction, which will be further explained in later section. The DAQ is connected to the external network, therefore data taking and DSP parameter setting can be controlled off-site.

Hermetic Shielding Design

At underground laboratory, radon gas and natural radioactivity from surrounding rock are one of the major external backgrounds. Figure 2 displayed the cross-sectional view and photographic image of the HPGe detector system. The outer lead and inner copper shields are 150 mm thick and 50 mm thick respectively. To achieve low background condition, special attention was paid when designing the shields. (1) Low radioactivity lead was melted and made into desired shape, which only have three segmentations and very hermetic. This design minimize the empty space between shield blocks and provide airtight condition. (2) OFHC copper shield was made of zig-zag shape long bar

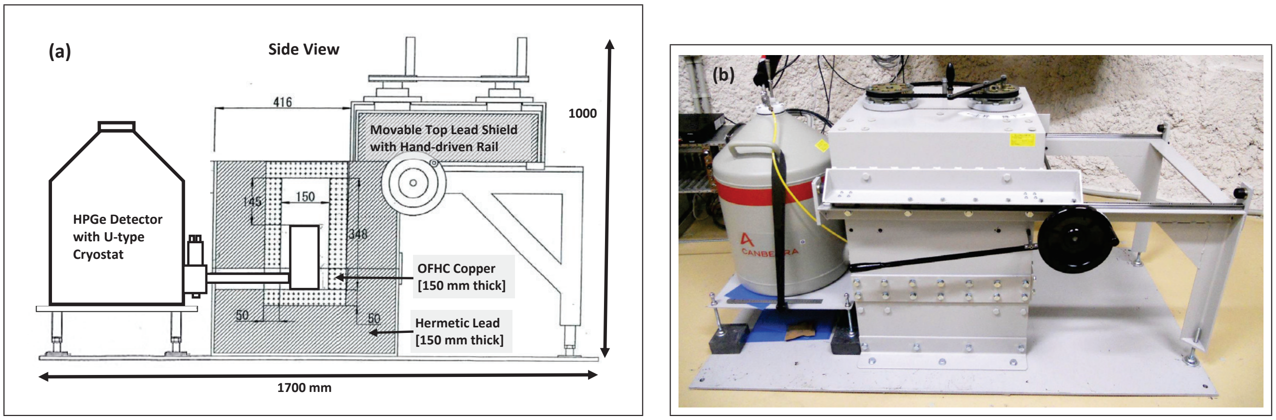

FIGURE 2. (a) Cross-sectional side view of HPGe detector and shields. (b) Photographic image of the detector system.

to avoid γ-ray penetration through gaps. (3) When lower background level is required, the empty space within the chamber can be assembled with additional inner copper blocks. (4) Hand-driven rail is used to move the top lead shield side way for easy access to detector's chamber.

Data taking of the detector was started from year 2013. Since then, the detector system is continuously running and improving. Sample exchange and shield upgrade can be easily done owing to the compact design.

Background Spectrum

In Figure 3, background spectrum of experiment set up without shield was compared with full shield. The background measurements were performed at Kamioka Underground Observatory for one day. Effectiveness of passive shields for background reduction is obvious. In the energy range of 40 keV to 3400 keV, the total event rate without shield was around 480,000 cts hour^{-1}. After assembled with shields and flowed with nitrogen gas, the total event rate reduced 4 orders of magnitude to around 40 cts hour^{-1}. Many background events from ^{40}K, U-chain, Ac-chain and Th-chain were shielded way.

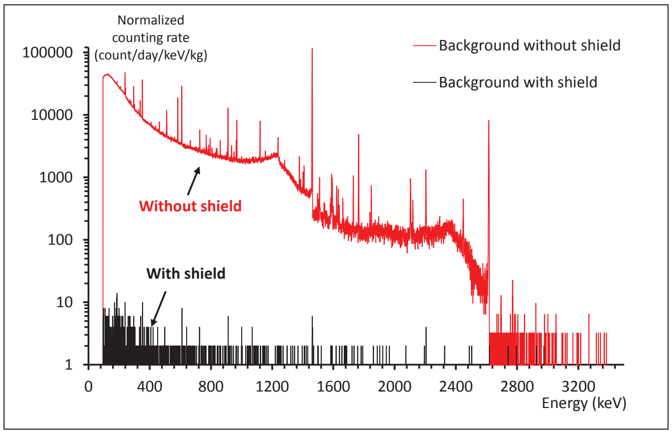

FIGURE 3. Comparison of background spectrum without shield and with shield for one day measurement.

Pulse Shape Discrimination (PSD) for HPGe detector

Instead of hardware improvement, off-line data analysis is another low background technique. For example, double beta decay experiments such as GERDA [3] and MAJORANA Demonstrator [4] used PSD to reject multi-site events. In this research, a new type of PSD method was created to select event that happen at the detector surface. The motivation is that low energy γ-ray from sample will mostly deposit on detector's surface, whereas background event like Compton scattering will distribute uniformly in the detector's bulk.

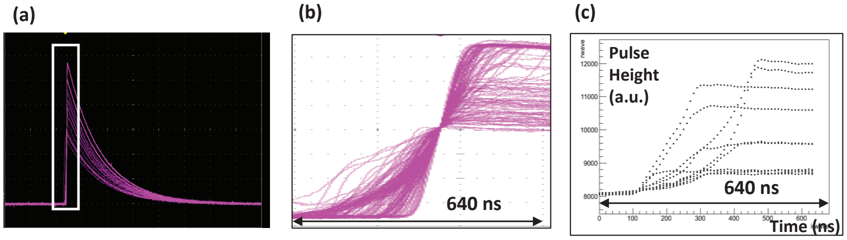

FIGURE 4. The oscilloscope images of (a) preamplifier signals and (b, white box in (a)) rise wave. (c) The rise wave of preamplifier signals was digitized and recorded by DSP.

The preamplifer signal observed by oscilloscope (Figure 4 (a, b)) can be digitized and recorded by DSP (c). Rise wave is refer to the rising part of the preamplifier signal pulse shape, which is defined with time range of 640 ns. Each event has unique rise wave due to the different velocity of charge carriers (electron or hole) in Ge crystal.

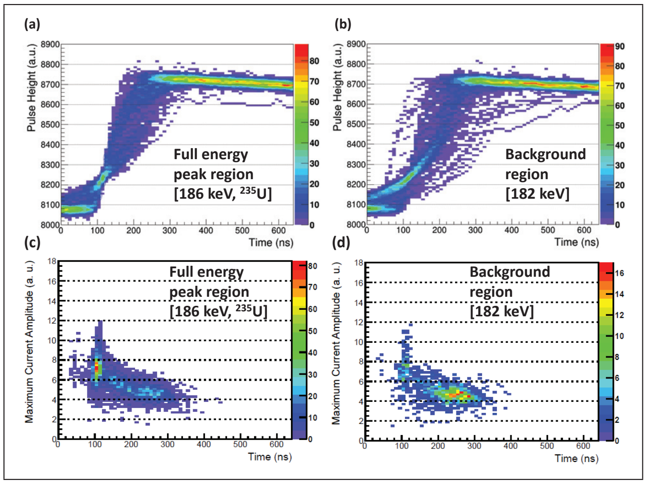

FIGURE 5. The rise wave distributions of (a) full energy peak region and (b) background region. The maximum current amplitude distribution of (c) full energy peak region and (d) background region. For PSD study, specific region in the maximum current amplitude distribution plot was selected.

The rise wave distribution of multiple events were plotted in Figure 5 for full energy peak region (a) and background region (b). In this case, events around 186 keV±1 keV (^{235}U peak) and 182 keV±1 keV (side band of ^{235}U) were compared. Pulse shape analysis was done by differentiate rise wave's pulse height with respect to time and convert the signal to current pulse. The maximum amplitude of current pulse for each event was then plotted in Figure 5 for full energy peak region (c) and background region (d). There is a significant difference in the maximum current amplitude distribution plots, where full energy peak and background events were concentrated around 100 ns and 250 ns respectively. To reject background event, PSD is applied by selecting specific region in this distribution plot. With PSD cut, microphonics noise and background event at low energy region less than 200 keV can be rejected effectively. For energy region higher than 200 keV, this PSD method became less effective because higher energy γ-ray can penetrate deeper and deposit uniformly in the detector bulk.

GEANT4 Simulation

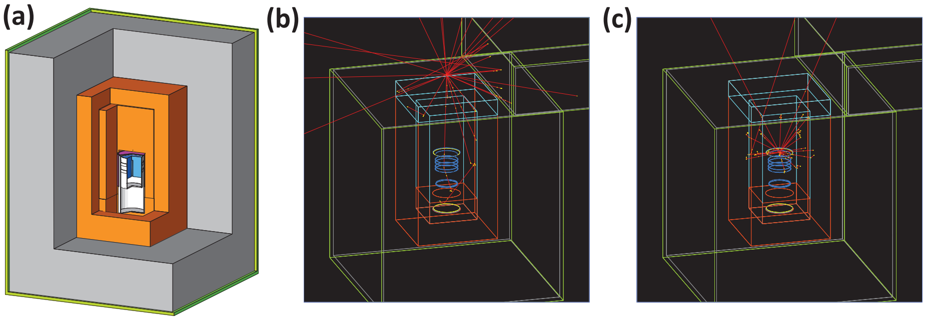

FIGURE 6. GEANT4 simulation model of CANDLES HPGe detector system. (a) Cross-sectional view of the detector, shield and sample configuration. Radiation paths when gamma source was (b) 250 mm or (c) 5 mm above detector's endcap.

Monte Carlo simulation by GEANT4 was employed to make the HPGe detector system model. The actual geometry of the detector, sample and shields were reconstructed, as shown in Figure 6 (a). Simulation is used to study the attenuation of γ-ray, effective thickness of sample, detection efficiency of measurement, etc. For instant, the interaction of emitted γ-rays with detector system can be observed by simulation. Figure 6 (b) displayed the radiation path when source was placed 250 mm away from top of endcap, which represent the measurement condition during calibration run. On the other hand, Figure 6 (c) shown the γ-rays interaction with detector when source was placed very close to the endcap (same condition as physics run).

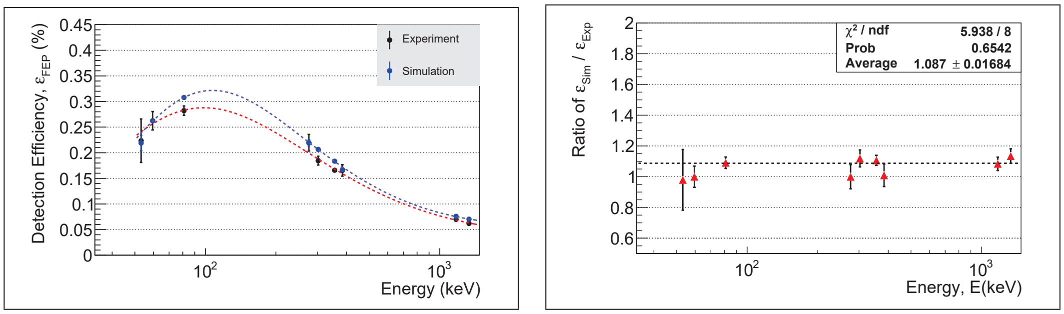

FIGURE 7. Comparison of (left) detection efficiency curve and (right) ratio between experimental data and simulation for full energy γ-ray peaks.

For verification of the simulation model, detection efficiency curve was compared between experiment data and simulation. Comparison of detection efficiency curve and ratio is shown in Figure 7. In this case, gamma source was set at 250 mm above endcap and Ge crystal's dead layer was set at 0.3 mm. The result shown that simulation has reproduced the experiment data very well with systematic error of 8.7 %.

HALF LIFE MEASUREMENT OF ^{180}Ta^m

Among all nuclear isomers that exist in nature, ^{180}Ta^m has the longest half-life which is yet to be finalized up until now. The latest published result was done by a research group at HADES Underground Laboratory, with $T_{1/2}$ limit of 4.5 $\times 10^{16}$ yrs [5]. Isomeric transition to ground state ($J_\pi = 9^- \rightarrow 1^+$) of ^{180}Ta^m was found to be very unlikely with lifetime greater than 10^{27} yrs. Therefore, the possibility for ^{180}Ta^m to undergo β^- decay to ^{180}W or EC decay to ^{180}Hf is higher. By detecting the cascading γ-rays (region of interest from 90 keV to 360 keV), ^{180}Ta^m decay can be confirmed.

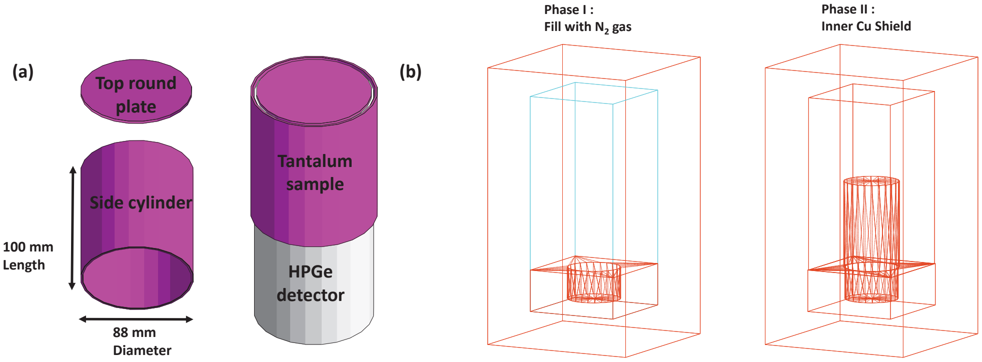

FIGURE 8. (a) Two segmentation of tantalum sample and set up on HPGe detector. (b)The copper shield configuration of Tantalum Phase I and Phase II measurements.

In this research, a tantalum sample made up of top round plate (2 mm thick) and side cylinder (1.5 mm thick) with total mass of 863.0 g was used for long-term tantalum measurement (Figure 8 (a)). The tantalum sample was placed closely on the HPGe detector's endcap to optimize detection efficiency. There were two sets of tantalum physics runs, Tantalum Phase I and Phase II measurements. The major difference between these two phases were shield configuration. As shown in Figure 8 (b), the empty space inside detector chamber during Phase I was filled with boil-off nitrogen gas. In Phase II, this empty space was replaced with OFHC inner copper shield. The background reduction effect of inner copper shield is significant, the total event rate has reduced 46 % in the energy region of 40 keV to 1540 keV.

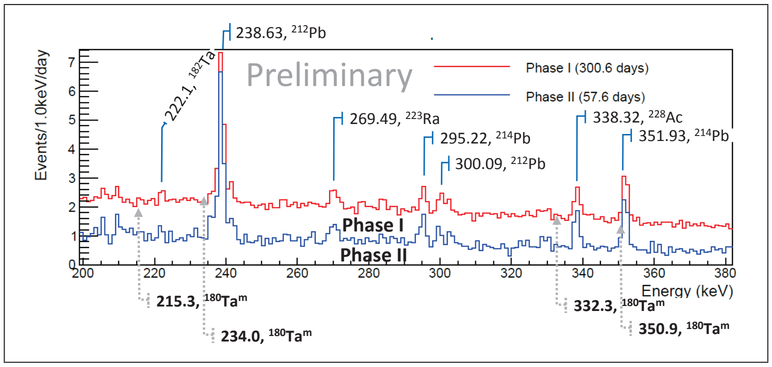

FIGURE 9. Energy spectrum of Tantalum Phase I and Phase II measurements. Interested peaks of ^{180}Ta^{m} decay were indicated with grey dotted line. The spectrum is preliminary result without apply any PSD.

Figure 9 shown the tantalum spectrums of Phase I and Phase II measurement , which live time were 300.6 days and 57.6 days respectively. The continuum background level of the Phase II was about half of the Phase I, due to the additional inner copper shield. Interested ^{180}Ta^{m} peaks region were pointed out by grey dotted line. The spectrum is preliminary result without apply any PSD. No significant ^{180}Ta^{m} peak was confirmed, hence $T_{1/2}$ limit was drawn.

The $T_{1/2}$ limit was calculated by consider the background level in region of interest. For β^{-} decay branch, 234.0 keV peak region was used because 350.9 keV peak was greatly suppressed by background peak of ^{214}Pb. For EC decay branch, 332.3 keV peak region was selected. Result of the $T_{1/2}$ measurement of ^{180}Ta^{m} is listed in Table 1.

TABLE 1. Result of $T_{1/2}$ measurement of ^{180}Ta^{m}

	EC branch	**β^{-} branch**	**Total**
$T_{1/2}$ **limit (yrs)** (90 % C.L.)	1.99×10^{17}	1.66×10^{17}	9.03×10^{16}
logft	25.0	23.6	-

This is preliminary result.

CONCLUSION

The low background HPGe detector system of CANDLES was fully developed and is now running. New PSD method to remove background event less than 200 keV is successfully created. For ^{180}Ta^{m}, the world most stringent total $T_{1/2}$ limit is achieved with 9.03×10^{16} yrs, which is factor of two higher than the latest published result.

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