Experimental Study on the CsI(Tl) Crystal Anti-Compton Detector for Dark Matter Search*

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Abstract A dark matter search experiment is being carried out with ultra-low energy HPGe detector at Y2L underground laboratory in Korea. Before the system was set up, the active shielding, CsI(Tl) anti-Compton detector, was studied for its performance. By using some radioactive source and recorded data with an FADC, the pulse shape was studied to get a better energy resolution and further PSD method application. The relative light output of crystal at different particle incident positions were compared for setting the threshold for CsI(Tl) detector. The internal background of the crystal was measured with an HPGe detector and the content of ^{137}Cs and ^{134}Cs isotopes were obtained. An about 18-day test run has been finished and the veto efficiency of CsI crystal anti-Compton detector is about 31% and the event rate of background spectrum of HPGe detector is about 133cpd. Further methods have to be explored to suppress the background level.

Key words dark matter, CsI(Tl) crystal detector, pulse shape discrimination, internal background

1 Introduction

Non-baryonic dark matters are the dominant ingredients of dark matter according to more and more evidences[1]. Direct detection of this kind of dark matter may deepen our understanding of the essence of dark matter and the cross-sections between dark matter particles and nuclei. Many experiments for direct detection of dark matter have been run or planned now based on different strategies[2]. According to the SUSY theory, the most possible candidate for non-baryonic dark matter particles is the Lightest Supersymmetric Particle (LSP), which has a mass less than a few TeV and a weak-scale interaction cross-section with the normal nuclei. We refer this LSP particle as neutrilino (χ). This kind of neutrilino is defined as the linear superposition of four supersymmetric particles that are photino, zino and two neutral higgsinos. The main principle of direct detection of non-baryonic dark matter is to detect the recoiled nuclei elastically scattering off by incident neutrilino particles. Usually the energies of the recoiled nuclei are less than 100keV and event rates will have an exponential decrease when energy increases (with energy). Now many experiments focus on the detection for ~100GeV neutrilino particle. This is a balanced result between the physical object and experimental technology partly due to the Not-Low-Enough energy threshold of these detectors and partly the possible higher event rate. The recent results for the direct detection of neutrilino have been given by several groups[2].

We plan to do detection for lower mass neutrilino using ultra-low-energy HPGe detector array, especially

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focusing on neutrilino particles with energy less than 10GeV. The first 5g prototype HPGe detector has been installed for the R&D measurement[3] and the Germanium detector will upgrade to 1kg (200×5g) in the near future. We choose CsI(Tl) crystal anti-Compton detector as an active shielding for the HPGe detector. This active shielding was built by high-pure CsI(Tl) powder in order to decrease its internal radioactive isotopes.

Before installing the HPGe detector, we did some experimental research for this anti-Compton detector at our experimental site—a 700m-deep underground laboratory (Y2L) in Korea. This underground laboratory has a 5 order less cosmic-ray level than on the ground and this makes it a good place for our dark matter detection experiment. This paper will describe the experimental setup and results for the anti-Compton CsI(Tl) detector testing such as the energy resolution, position dependence of light output and the internal background, and so on.

2 Experimental setup

The ultra-low-energy prototype 5g HPGe detector has been installed at 700m-deep Y2L (YangYang underground Laboratory) in Korea. The passive and active shielding and HPGe detector are shown in Fig. 1. The shielding materials from outside to inside are 15cm lead, 5cm Oxygen-Free High-Conductivity (OFHC) Copper, high purity CsI(Tl) crystal. The internal area of CsI(Tl) crystal active shielding is the low-energy HPGe detector with the energy threshold below 100eV[3]. The CsI(Tl) crystal detector is composed of three parts: top-part (5cm deep) which is attached to PMT to collect the scintillation light, cylinder-part (3cm deep) and bottom-part (3cm deep). Three parts of CsI(Tl) crystal are assembled into one detector by optical grease for good lighting transportation. The whole structure (shown in Fig. 1) will be put into a cosmic-ray veto box using a 30cm thick liquid scintillator as the neutron shielding. Most of the incident neutrons are thermalized by liquid scintillator except very high energy neutrons (∼100MeV) that are induced by cosmic ray. The energies of recoiled nuclei induced by neutrons will be background of our detector and be studied in other experiments and simulations.

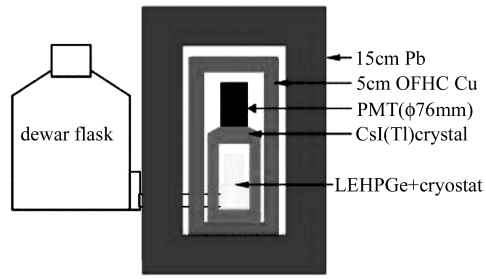

Fig. 1. Main structure of the HPGe detection system.

The low-background-window PMT (Hamamatsu CR119) was coupling to the top part of CsI(Tl) crystal for the scintillation light collection. The current pulse shape of PMT output will be amplified by home-made preamplifier and then sent to be digitized by a 600MHz 8 bit FADC (Lecroy 9361). Now we just use 100MHz sampling rate which is good enough for the relatively long decay time (∼ μs scale) of scintillating light from CsI(Tl) crystal. The time window of FADC for recording the current pulse shape is 20μs (2000 FADC Channels, 10ns per channel), and 4μs pre-trigger time scale was chosen to calculate the pedestal of each event. The whole current shape of each event will be recorded by the DAQ system for offline data analysis. For each PMT signal, high gain and low gain outputs of preamplifier have been recorded respectively for the detailed research of low energy part (<600keV) and the whole energy range (<3MeV).

3 Current pulse shape and the charge value Q

As described by many references[4], the decay time for the scintillating light of CsI(Tl) crystal has different constants for different kinds of incident particles(for example: γ and α), and noises. This can be used to discriminate the different incident particles or differentiate signals from noise. The profile $\bar{Y}(t)$ of a typical pulse recorded by FADC depicted in Fig. 2

can be described by the following function[5]:

$$\overline{Y}(t) = N\left[1-\exp\left(-\frac{t}{\tau_0}\right)\right]\left[\frac{1}{\tau_1}\exp\left(-\frac{t}{\tau_1}\right)+\frac{r}{\tau_2}\exp\left(-\frac{t}{\tau_2}\right)\right]. \qquad (1)$$

The rise time τ_0 and fall time τ_1, τ_2 as well as the ratio between the slow and fast decay components r are well known for different incident particles. The normalization constant N is chosen to make the peak amplitude equal to unity. The value of τ_0 is dominated by the electronics shaping rise time (for our situation, it is about 20ns), while τ_1, τ_2 are due to the characteristic time profile of CsI(Tl) crystal. This property of CsI(Tl) detector is useful for us to discriminate the signals from noises and other different signals.

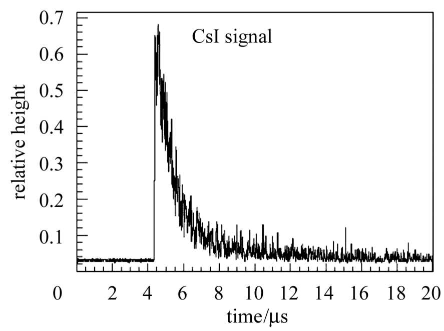

Fig. 2. Current pulse shape of gamma signal.

In order to get the total integrate charge Q value that is proportional to the deposited energy of incident particles, we should integrate the whole current pulse shape (2000 channel) after subtracting pedestal to get the total charge (Q). One can see from Fig. 2 that the long tail of current pulse shape will introduce more noises and will make the worse resolution for photo-electron peak. On the other hand, we want to integrate as many as possible channels to get the whole charge Q. These two sides have to be balanced by choosing the optimal integrating time window. We have analyzed this parameter and the results are shown in Fig. 3. Two gamma lines (662keV from ^{137}Cs and 1173keV from ^{60}Co) have been used to do this analysis. We select different channels (or different time window) for integrating to get the charge and compare the resolutions respectively. Here we define two parameters: $Q_{\rm t}$ and $Q_{\rm p}$. $Q_{\rm t}$ means the total charge obtained by integrating 2000 channels of time window for a current pulse. $Q_{\rm p}$ is the charge by integrating different channels of time window. One parameter $r=Q_{\rm p}/Q_{\rm t}$ was used to describe the selection for optimizing the integrated time window. One can see that when the part charge $Q_{\rm p}$ is obtained by integrating 1300ch of time window, the parameter r is more than 90% and the resolution is also very good.

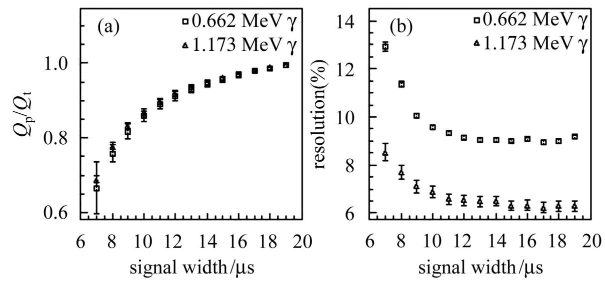

Fig. 3. Pulse shape analysis by different integrated width.

4 Pulse shape discrimination

Pulse shapes are recorded by FADC system that can provide pulse shape discrimination analysis for different kinds of events. From calibration data, four kinds of typical pulse shape are found and shown in Fig. 4, they are caused by gamma event, alpha event, noise and pedestal signal.

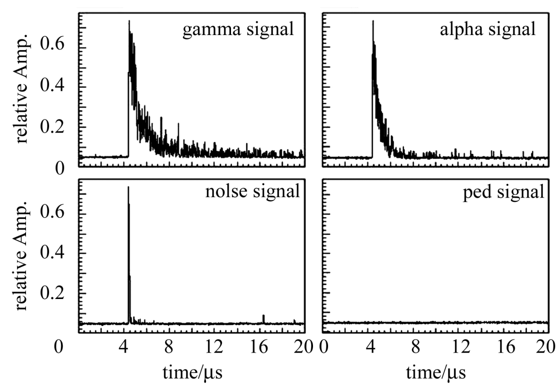

Fig. 4. Four kinds of typical pulse shape.

From Fig. 4 one can see that different kinds of signals have different decay tails, and based on this characteristic t-bar method was carried out in high gain signals to discriminate them. We define t-bar as follows:

$$\bar{t} = \frac{\sum\limits_t \overline{Y}(t)\cdot t}{\sum\limits_t \overline{Y}(t)}. \qquad (2)$$

For a 2000-point signal, "t" means channel number, here from 0 to 2000, and "$\bar{Y}(t)$" is the charge value of the t_{th} channel. Because the pre-trigger part and long tail in the signal are helpless for this discrimination, we only choose the "t" from 400 to 800(not the 1300ch which we have chosen as the width of time window for further data analysis) to get a better discrimination. In this case, we can know that the t-bar value for sharp signals will be near the trigger point (436 in our signals), while the t-bar value for the wide signals with long tails will be near the middle point (600).

The t-bar result of a background run is shown in Fig. 5, here X axis shows particle energy and Y axis shows t-bar result. From this plot, one can see four regions which stand for four kinds of signals shown above. Most of them are gamma signals from environment, and it ends at the energy about 0.9MeV which was limited by high gain range. The big branch in the left is caused by noise from electronics or PMT. They are very sharp and narrow, so t-bar value and energy are both very small. The dots between the former two branches are alpha signals, for their pulse shape is narrower than that of gamma events', and the t-bar value is smaller than that of the gamma's with the same energy. The others are pedestal signals, they distribute in a round area with energy around zero and t-bar value around 600 which is the average of channel number which starts from 400 and ends at 800. With this method, we can discriminate gamma signals from others in the energy range above 0.1MeV.

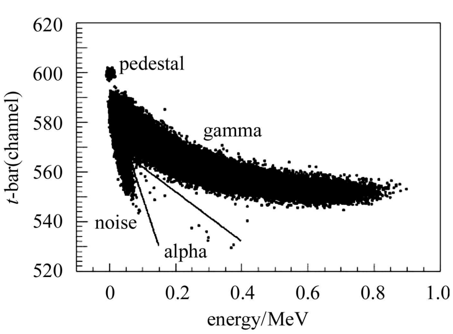

Fig. 5. t-bar result of a background run (totally 10000 events).

5 Energy and position calibration

Due to the large size and the complex shape of the anti-Compton CsI(Tl) detector, it is important to know the relative light output and resolution in different parts of the detector. We have done the calibration using a ^{137}Cs source putting in different positions, from the bottom (0cm) to the top (28cm) of the detector. The relative light output of photoelectronic events for different positions is shown in Fig. 6(a) and energy resolution of 661keV photoelectron peak is shown in Fig. 6(b). The 1σ error bars are given in Fig. 6(a). From the results, one can see that the relative light output for the top part is about 1.5 times than that of the bottom part due to the different efficiency of light collection and transportation. This result will be helpful for us to choose the low energy threshold for the anti-Compton veto detector.

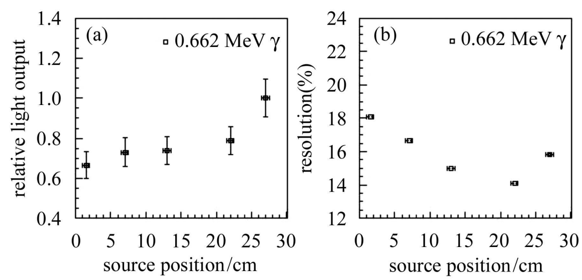

Fig. 6. Gamma-ray incident position dependency of CsI detector performance.

6 Internal radioactive isotope contents

Although CsI crystal has no natural radioactive isotopes, there are still many kinds of trace elements that may become important sources of internal background of CsI crystal detector, which will be one of the main sources for HPGe detector background. For the choice of CsI powder and crystal production, we have paid much attention to purifying the materials without inducing outer radioactive isotopes. However, due to the mankind nuclear activity and environmental pollution, a long-life isotope ^{137}Cs has been found in the CsI powder. Also, ^{134}Cs was induced by cosmic ray when the detector was put on the ground. So it is important for us to make experimental measurement for the internal background of CsI crystal.

The low background measurement has been done at Y2L underground Lab using a large HPGe detector covered by 5cm copper and 10cm lead shielding.

For convenience, only the bottom part of CsI crystal (weight 2.473kg) was put in the shielding and measured for 1619418s (about 18.7d). When the result was compared with background spectrum got by only large HPGe detector, three full-energy peaks were found corresponding to gamma rays of Cs isotopes, while no peak in background spectrum at the same energy positions. After fitting the background spectrum, the net counts of Cs full-energy peaks were gotten. At the same time, a Monte Carlo program was built to calculate the HPGe's detection efficiency for full-energy peaks of gamma rays produced by Cs isotopes. The full-energy peak efficiency was defined as the ratio of full-energy peak counts of HPGe detector to the total number of gamma produced in CsI crystal. At last, considering the decay branching ratio, the activity of Cs isotopes was calculated. The data of this analysis are shown in Table 1. With this result, we can estimate how much count rate of the inner Ge detector will be caused due to the Cs radioactive isotopes.

Tabel 1. Activity of Cs isotopes.

Cs isotope	^{134}Cs		^{137}Cs
Gamma(peak) energy/keV	604	796	662
full-energy peak net counts	1307±36	1085±32	242±18
full-energy peak efficiency(%)	1.79±0.01	1.63±0.01	1.76±0.01
branch ratio(%)	98.20	85.79	94.40
time/s	1619418		
weight/kg	2.374		
activity/(mBq/kg)	19.8±0.2		3.8±0.3

7 Veto efficiency

After experimental researches of the performance of CsI(Tl) crystal anti-Compton detector, the whole dark matter detection system was assembled and a test run started. The high voltage of HPGe detector was set as −500V and CsI detector −1300V. The test run lasted about 1619418s (about 18.7d) to take the background data. Two channels have been used to record the HPGe output signals respectively, one is for high gain and the other is for low gain. The spectra for both high gain and low gain are given in Fig. 7(a) and Fig. 7(b). Our focused energy range for high gain and low gain are less than 5keV and 5keV—55keV. The threshold of the high gain channel of the HPGe detector was set as 265eV and the signal from this high gain channel was used as trigger signal of the whole detector system. At the same time, the threshold of CsI crystal detector is set at 50keV, which is the optimal value to separate the signal and electronic noises. The signals from CsI(Tl) crystal detector are used as anti-coincident signals for the HPGe signals. Based on this arrangement, we get totally 1180 (813) events before (after) CsI crystal detector veto and the results are shown in Fig. 7. Because special processing was used to purify the ultra-low energy high purity germanium detector, we assume that events caused by inner radioactivity of HPGe detector are negligible compared to events caused by particles form outside. With this assumption the veto efficiency we get from these two spectra is about 31%. We can see that the larger the energy of event, the better the veto efficiency of CsI(Tl) crystal anti-Compton detector. After veto by CsI(Tl) crystal anti-Compton detector, the event rate of germanium detector is about 133counts/(kg·keV·day), that is not low enough for us to do the dark matter search experiment. In the near future, we will adjust the parameters of CsI detector to lower the threshold and improve the veto efficiency so that the event rate of background can be decreased.

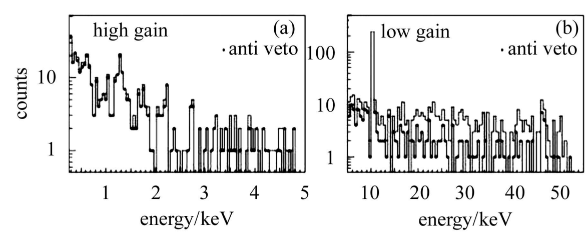

Fig. 7. Energy spectra of HPGe detector (high gain and low gain) before and after CsI(T1) anti-Compton detector veto.

8 Summary

An experiment using ultra-low-energy HPGe detector for cold dark mater search is being carried out in an underground laboratory in Korea. The CsI detector used for active shielding in this system has been studied for its performance before the system was set up. CsI signals were recorded by a FADC and the data were saved for offline analysis.

The current pulses have been studied with two considerations: charge ratio and spectrum resolution. As a compromise of those two, 1300 channels for signal width will be the optimal choice. The *t*-bar method was used for pulse shape discrimination. Only 400 channels were chosen for *t*-bar calculation and finally gamma signals can be well discriminated from alpha signals and others in the energy region above 0.1MeV. Incident particle position dependency was studied for different light collection efficiency. The result shows that when incident particle position moves far away from the PMT, the light collection efficiency decreases. The best place is near the top of crystal, which has the efficiency about 1.5 times larger than the worst place near the bottom. Internal background caused by two Cs isotopes is measured using an HPGe detector. With the detection efficiency simulated by MC program, the activity was calculated. This result can be used for simulation of inner Ge detector signals caused by Cs radioactive isotopes.

The system was assembled and an 18-day test run had been finished. In the data analysis, the threshold of CsI(Tl) crystal anti-Compton detector was set as 50keV to separate signals from noise and the threshold of HPGe detector is 265eV. About 31% of the veto efficiency is obtained for this test run. After veto the event rate of HPGe detector is about 133 counts/(kg·keV·day). That is still very high. Much work has to be done for this detector system to suppress the background level in order to do the dark matter detection.

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暗物质寻找实验中CsI(Tl)晶体反符合探测器实验研究*

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摘要　一个正在建设的位于韩国Y2L地下实验室的低能暗物质探测实验中, 采用了CsI(Tl)晶体反符合探测器作为主动屏蔽体. 本工作对CsI(Tl)晶体反符合探测器的实验性能进行了研究. 通过FADC系统记录的脉冲波形数据, 研究了探测器的能量分辨率和波形甄别的能力; 研究相同能量γ射线入射到反符合探测器不同位置的相对光输出将有助于选择探测器的工作参数; 为了解晶体自身放射性对暗物质测量的影响, 利用低本底HPGe探测器对CsI(Tl)晶体内部的放射性进行了测量, 得到晶体内部Cs同位素的放射性活度. 探测器系统进行了约18d的试运行取数. 实验数据表明, CsI(Tl)晶体探测器的反符合效率约为31%, HPGe探测器的本底计数率水平约为133cpd. 为了进行暗物质探测研究, 需要采取有效的方法进一步降低探测器的本底水平.

关键词　暗物质　CsI(Tl)探测器　脉冲形状甄别　内部本底

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