# Status of ULE-HPGe Detector Experiment for Dark Matter Search*

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**Abstract** An Ultra Low Energy HPGe (ULE-HPGe) detector, with CsI (Tl) active shielding, is applied to the direct detection experiment for weakly interacting massive particles (WIMP), and located in Korea. The setups for the whole system and the calibration have been completed and more than half a year's background data have been accumulated. Some external neutron and gamma source experiments were carried out to study the origin of the background. The analysis and preliminary results are shown, and an attractive future is also provided.

**Key words** dark matter, WIMP, ULE-HPGe detector, calibration, veto efficiency

## 1 Introduction

The detection of dark matter which is to be thought as the major mass part of our matter world has been one of the highlight topics for particle physics, astronomy physics and cosmology. According to some theoretical and experimental results, the major part of dark matter is composed of non-baryonic particles[1]. WIMP is one of the most attractive candidates of non-baryonic particles. Direct detection of WIMP can give us the clearer image about the interaction between dark matter particles and nuclei, which will be helpful for our understanding of the essence of dark matter.

The typical WIMP search experiments such as DAMA, CDMS and UKDMC have given their experimental results, which turn to be the stringent exclusive curves in two dimensions of the WIMP-nucleus elastic scattering cross-section vs. WIMP mass[2]. Due to the relatively higher energy threshold of the detectors, the low mass WIMP space has not been scanned by these experiments. One new experiment has been established for non-baryonic dark matter search with ULE-HPGe detector, which mainly focuses on the low mass region of dark matter mass spectrum. In this paper, some details of our low mass dark matter experiment will be described and a preliminary result given. The target for this experiment will detect directly the WIMP with 1kg multi-channel ULE-HPGe detector and as the first step, one 5g prototype ULE-HPGe detector has been established to study this feasibility.

## 2 Experimental setup

The ultra-low-energy prototype of a 5g HPGe detector has been installed at 700m-deep Y2L (Yangyang Underground Laboratory) in Korea. Fig. 1(a) shows the HPGe detector, with both passive and active shielding. The shielding materials

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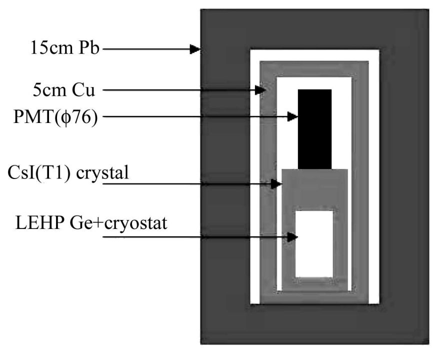
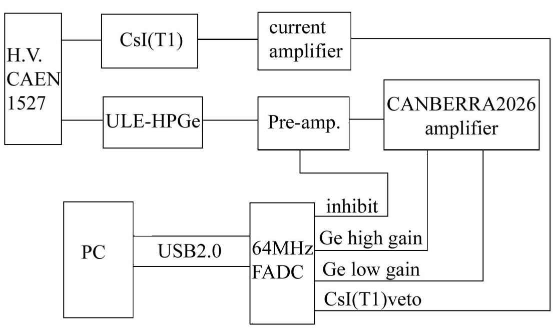
from outside to inside are 15cm lead, 5cm oxygen-free high-conductivity (OFHC) copper, and high purity CsI(Tl) crystal. Inside the CsI (Tl) crystal active shielding used to veto Compton scattering event, is the ultra-low-energy HPGe detector with a low energy threshold[3]. The CsI (Tl) crystal detector is composed of three parts: the top part (5cm thick), the cylinder part (3cm thick and 25cm deep) and the bottom part (3cm thick). Three parts of CsI (Tl) crystal are assembled into the veto detector with optical grease for light transportation.




(a)




(b)

Fig. 1. (a) The structure of ULE-HPGe detector and its shielding system; (b) The schematic diagram of the experimental setup.

The low-background-window PMT (Hamamatsu CR119) is coupled to the top part of CsI (Tl) crystal for the scintillation light collection. The current pulse shape of PMT output will be amplified by the home-made preamplifier and then sent to a 4-channel, 12-bit and 64MHz FADC for digitization. PSD (Pulse Shape Discrimination) method can be used to reject the noise.

For the kernel, in order to get a low energy threshold, the Canberra 2008S preamplifier is selected for HPGe detector, attached closely near the prototype Ge, inside the cryostat, kept at the temperature of liquid nitrogen. The signal from preamplifier, with the baseline reset about every one second, will be sent to the main amplifier, Canberra 2026. The shaping time is set at 6μs. The signal gets amplified with different gains, output as two channels, and then digitized by the same FADC mentioned above. The difference between high gain and low gain is about 10 times. So the high gain channel scans the energy region of 0∼9keV, while the low gain channel covers 0∼100keV. Because of the resetting, some huge minus shoot pulses will be generated in the main amplifier, and the inhibit signal is used to reject these events.

All of the signals, HPGe high and low gain channels, CsI (Tl) crystal scintillation pulse and the inhibit signal, are digitized by the FADC, and transferred to computer by USB2.0 interface. The DAQ program is edited under ROOT version 5.02.00, and it will record the pulse shapes of all the channels. The schematic diagram is shown as Fig. 1(b).

## 3 Energy calibration

After shaping, the amplifier outputs a semi-Gaussian pulse, whose height corresponds to the energy of the incident particle. So the fitted height, with pedestal subtracted, is used to calibrate the HPGe detector. The pedestal can be measured by the FADC hardware, and can also be calculated from the recorded pulse shape. After comparison, the hardware measured pedestal is considered to have a better energy resolution, even though only to a small extent, so it is selected for calibration. Because our interest is in low energy region, while the 0.6mm thick carbon window will obviously reduce the detection efficiency with the energy lower than 1.5keV, the characteristic X-rays from many target materials, including $CaMoO_4$, CsI (Tl) crystal and the metal of Ti, are used to touch the range as low as possible. The Cool-X pyroelectric X-ray generator produced by Amptek Company is chosen as the cannon to shoot those targets. The X-ray generator uses a pyroelectric crystal, $LiTaO_3$, as the target for accelerated electron to emit X-ray, so the M-series X-ray from Ta is contained in the spectrum, the same as Fe and Cu (K series), from the support material of X-ray generator and cryostat. Including the classic $^{55}$Fe source (characteristic X-ray from $^{54}$Mn) for calibration, totally 14 points are got in the plot, fitted with linear function, shown in Fig. 2(a). The sources of $^{241}$Am (60keV $\gamma$ and Np L-series X-ray) and $^{109}$Cd (Ag K-series X-ray) are used for low gain channel calibration, which is shown in Fig. 2(b). Due to the good energy resolution, we cannot see the error bar of each energy point from Figs. 1(a) and (b).

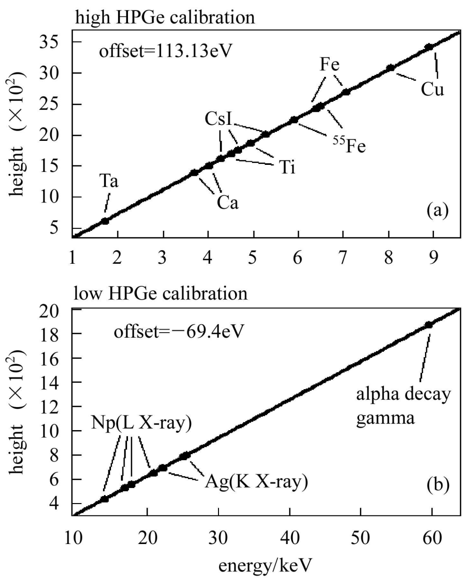



Fig. 2. (a) high gain channel calibration; (b) low gain channel calibration.

The calibration equation is:

$$\text{height(ADC ch)} = p_0 + p_1 \times \text{energy(keV)}, \qquad (1)$$

$$\text{offset(keV)} = -\frac{p_0(\text{ADC ch})}{p_1(\text{ADC ch/keV})}. \qquad (2)$$

From fitting results, the linearity of both high gain and low gain channels is acceptable, but the offset of calibration equation, which is the corresponding energy value when the pulse height is assumed at zero, is very obvious. In the high gain calibration equation, the value of $p_0$ is $-43.851$ and $p_1$ is 387.617, while in the low gain calibration equation $p_0$ is 2.18559 and $p_1$ is 31.4929. For the low gain channel, $-69.4$eV can be admitted with a large energy region about 100keV, but in the high gain channel, 113.13eV has been comparable to our expected threshold, which is observed and measured, but not comprehended.

The calibration for CsI (Tl) veto detector is also completed, and four sources, $^{109}$Cd (Ag X-ray), $^{241}$Am, $^{238}$U (decayed $\gamma$-ray from the daughter isotope $^{234}$Th) and $^{57}$Co, are used to calibrate it. Even though CsI (Tl) crystal detector is only used as active shielding, which means that it is enough whether the CsI (Tl) channel gives out a real veto signal can be discriminated, in fact, the energy linearity and offset are satisfactory for this CsI (Tl) active shielding detector.

## 4 Background data analysis

Since the whole system setup and calibration were completed in October 2005, the background data taking has been run for more than half a year. Except the time spent on other research experiments, about 155days' data have been accumulated. But the HPGe mass is so small, 5g, so it is only 7.75kg · day's data from which the preliminary results are concluded.

During the data acquisition, there is some electronic noise, with obvious large minus shoots in all channels, while the normal pulse should be positive after FADC digitization. So the electronic noise can be rejected easily, even with the online DAQ program. Meanwhile, in the CsI (Tl) crystal, some sharp event, with its pulse shape similar to single photon response, appears frequently. This kind of scintillation noise can be rejected with pulse shape discrimination methods. Mean time is used as the PSD parameter and $I_i$ is the current amplitude corresponding to the time $t_i$:

$$\bar{t} = \frac{\sum_i I_i t_i}{\sum_i I_i}. \qquad (3)$$

After searching the current pulse peak, the energy and mean time can be calculated, and the distribution of PSD parameter can be shown as in Fig. 3(a). With the center energy around 124keV, the conglomeration of small squares is from the $^{57}$Co calibration file, pure $\gamma$-ray events. And the source events in the area with the energy higher than 150keV and mean time larger than 2.5μs are overlapped events, with two consecutive $\gamma$ particles in one recorded window, which will hardly occur during the background data taking. The small dots are from the background events. So the three solid lines are set as the cutting boundary, and the inner region is considered as $\gamma$ events generated by the scattering with injected particles. The event outside is for scintillation noise which is not the valid veto signal, no matter whether the density of single-photon shape noise is large or small. In Fig. 3(b), the distribution of CsI (Tl) mean time is shown for the effective background events whose energy of HPGe pulse is higher than the threshold. The three solid lines are the same as in Fig. 3(a), determining the region of the valid CsI (Tl) veto signal. The solid squares, in the valid region, correspond to the scattering events coming from outside. The circles present the events without effective CsI (Tl) respondence, just small noises, and the triangles for the events with large CsI (Tl) noises, both of which cannot be vetoed. In Fig. 3(b), the HPGe energy of all these events is higher than the threshold, so they are effective information, about 60% of which have effectual veto response, meanwhile, shown as the solid squares. In the background data, in all the events whose CsI (Tl) PSD behaviors are invalid, only 0.03% coincidently have effective HPGe information, and the others are just noises.

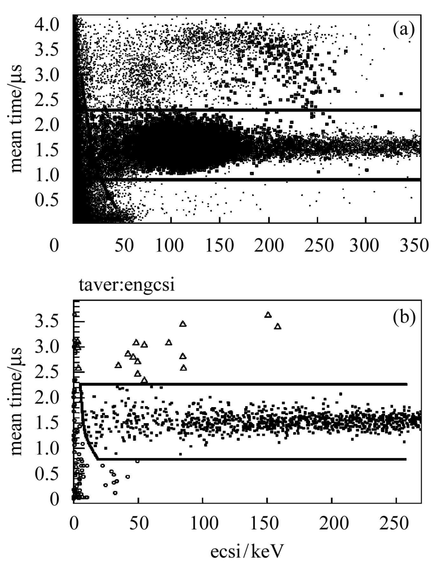



Fig. 3. (a) PSD plots for CsI (Tl) crystal scintillation detector; (b) CsI (Tl) mean time distribution of the effective background events.

And the time difference between CsI (Tl) and HPGe channels is a definite value, generated from physics reaction and electronic delay, with a little bit statistical extension. The time relation is checked with some $\gamma$-source experiment files and a neutron-source experiment file. The two source test experiments will be discussed with more details in the next part. Only the CsI (Tl) recorded pulse, which satisfies both of the PSD selection and time relation, is thought of as valid veto signal. From the raw data, after veto process, the energy threshold and background level can be got, which are shown in Figs. 4(a) and (b).

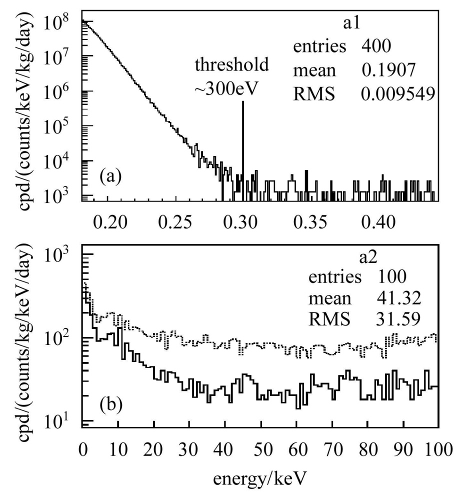



Fig. 4. (a) the energy threshold of HPGe detector; (b) the background level spectrum.

In Fig. 4(b), the upper dot line is the energy spectrum of HPGe detector before veto; the lower solid line is the background left, after veto process. In the veto process, the time relation analysis is used to reject randomly coincident events; the PSD of CsI (Tl) is applied to remove the invalid veto signals caused by the noise in CsI (Tl) crystal, to save the real background events in HPGe record from being wrongly vetoed. The veto efficiency in the whole region from the threshold to 100keV is about 60%. The background energy spectrum is exponential shape.

So far, with the 5g plate-shape Ge detector (the active area being 100mm$^2$, and the thickness 10mm), the energy threshold is about 300eV, and the quenching factor for nuclear recoil event is measured as 0.25[4]. The average background level from the threshold to 100keV is 40cpd (counts/kg/keV/day), with about $10^3$cpd at the threshold and less than 30cpd in the region higher than 20keV.

In the accumulated background data, after veto, two internal characteristic peaks are discovered, with their energy at 0.923keV (94 events totally in 155days) and 10.08keV (90 events totally). The latter one is considered as the K-series characteristic X-ray of Ge and the former one may be generated from Ge L-series and Cu L-series and the elements in Teflon, which are the materials in or around the detector and cryostat. More background data are being accumulated to observe the decay of these two internal peaks. And more accurate calibration and simulation for the internal background are needed to understand their generation mechanism. The energy spectrums for them are shown in Figs. 5(a) and (b).

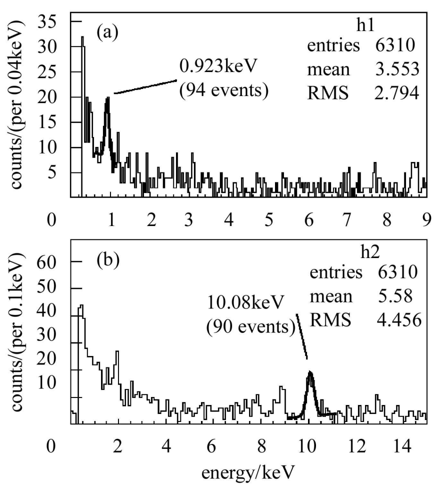



Fig. 5. (a) The energy spectrum of 0.923keV peak; (b) the energy spectrum of 10.08keV peak.

## 5 Neutron and $\gamma$ source experiments

A neutron source $^{252}$Cf was put on the top of lead shielding to test the system response to environmental neutron. The intensity of the source was about several μCi, and the neutron source experiment lasted for about five hours, because of the worry concerning the elements in the detector and shielding which could be activated and the background level might be increased. Two weeks later after neutron irradiation, some strong $\gamma$ sources ($^{238}$U, $^{232}$Th and $^{152}$Eu) were used to do $\gamma$ irradiation experiment and the $\gamma$ source was put outside the CsI (Tl) shielding detector but inside of the Cu shielding.

From the neutron and $\gamma$ source files, the distribution of CsI (Tl) crystal veto efficiency vs. HPGe event energy can be calculated. Then the origin of background events will be inferred from the comparison of veto efficiency distribution between the background data and the outer source events generated by the pure neutron or pure $\gamma$ source. The distribution histogram is shown in Fig. 6(a).

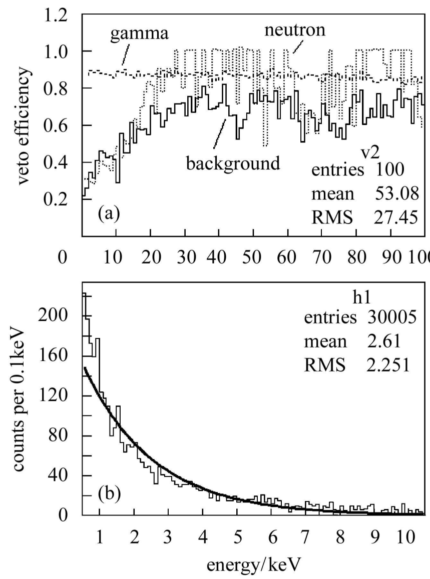



Fig. 6. (a) The veto efficiency distribution from different sources; (b) the recoil energy spectrum with outer neutron source $^{252}$Cf.

The almost straight dashed line with its $y$-coordinate at about 87% is from the $\gamma$ source events, which means the CsI (Tl) active shielding can reject 87% outer $\gamma$ injection. In the two left curves, the little bit lower solid one in the region higher than 20keV is from the background data, and the other dot one is from the neutron file. Because the event number of neutron source file is very few, the statistical fluctuation of neutron histogram is very large, but the trend of neutron veto efficiency distribution is still clear, and it is convincing that the background veto efficiency distribution resembles the distribution of neutron much more, from which it is inferred that the origin of background events is environmental neutron.

From the neutron experiment file, the neutron recoil energy spectrum is also measured, and it is shown in Fig. 6(b), the typical exponential spectrum, which is familiar with the exponential spectrum of background. This is also an evidence that the origin of background should be neutron from outside. Both of the veto efficiency distribution and the neutron recoil energy spectrum have been validated by Monte-Carlo simulation with Geant 4, and the paper about the simulation is being prepared.

## 6 Summary and future plan

Until now, with 5g prototype HPGe detector, the energy threshold of 300eV and the average background level of 40cpd are achieved, with about $10^3$cpd at the threshold. The source of background is known as environmental neutron. All above are satisfactory and lead us to the next step.

Based on the research of background origin, the neutron shielding will be established. And the mass of detector is intended to be increased, and the threshold and background level should be reduced obviously. Because of the internal noise, the large mass detector should be designed to be an array of small semiconductors. From the coincidence between different channels, the electronic noise and injected scattered particles can be rejected. More simulation is also necessary for the detector and shielding design, and then the comparison to experimental measurement. With about 1kg detector mass, the background level with the same power as 1cpd and much lower threshold, lower than 200eV, are expected. In the low WIMP mass region, lower than 10GeV, a more impressive and competitive result is promising.

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# 低能量阈高纯锗探测器用于暗物质探测实验研究*

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**摘要** 一个位于韩国江原道襄阳郡地下实验室的暗物质WIMP探测实验中, 采用了低能量阈高纯锗探测器, 带有碘化铯晶体反符合探测器作为主动屏蔽体. 整个系统设置和能量标定已经完成, 并且已经积累了约155d的本底数据. 还应用外置伽玛源和中子源进行了实验, 以判断本底的来源. 介绍了数据的分析和初步结果, 并给出了实验诱人的前景.

**关键词** 暗物质 WIMPs 低能量阈高纯锗探测器 标定 反符合效率

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