

PICO-LON Dark Matter Search

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Abstract. It is an important task to find an annual modulation of WIMPs signal for identifying dark matter signal. To search for annual modulation signal by means of inorganic scintillators, a large mass and a highly radiopure detector is needed. PICO-LON (Planar Inorganic Crystal Observatory for LOw background Neutr(al)inos) is a dark matter search project with multi-array NaI(Tl) scintillators. The test module of PICO-LON whose dimension is 15cm×15cm×0.1cm gives enough performance, energy resolution and low energy threshold, for dark matter search. The highly radiopure NaI(Tl) crystal is indispensable to start a large mass experiment. We have developed highly radiopure NaI(Tl) scintillator. The U and Th chain impurities were precisely measured by means of pulse shape analysis for NaI(Tl) scintillators. The future plan of KamLAND-PICO dark matter search project is proposed.

1. Introduction

The observation of annual modulation in dark matter signal is the complementary work to directional search for dark matter. The relative velocity of the Earth to the Galactic rest frame is expressed as

$$\vec{v}_E = \vec{v}_\odot + v_{ER} \cos \theta, \quad (1)$$



where \vec{v}_E is the Earth's velocity to Galactic rest frame, \vec{v}_\odot and v_{ER} are the Sun's velocity to Galactic rest frame and the velocity of the Earth's revolution [1]. The WIMPs (Weakly Interacting Massive Particles), which is the most promising candidate of dark matter [2], has an isotropic directional distribution of velocity to the Galactic rest frame. Consequently, the relative velocity of WIMPs against the Earth modulates with its maximum in June and its minimum in December.

The direction of coming WIMPs velocity cannot be observed by conventional solid state detector, however, the small modulation of energy spectrum is observed by using huge volume detector. DAMA/LIBRA has investigated the annual modulation by using huge highly radiopure NaI(Tl) scintillator, $\simeq 100\text{kg}$ for 7 years and $\simeq 250\text{kg}$ for 6 years. They have reported a significant modulation signal between 2 keV_{ee} and 6 keV_{ee} and no significant modulation above 6keV_{ee}, where a subscript *ee* stands for electron equivalent energy[3]. Another experiments with different target reported also the significant annual modulation signals. CDMS and CoGeNT applied Ge detector to search for WIMPs. The cryogenic Ge detector has a great advantage to distinguish a nuclear recoil signal and a β/γ signal. A significant excess in the low energy region which is supposed to WIMPs signal has been reported. However, the regions of WIMPs mass and cross section were completely different.

We propose a dark matter search project using high sensitivity NaI(Tl) scintillator in the northern hemisphere. The huge and highly radiopure NaI(Tl) scintillator will be installed in KamLAND to verify the annual modulation signal.

In the following sections, KamLAND-PICO collaboration will be described. The KamLAND-PICO promotes a high sensitive detection and measurement of WIMPs dark matter. The prototype detector of PICO-LON module and purification of NaI(Tl) crystal will be described.

2. PICO-LON for dark matter detector

PICO-LON stands for Planar Inorganic Crystal Observatory for LOw background Neutralino[6]. Single module of PICO-LON is a thin and wide area NaI(Tl) crystal whose dimension is 0.1 cm in thickness and 10 cm~15 cm square. The principle of WIMPs selection is shown in Fig.1. A

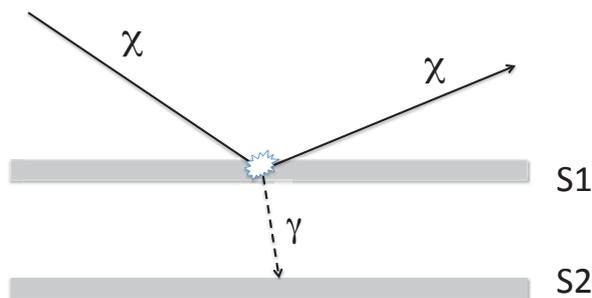


Figure 1. Schematic drawing of the WIMPs detection by inelastic excitation of nucleus.

highly segmented detector system enhances the background reduction power and signal selection power.

The interaction cross section of WIMPs-nucleus scattering is so small that WIMPs can interact with only one module. Background events due to gamma ray and beta ray are rejected by anti-coincidence measurement with neighboring modules.

The another important channel for WIMPs-nucleus interaction is inelastic excitation of nucleus[7]. ^{127}I has a low energy excited state at 57.6 keV which is excited by spin-dependent interaction. The WIMPs with high kinetic energy can easily excite the ^{127}I nuclei and the interaction is followed by immediate radiation of 57.6 keV gamma ray. The experiments using a large volume detectors [8, 9] observe the total energy deposition which is the sum of recoil

energy and gamma ray energy. The inelastic signal consequently shift to higher energy region. The large amount of background suffers the sensitivity to inelastic excitation for normal large volume detectors.

PICO-LON detector system enables to make a coincidence measurement of inelastic excitation signal. The thickness of the scintillator is as thin as 0.1 cm. Thus the gamma ray escapes from the interaction module (S1) and is detected by the adjacent module (S2). Then the nuclear recoil signal from S1 is measured in coincidence with the gamma ray signal from S2.

The performance of a prototype module of PICO-LON was tested. The energy resolution and the energy threshold were measured by irradiating low energy gamma rays. The scintillation photons were collected from four thinner edges by photomultiplier tubes (PMT) through a lightguide. The lightguide which was made of acrylic plastic acts as airtight container as well. Three modules of PMTs whose diameter is 2 inches were glued on each thinner edge of light guide. The PMT outputs from four edges were individually input into analog-to-digital converter.

The energy spectrum taken by PICO-LON single module which was irradiated by a ^{241}Am gamma ray source is shown in Fig.2 The good energy resolution was obtained by using

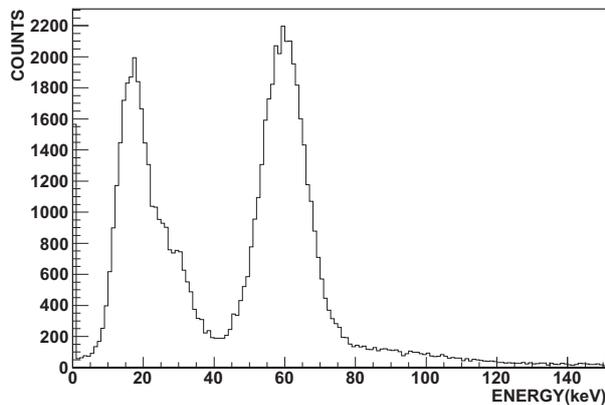


Figure 2. The energy spectrum obtained by PICO-LON module by irradiating ^{241}Am source.

uncollimated irradiation. The energy resolution at 59.5 keV γ ray was 14 keV in full-width-half-maximum. The energy threshold of the detector was limited by electrical noise which was mainly from PMT dark current and base line fluctuation. The obtained energy threshold was as low as 2 keV electron equivalent energy. Both the energy resolution and the energy threshold were good enough to search for WIMPs[10].

Purification of NaI(Tl) crystal is the most important task for dark matter search. DAMA group developed extremely radiopure NaI(Tl) crystals [11]; the concentration of U-chain and Th-chain impurities are less than 10 ppt. Japanese companies are also developing high purity NaI(Tl) crystals. Recently, we restarted to develop highly radiopure NaI(Tl) crystal. Present status of impurities in NaI(Tl) scintillator reported by DAMA and the present work are shown in table 1. One of the most serious impurities is ^{210}Pb which makes various types of background against dark matter search. In the present work, a sufficiently small concentration of ^{210}Pb was obtained by the Japanese maker.

3. KamLAND-PICO for dark matter search

Kamioka Liquid Scintillator Anti-Neutrino Detector (KamLAND) is the huge neutrino detector which is located in Kamioka underground laboratory in Japan [12]. The center of the detector is 1 kton of ultrapure liquid scintillator (LS) contained in 13-m-diameter spherical balloon made of 135 μm -thick transparent nylon/EVOH (ethylene vinyl alcohol copolymer) composite film.

Table 1. Impurities of NaI(Tl) reported by DAMA and our present crystal. The goal of PICO-LON project is also shown.

Impurity	DAMA	Present Crystal	Goal of PICO-LON
^{40}K	< 20 ppb	Not yet	< 20 ppb
Th chain	0.5~0.7 ppt	< 1 ppt	< 1 ppt
U chain	0.7~10 ppt	8 ppt	< 1 ppt
^{210}Pb	5~30 $\mu\text{Bq/kg}$	50 $\mu\text{Bq/kg}$	< 100 $\mu\text{Bq/kg}$

The radioactive impurities in LS are sufficiently small for dark matter search. The concentrations of U-chain and Th-chain was $(3.5 \pm 0.5) \times 10^{-18}$ g/g and $(5.2 \pm 0.8) \times 10^{-17}$ g/g, respectively. The impurity of ^{40}K is less than 2.7×10^{-16} g/g, which is sufficiently low for dark matter search.

KamLAND-PICO is the project which searches for WIMPs dark matter by installing PICO-LON detector into KamLAND. The final phase of KamLAND-PICO consists of 1 ton of multilayer NaI(Tl) scintillator and the huge LS tank. First phase of KamLAND-PICO detector consists a simple bulk NaI(Tl) scintillator whose total mass is 1 ton. The first phase of KamLAND-PICO aims to find WIMPs signal using ultra pure NaI(Tl) crystal. The final phase of KamLAND-PICO aims to determine the property of WIMPs interaction.

4. Conclusion

PICO-LON has shown enough performance of low energy threshold (~ 2 keV) and good energy resolution (23% FWHM at 60 keV). The low background which is the most important property has been established by selecting surrounding materials. The purity of NaI(Tl) ingot is as low as 8 ppt for U-chain and less than 1 ppt for Th-chain contaminants. Further improvement of impurity and stability test is in progress.

The sensitivity to WIMPs in the first phase of KamLAND-PICO is enhanced by a large volume detector and high selectivity using an efficient active shield. The expected sensitivity for spin-independent WIMPs reaches to the order of 10^{-9} pb for 40~100 GeV/ c^2 .

References

- [1] K.Freese, J.Freeman and A.Gould, Phys. Rev. **D37** (1988) 3388.
- [2] G.Jungman, M.Kamionkowski and K.Griest, Phys. Rep. **267** (1996) 195.
- [3] R.Bernabei et al., arXiv:1301.6243.
- [4] R.Agnese et al., arXiv:1304.4279.
- [5] C.E.Aalseth et al., Phys. Rev. Lett. **106** (2011) 131301.
- [6] K.Fushimi et al., J. Phys. Soc. Jpn. **74** (2005) 3117.
- [7] J.Ellis, R.A.Flores and J.D.Lewin, Phys. Lett. **B212** (1988) 375.
- [8] H.Ejiri, H.Ohsumi and K.Fushimi, Phys. Lett. **B317** (1993) 14.
- [9] R.Bernabei et al., New Jour. Phys. **2** (2000) 15.1.
- [10] K.Harada et al., KEK Proceedings of the 26th Workshop on Radiation Detectors and Their Uses, (2012) 122.
- [11] R.Bernabei et al., Nucl. Instru. & Meth. in Phys. Res. **A592** (2008) 297.
- [12] K.Eguchi et al., Phys. Rev. Lett. **90** (2003) 021802.