

KamLAND-PICO dark mater search project

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Abstract

Dark matter search project KamLAND-PICO is proposed. The first phase of the project aims to verifying the annual modulation signal which has been reported by DAMA/LIBRA. The last phase of the project aims to determining the type of interaction between WIMPs and nucleus. The thin and wide area NaI(Tl) detector PICO-LON has been developed to determine the type of WIMPs interaction. The good performance of PICO-LON detector was obtained. The energy threshold was as low as 2 keV_{ee} and the the energy resolution was as small as 25 % at 60 keV_{ee}. The highly pure NaI(Tl) crystal has been developed in collaboration with the Japanese developer. The purity of U and Th chain contaminants have been reduced to the order of a few tens of ppt. It should be remarked that the concentration of ²¹⁰Pb was reduced to about 60 μBq/kg. The sensitivity to spin-independent WIMPs are discussed by applying 170 modules of NaI(Tl) with the dimension of 5 inch φ×5 inch.

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1. Introduction

Weakly interacting massive particles (WIMPs) are one of the most promising candidates for cosmic dark matter. Many groups in the world have tried to find the signal for WIMPs by various target nuclei and various methods. Recently some groups have reported the significant candidates for WIMPs signal.

DAMA/LIBRA has been continuously measured an annual modulating signal for WIMPs by means of 250 kg highly radiopure NaI(Tl) detector. They have observed the 8 σ significance of modulating signal for 13 annual cycles[1]. Another groups reported small number of candidate signals by Ge and Si target nuclei. The CDMS-II experiment reported three significant events by using Si detector[2]. Using the Ge target, the CoGeNT experiment reported another signal for WIMPs candidate. The CRESST experiment applied to CaWO₄ and reported another significant events.

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All the mass and cross section which have reported by these groups are different from each other. Moreover, almost all the region of their regions of were excluded by large volume Xe detector experiments[3, 4]. To solve the present confusing status, one need to apply a large volume detector which has higher sensitivity to WIMPs. The large mass (a few ton) and a highly radiopure (less than a few $\mu\text{Bq/kg}$) is needed.

The KamLAND-PICO project aims to search for WIMPs candidate by means of highly radiopure NaI(Tl) scintillator which is installed into KamLAND detector system. The KamLAND detector is a huge liquid scintillator whose diameter is as large as 13 m. The huge volume liquid scintillator acts as an ideal active shield against gamma ray and neutron. The PICO-LON (Planar Inorganic Crystal Observatory for LOW-background Neutr(al)ino) detector proposes a highly selective measurement of nuclear and particle rare processes by a large volume NaI(Tl) detector[5]. The thin layer detector system enables the precise measurement of WIMPs interaction, spin-dependent (SD) or spin-independent (SI). In the present paper, the performance of thin NaI(Tl) scintillator and purification of NaI(Tl) crystal. In the next section, the basic concept of our final detector system PICO-LON which enhances the sensitivity to WIMPs. The performance of thin (0.1 cm) and wide area (15 cm \times 15 cm) NaI(Tl) scintillator is reported in section 3. The purity of radioactive contaminants are the most serious problem for WIMPs search, the result of purification of NaI(Tl) is reported in the section 4.

2. Concept of PICO-LON

PICO-LON is a NaI(Tl) array system which enables the precise analysis of WIMPs interaction and effective reduction of low energy background. The origin of low energy background is mainly due to the scattered high energy gamma rays. The low energy background events originated by Compton scattering is effectively tagged and removed by constructing the detector array and the active shield with 4π solid angle.

The other important feature of the thin NaI(Tl) array is to measure the low energy gamma ray which is excited by spin-dependent excitation of ^{127}I nucleus. The low-lying excited state at 57.6 keV in ^{127}I is easily excited by spin-dependent interaction[6, 7]. The inelastic excitation of ^{127}I nucleus extracts the spin-dependent interaction between WIMPs and nucleus. The ratio between the event rates of elastic scattering and inelastic one gives the important information for the interaction between WIMPs and nucleus.

The required performances of NaI(Tl) detector to search for WIMPs are listed below.

1. Low energy threshold

The scintillation output for nuclear recoil in NaI(Tl) scintillator is, unfortunately, largely suppressed relative to the electron recoil. The quenching factor which is defined by the ratio of scintillation output due to electron I_e and due to nuclear recoil I_N with the same kinetic energy as

$$f \equiv \frac{I_N}{I_e}.$$

The quenching factor for the recoil of iodine nucleus is $f_I = 0.05$ and for the one of sodium ion is $f_{\text{Na}} = 0.2$ [8]. Moreover, the form factor for spin-independent elastic scattering goes through zero at about 5 keV electron equivalent energy. The energy threshold of NaI(Tl) scintillator must be lower than 2 keV $_{ee}$ to have a significant sensitivity to WIMPs, where, keV $_{ee}$ stands for the electron equivalent energy.

2. Good energy resolution

The good energy resolution about 25% at 60 keV $_{ee}$ is needed. The good energy resolution enhances the selection power of inelastic nuclear excitation of ^{127}I and inelastic atomic excitation. Both the case, the serious background peak is arisen by ^{210}Pb at 46.5 keV $_{ee}$. Since the good energy resolution is related to the large scintillation output, the design of the detector is optimized to collect the scintillation photons efficiently.

3. Low background

The low background is the most important feature for WIMPs detector. To achieve the sensitivity to the WIMPs-proton cross section down to 10^{-42} cm 2 , the density of radioactive contamination must be lower than a few $\mu\text{Bq/kg}$.

3. Performance of PICO-LON module

The goal of KamLAND-PICO project is to determine the type of WIMPs-nucleus interaction. To determine the ratio between SI and SD interaction in WIMPs-nucleus interaction, the nuclear excitation of ^{127}I plays the important role. In order to perform the coincidence measurement of recoil nucleus and gamma ray which is emitted immediately after the excitation, the thin and wide area NaI(Tl) scintillator has been developed[9]. The dimension of the thin and wide area NaI(Tl) scintillator was $15\text{ cm} \times 15\text{ cm} \times 0.1\text{ cm}$. The wider surface of the crystal was polished to guide the scintillation photons to the thinner edges. The photons which failed to total reflection was guided to the thinner edges by a reflector sheets. The four thinner edges were ground in order to the scintillation photons go out of the crystal. To avoid deliquescing the NaI(Tl) crystal, the light guide were put on the thinner edges and the thin aluminum sheets were glued on the reinforcement frame.

Twelve modules of square photomultiplier tubes (PMTs) are glued on the thinner edges of the detector by silicon oil. The current outputs of three PMTs on one edge were summed and introduced to the data acquisition system. The low energy spectrum was taken by irradiating a standard gamma ray source, ^{133}Ba . The energy spectrum is shown in Fig.1. It should be noted that the low energy X ray peak at 4.2 keV_{ee}

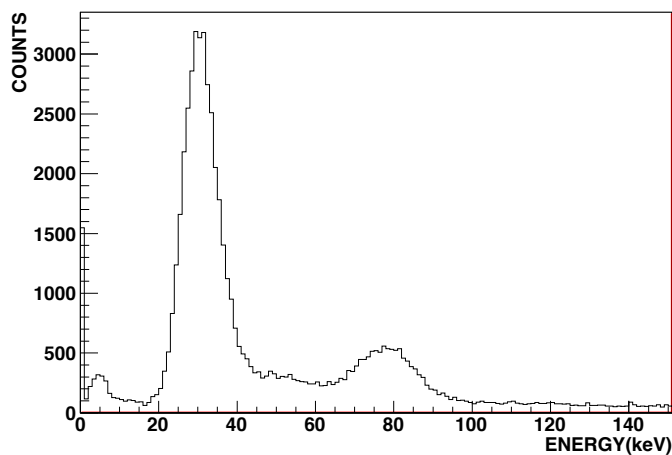


Fig. 1. The energy spectrum taken by thin NaI(Tl) scintillator. The gamma ray source was ^{133}Ba .

was clearly observed. The energy threshold was as low as 2 keV_{ee} , which is sufficiently low to search for WIMPs. The energy resolution was calculated from the 81 keV gamma ray peak as 25% in full-width-half maximum.

4. Development of pure NaI(Tl) crystal

Although many groups in the world are trying to reduce the radioactive contamination in NaI(Tl) crystal[10, 11, 12], the NaI(Tl) crystal purer than the one operated by DAMA/LIBRA has not been developed yet. The most serious contamination in NaI(Tl) is ^{210}Pb and its progeny. The ^{210}Pb emits low energy beta rays ($E_{\beta,Max} = 16.5\text{ keV}_{ee}$ and 64 keV_{ee}) and the ^{210}Bi emits beta rays with higher energy ($E_{\beta,Max} = 1162\text{ keV}_{ee}$). All the beta rays and the gamma ray from the progeny of ^{210}Pb seriously reduces the sensitivity to WIMPs search. The groups trying to make a highly pure NaI(Tl) have been suffered by a large contamination of ^{210}Pb with its concentration of about 1 mBq/kg .

In the present work, the concentration of ^{210}Pb was effectively reduced by controlling environmental conditions. Clean air through a HEPA filter was continuously flushed into the booth for material preparation. The lead ion was removed by ion exchange resin. The solution of NaI(Tl) was dried by a rotary evaporator and a vacuum dryer. Pure nitrogen gas was introduced when the vacuum was broken.

DAMA/LIBRA group used a pure crucible made of pure platinum. It is difficult to develop a good NaI(Tl) crystal by small platinum crucible because a NaI(Tl) crystal adheres to a platinum. In the present work, we selected the material which does not adhere to a NaI(Tl) crystal to get a good crystal with higher yield. The impurity of a crucible material was tested and the concentration in the material was less than 20 ppb for U and Th, 200 ppb for potassium. The selected crucible avoids the contamination from the crucible during crystallization.

The measurement of the densities of the progeny of U and Th chain in NaI(Tl) was measured by counting the alpha ray events. The difference between pulse shape due to beta/gamma ray and alpha ray was analyzed to distinguish the alpha ray events. The decay time of scintillation photons by beta/gamma ray event is 230 nsec, while the one by alpha ray event is 190 nsec[13]. The pulse shape discrimination method enables to perform the background-free measurement for the contaminants which emits alpha rays in a surface level laboratory.

The difference of the alpha ray energy spectra between before and after purification is shown in Fig.2. The energy spectrum before purification consists of a large bump of alpha rays due to mainly ^{210}Po and

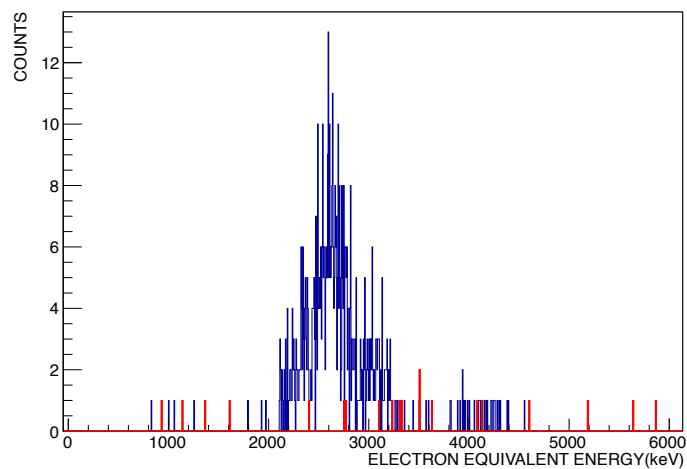


Fig. 2. The energy spectra of alpha ray before and after purification. Blue: Before the purification. Red: After the purification.

secondary U chain. The event rate of alpha ray was reduced by two orders of magnitude after the purification process.

The measurement of purity was performed by making a $3' \phi \times 3'$ NaI(Tl) detector. The measurement was performed for 26 days of live time at the surface level laboratory in Tokushima University. The obtained energy spectrum of alpha ray which was measured by the final ingot (ID 23) is shown in Fig.3. Three prominent peaks by the progeny of ^{226}Ra were clearly observed. The intensities of alpha rays were the same because the progeny of ^{226}Ra are in secular equilibrium. The density of ^{226}Ra and their progeny were $104 \pm 17 \mu\text{Bq/kg}$ each. The alpha ray events due to ^{214}Po were clearly observed around 7.8 MeV with a smaller efficiency. The half life of ^{214}Po is so short as $164 \mu\text{sec}$ that a large part of the ^{214}Po decays during the data acquisition system is processing the prompt decay events of ^{214}Bi . The radioactivity of Th chain was determined by a small peak around 6.8 MeV which were the events from ^{216}Po .

The other nuclei in U chain and Th chain progeny made no prominent peaks. The origin of the continuum in the energy spectrum is supposed to be the unresolved peaks or to be the alpha rays which loosed their energy in the PTFE sheet. In the present analysis, we assumed that all the alpha rays were originated from the progeny in NaI(Tl) crystal. The yields of unresolved peaks were calculated from the event numbers of the energy regions shown in Table 1. The intensity of ^{216}Po is immediately derived by the peak yield Y_E .

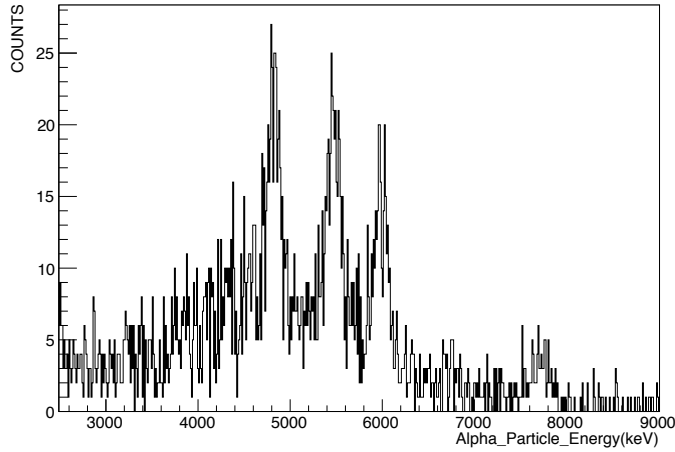


Fig. 3. The energy spectrum of α ray measured by ID 23.

Table 1. The intensities of each energy regions and the progeny of U and Th chains in each regions.

Region	Energy region (keV)	Nuclei (Chain)	Yield [$\times 10^{-6}$ /sec/kg]
A	3870 – 4275	^{232}Th (Th), ^{238}U (U)	79 ± 6
B	4524 – 4996	^{226}Ra (U), ^{230}Th (U), ^{234}U (U)	197 ± 9
C	5227 – 5762	^{210}Pb (U), ^{222}Ra (U), ^{223}Th (Th), ^{224}Ra (Th)	192 ± 9
D	5775 – 6365	^{218}Po (U), ^{212}Bi (Th), ^{220}Rn (Th)	134 ± 7
E	Fitted by Gaussian	^{216}Po (Th)	13 ± 8

The assumption of radioactive equilibrium in Th chain leads to the following equations.

$$Y_{216\text{Po}} = Y_E \tag{1a}$$

$$Y_{216\text{Po}} = Y_{232\text{Th}} = Y_{228\text{Th}} = Y_{224\text{Ra}} = Y_{220\text{Ra}} = 2.87Y_{212\text{Bi}} \tag{1b}$$

$$Y_{218\text{Po}} = Y_D - 1.35Y_E \tag{1c}$$

$$Y_{218\text{Po}} = Y_{226\text{Ra}} = Y_{222\text{Rn}} \tag{1d}$$

$$Y_{210\text{Po}} = Y_C - 2Y_E - Y_{222\text{Rn}} \tag{1e}$$

$$Y_{238\text{U}} = Y_A - Y_E \tag{1f}$$

$$Y_{230\text{Th}} + Y_{234\text{U}} = Y_B - Y_{226\text{Ra}} \tag{1g}$$

The calculated radioactivity of ^{218}Po was consistent to the fitted value derived the previous analysis. The radioactive densities of ^{238}U , ^{210}Pb and $^{230}\text{Th} + ^{234}\text{U}$ were $66 \pm 10 \mu\text{Bq/kg}$, $58 \pm 26 \mu\text{Bq/kg}$ and $89 \pm 21 \mu\text{Bq/kg}$, respectively.

The present work is compared to the other work as listed in Table 2. The world leading experiments, DAMA/LIBRA [13] and DM-ICE [14] was listed in the table. It should be remarked that the density of

Table 2. The concentration of radioactive isotopes in a NaI(Tl) crystal for WIMPs search.

	DAMA/LIBRA	DM-ICE	This work
^{232}Th	0.5-0.7 ppt	50 ppt	3.3 ± 2.0 ppt
^{238}U	0.7-10 ppt	7.5 ppt	5.4 ± 0.9 ppt
^{210}Pb	5-30 $\mu\text{Bq/kg}$	2000 $\mu\text{Bq/kg}$	$58 \pm 26 \mu\text{Bq/kg}$

^{210}Pb was effectively reduced by present work. The sufficiently low background NaI(Tl) crystal for WIMPs

search has been successfully developed by PICO-LON group. Further purification will be also applied to get more stringent limit on WIMPs.

5. Future prospect (KamLAND-PICO phase I)

KamLAND detector is a huge neutrino detector which is located in Kamioka Underground Observatory in Japan. It consists 13 meters diameter balloon which contains 1 kton of liquid scintillator (LS). The LS balloon is made of 135 μm -thick transparent nylon/EVOH (ethylene vinyl alcohol copolymer) composite film. The LS is 80% dodecane, 20% pseudocumene (1,2,4-trimethylbenzene), and 1.52 g/liter of PPO (2,5-diphenyloxazole) as a fluor. A buffer of dodecane and isoparaffin oils between the balloon and an 18-m-diameter spherical stainless-steel containment vessel shields the LS from external radiation.[15] Recently, the small balloon which contains ^{136}Xe loaded LS is installed in the central region of the LS balloon to search for $0\nu\beta\beta$ decays of ^{136}Xe [16].

KamLAND-PICO project will search for WIMPs installing the large volume and highly radiopure NaI(Tl) scintillator into KamLAND. In the first phase of the project, 170 modules of 5' ϕ \times 5' NaI(Tl) crystal will be installed. It aims at verifying the annual modulation signal reported by DAMA/LIBRA and finding the WIMPs signal by applying purer and larger NaI(Tl) crystal. The detector is designed to achieve the low energy threshold of 1 keV $_{ee}$.

The expected sensitivity to spin-independent WIMPs is shown in Fig.4. The red solid line indicates the

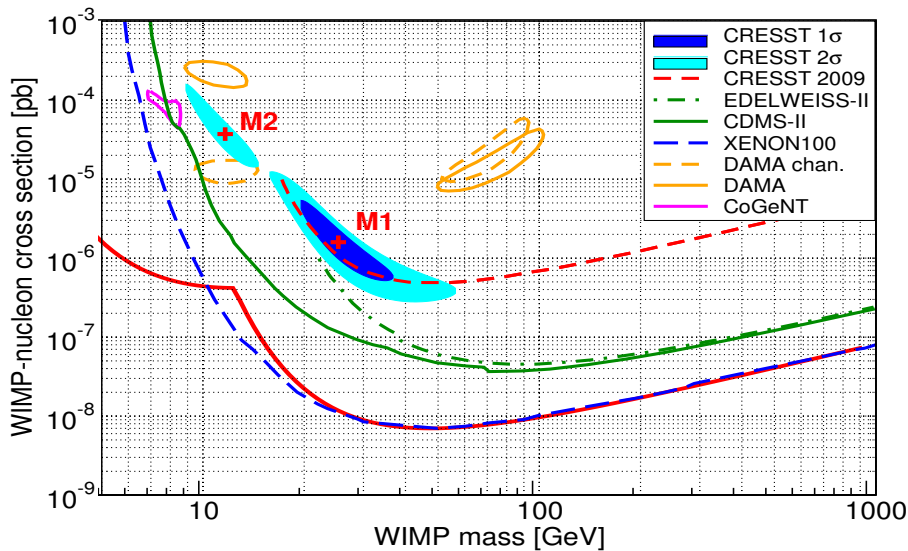


Fig. 4. The expected sensitivity for spin-independent WIMPs. The original sensitivity plot was drawn by CRESST-II[17].

expected sensitivity to WIMPs by KamLAND-PICO phase-I. The line was drawn in the following assumption.

- The expected background from all surrounding material was based on the measured values of concentration of radioactive impurities.
- The total exposure is 1 ton \times year.
- The energy threshold is 1 keV $_{ee}$ and the quenching factor for I nuclei and Na nuclei are 0.09 and 0.25, respectively[8].

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