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Status of the COSINE-100 experiment at Yangyang

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The COSINE-100 experiment at Yangyang searches for nuclear recoils by Weakly Interacting Massive Particle in the NaI(Tl) crystal scintillators targeting at a sensitivity comparable to the DAMA experiment. The goal of the COSINE experiment is to confirm or dispute the annual modulation signature claimed by DAMA in the same target material. The first phase COSINE-100 experiment completed in the summer 2016 consists of a total crystal mass of 106 kg submerged in 2000 liters of scintillating liquid. The experimental shielding includes the liquid scintillator, 3 cm copper, 20 cm leads, and 3 cm plastic scintillator panels. So far, a more than 9-month-long period of stable operation has been achieved and we continue to run the detector in this mode for another two years at which time a second phase of the experiment, called COSINE-200, will replace the first phase experiment. In this article, the status of the COSINE-100 experiment and the initial performance are presented.

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1. Introduction

Dark matter is known to exist everywhere, and yet we understand very little about it. We know that the dark matter is composed of about 27% of the total energy distribution in the Universe and there have been indirect evidences for the elusive energy via astrophysical observations [1, 2, 3]. However, the dark matter interacting with the regular matter has yet to be measured in a laboratory. Measurements of the dark matter not only bring a deeper understanding of the Universe but also open a door for new physics beyond the Standard Model. Theoretical models point to Weakly Interacting Massive Particles (WIMPs) as the most probable particle candidate for dark matter [4, 5]. A WIMP interacting with nuclei of normal matter can be measured by detecting a nuclear recoil signal with a very low-background detector in an underground laboratory [6].

Surprisingly, there is a claimed observation by the DAMA experiment in NaI(Tl) crystal detectors that reported a positive annual modulation signal at a phase consistent with expectations for the Earth's motion relative to the Galactic rest frame [7, 8, 9, 10, 11]. Using 1.33 ton $\cdot$ year data with 1 count/day/kg/keV (=differential rate unit or dru) background, DAMA's modulation amplitude in the single-site event distribution at the energy range between 2$-$6 keV is 0.0112 ± 0.0012 dru disfavoring no modulation at 9.3 σ. With the phase of $144{\pm}7$ days and amplitude of $0.998{\pm}0.002$ year, its signal is an indicative of WIMP interactions. However, at the same time, this modulation has been questioned continuously because other direct detection experiments using liquid Xenon or CsI(Tl) as a target observe no modulation [12, 13, 14].

Efforts to reproduce the DAMA result have been pursued by several groups including ANAIS [15], DM-Ice [16], KamLAND-PICO [17], SABRE [18], and KIMS [19] by developing low-background NaI(Tl) crystals. Particularly, KIMS and DM-Ice jointly formed the COSINE collaboration to build a single experiment at the Yangyang underground laboratory (Y2L) in Korea. As of 2016, KIMS and DM-Ice have contributed NaI(Tl) crystals to produce the eight crystal array with a total mass of 106 kg in the COSINE-100 experiment. The COSINE-100 experiment searches for nuclear recoils by WIMPs in the NaI(Tl) crystal scintillators. The main goal of the COSINE-100 experiment is to unambiguously reproduce what DAMA has shown using the same target crystals.

These crystal detectors are coupled with PMTs to obtain tiny scintillation light signals when a WIMP interacts with one of the nuclei in the crystals. The detector is equipped with several shielding materials such as lead, copper, and liquid scintillator to filter out backgrounds which would otherwise obscure faint WIMP-induced signals. Designed to be sensitive to WIMP-nucleon interactions at energies below 2 keV, COSINE-100 collects electron/gamma and nuclear recoils which can be used to study the annual modulation, a manifestation of WIMP interactions with matter.

At the dark matter search region below 10 keV, major internal background contributions for these NaI(Tl) crystals include the ^{210}Pb beta decays (Q = 60 keV), ^{40}K decay $\sim$3 keV X-rays, and cosmogenically-activated Te/I decay $\sim$4 keV X-rays. The ^{210}Pb contamination for both bulk and surface of a crystal that might have happened in the middle of crystal processing is critical to the experiment. This is because ^{210}Pb is a long-lived radioisotope ($T_{1/2}$ = 22.2 yr) and is difficult to remove from raw material with a purification method. For the ^{40}K contamination, it is important to tag an accompanying 1460 keV gamma-ray that escapes the crystal and otherwise the raw material purification is neccessary. For the cosmogenic components, we rely on a proper modeling by measuring their decay constants and by using up-to-date simulations.

2. COSINE-100 setup

2.1 Experimental site

The COSINE-100 experiment is installed at a newly developed A5 tunnel at the Y2L facility. The facility is situated next to the Yangyang hydroelectric power plant, South Korea and operates two laboratory spaces called A5 and A6. The tunnels at the depth of 700 m are composed of granite and provide overburden of 1800 meter-water-equivalent depth (cosmic ray muon flux is $2.7 \times 10^7/\mathrm{cm}^2$ [20]). The facility is accessed by car through about 2 km drive-way. The Korea Invisible Matter Search (KIMS) experiment at the A6 laboratory had been running for more than 15 years using CsI(Tl) crystals to look for the dark matter interactions. The A6 laboratory has been refurbished and is now mainly used for various R&D programs using NaI(Tl) crystals or liquid scintillators.

The COSINE detector room at A5 is 44 m^2 wide and 4 m high, and is managed as clean air environment. The detector room is equipped with several environmental monitoring systems to control humidities, radon level, and temperatures. Automatically regulated electrical power through uninterruptible supplies is provided and the stability of the power is continuously monitored though blackouts rarely happen. The system maintains the relative humidity at (40±3) %, the radon level at around 40 Bq/m^3 and the room temperature at (23.5±0.3) °C throughout a year. Since the crystal detector array is submerged in a large volume of scintillating liquid that has a relatively high heat capacity, the temperature variations near the crystals are reduced to ±0.05 °C.

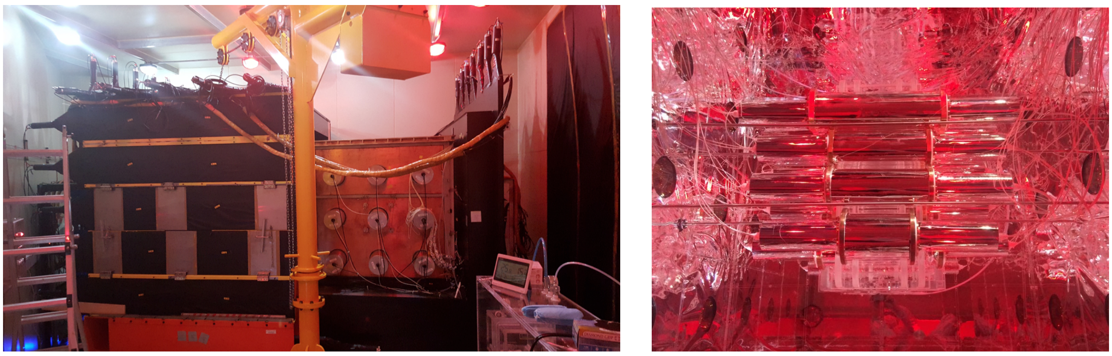

Figure 1: (left) A photo of the COSINE detector room with the detector door open. (right) Inside view of the four by two NaI(Tl) crystal arrangement.

2.2 NaI(Tl) crystal detectors

For the COSINE-100 experiment, we have developed the low background NaI(Tl) crystals (labeled C1−C8) in cooperation with the Alpha Spectra Inc. (AS). A series of NaI powder purifications was performed by the company before the crystal was grown. The grown crystals are machined in a cylindrical shape, wrapped by PTFE reflective sheets in the lateral part and encased in an oxygen-free copper barrel with quartz end windows coupled to each end of the crystals. The

12.0 mm-thick quartz window is light-coupled to each end of the crystal via an optical pad. These are, in turn, light-coupled to 3-inch Hamamatsu R12669SEL (selected for high quantum efficiency) PMTs via a small amount of high viscosity optical gel.

Those eight NaI(Tl) crystal assemblies are put in an array of 4×2 on the two-story acrylic table in the central region of the COSINE-100 experimental sheilding. The total crystal mass is 106 kg. Each crystal includes a 16 mm-diameter calibration window with a reduced thickness of 0.5 mm in the middle region of the copper encapsulation to facilitate the lowest energy source calibration. All crystals are positioned such that these calibration windows directly face to the nearest external calibration hole. The arrangement of the crystals is shown in Fig. 1.

2.3 Shielding structure

The COSINE-100 shield closely follows design features from its precursor KIMS experiment [21]. To attenuate or tag the influence of externally generated radiation from cosmogenic radioisotopes as well as intrinsic radioactivity in the environment and various external detector components, the detector is nested by layers of shielding materials, as shown in Fig. 2. From the inner center to outwards, the four shielding layers are scintillating liquid, copper box, lead-brick castle, and plastic scintillator panels.

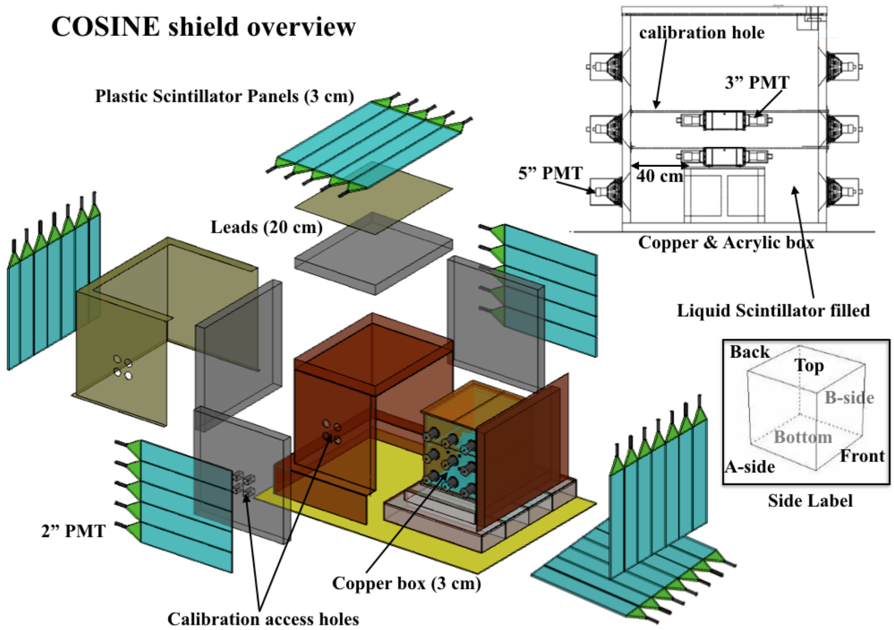

Figure 2: The 4π 4-layer shielding enclosure for the COSINE detector. From inside outward, eight encapsulated crystal detectors immersed in ~2 tons of scintillating liquid, a liquid and crystal supporting acrylic box (1 cm thick), 3 cm-thick copper box, 20 cm-thick lead-brick castle, and 37, 3 cm-thick muon panels are shown. Also indicated are the locations of the calibration holes, the size of the PMTs, and labels for sides. Here the lead shields at the bottom and the front side are omitted for clarity.

Various external backgrounds produced by radiogenic particles from the inner or outer detector materials, including PMT-originated background and NaI(Tl) internal background, are rejected by an anticoincidence requirement with PMT signals from the liquid scintillator (LS). The innermost active and passive shield is provided by Linear Alkyl-Benzene (LAB)-based LS. The LAB-LS contains a small amount (a few %) of 2,5-Diphenyloxazole for fluor and for scintillator/wavelength-shift, and a trace amount of p-bis-(o-methylstyryl)-benzene as the second wavelength shifter. A volume of 2000 L is filled into an acrylic container that is nested inside the copper box. The LS-produced photons are detected by eighteen, 5-inch Hamamatsu PMTs (R877) that are attached to the A- and B-sidesof the box. The radioactivity of the LAB-LS has been measured to be below 7 ppt and 4 ppt for ^{238}U and ^{232}Th , respectively and does not affect the crystal data as an external background significantly. The minimum distance between the crystal PMTs and the copper-box inner wall is approximately 40 cm (see Fig. 2.) in which the GEANT simulation shows that more than 70% of ^{40}K -induced events can be tagged together with other crystals.

The copper box serves as a gamma attenuator and a support for the liquid scintillator. The copper box is 3 cm-thick and is made of oxygen-free copper plate ingots. The gamma- and X-rays that exit the lead castle are attenuated by the copper walls. The 1 cm-thick acrylic box for the liquid scintillator container is fit to inner walls of the copper box. Next, the external gamma rays are additinoally attenuated by a 20 cm-thick lead wall that surrounds the copper box.

Thirty-seven plastic scintillator panels in the outer most part of the shield tag cosmic-ray muons that pass through or near the detector. The array records and flags cosmic-ray muons and muon-induced events in the same data stream as the crystal data. The main purpose of this system is to study the correlations between cosmic-ray muons and crystal signals, where the high-energy muons might affect the crystal response over a time interval that is much longer than the 8μs window of the crystal readout system. The cosmic-ray muon flux measured at the COSINE-100 setup is $344 \pm 1(\text{stat.}) \pm 34(\text{syst.})$ muons/m^2/day [22]. A photograph of the the detector with the door open is shown in Fig. 1.

2.4 DAQ

There are 16 3-inch PMTs for the crystal readout, 18 5-inch PMTs for the LS system and 42 2-inch PMTs for the muon system. For the crystals, a high-gain signal from the anode is amplified $\times$30 with a preamplifier while a low-gain signal from a 5$^{\text{th}}$ stage dynode is amplified $\times$100. Both outputs are connected to 500 MSPS (Megasamples per second) Flash Analog-to-Digital Converters (FADCs) to store low energy and high energy waveforms for each event. Signals from the LS PMTs are amplified $\times$30 and connected to a charge sensitive 64 MSPS ADC (M64ADC) while signals from the muon panels are directly connected to M64ADCs. When there is a crystal trigger formed by a coincidence signal from each PMT within 200 ns, the M64ADC passively returns the integrated charge and the time of a pulse. The total trigger rate for the physics run is 28 Hz.

3. Initial performance of the NaI(Tl) crystals

The COSINE-100 physics run started on September 2016. The detector runs smoothly for more than eight months without a major failure. After excluding runs with initial tests and calibration runs, we have achieved about 80% total livetime of which about 70% is determinded as good data, as shown in Fig. 3.

The NaI(Tl) crystals were evaluated in the KIMS-CsI setup at A6 [19] and moved to the COSINE-100 shield to make sure that those crystals were free of additional contamination. Overall, these crystals show high light output and acceptable ^{238}U and ^{232}Th contaminations (see Table 1). Also, the powder grade is closely correlated with the contamination level of the grown crystals, as can be seen for the level of ^{40}K , which depends on the powder batch. Within a specific batch of powders, radioactivities are consistently reproduced. However, the level of alpha particles due to ^{210}Po is higher than that achieved by DAMA [8] while its origin is not fully understood yet.

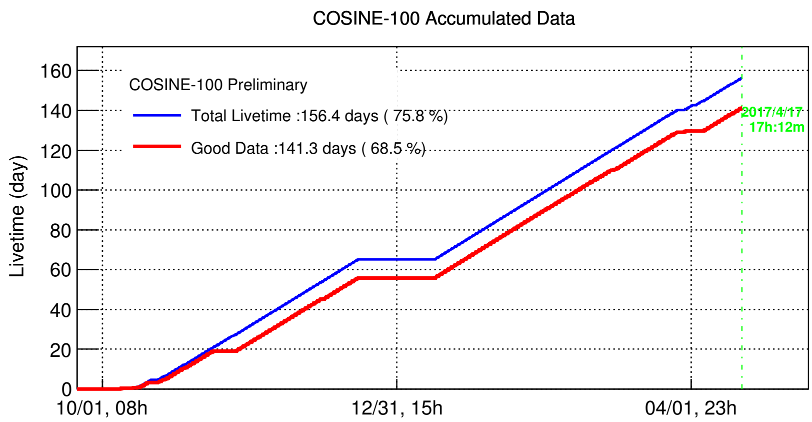

Figure 3: The cumulative total exposure.

Four different powder grades are used for the eight crystals (see Table 1). The results of detailed studies of these powders and crystals are described in Refs. [23, 19]. For the C3 and C4 production, AS reportedly developed additional background reduction methods, especially aimed at reducing ^{210}Pb contamination in the powder preparation and the crystal-growing process. The batch of powder used for these crystals is called AS-WSII. For the C6 and C7 crystals, AS further reduced the ^{40}K background and developed additional background reduction methods in the production of a new powder grade (called AS-WSIII). However, these crystals have a ^{210}Pb background contamination that is twice as high when compared to that achieved with AS-WSII.

The performance of the crystals and liquid scintillators is monitored with a variety of calibration sources. Four different γ-ray sources, ^{241}Am , ^{57}Co , ^{137}Cs , and ^{60}Co are used for the energy calibration. Table 1 shows the initial performance of these crystals. The light yield is measured at 59.6 keV with a ^{241}Am source and checked for consistency with the 46.5 keV internal ^{210}Pb gamma peak. Compared to DAMA's measurement, the COSINE-100 crystals show roughly twice high light yields ($\sim$15 PEs/keV). Alpha rates are measured by counting total alphas after application of a pulse shape discrimination between gamma and alpha events. For the ^{40}K measurement, we use multiple-hit spectrum by selecting event rate for 3 keV in the crystal being tested and 1460 keV in other crystals or the liquid scintillator. For ^{238}U and ^{232}Th activities, we use the alpha events to auto-correlate with subsequent alphas or betas and search decay time components that are consistent with known values.

Table 1: Measured radioactivity levels in the COSINE-100 crystals. The "Powder" acronyms are AS-B (AS-C):Alpha Spectra purified powder, AS-WSII: Alpha Spectra WIMPScint-II grade powder and AS-WSIII: Alpha Spectra WIMPScint-III grade powder.

Crystal	Mass (kg)	Powder	Alpha Rate (mBq/kg)	^{40}K (ppb)	^{238}U (ppt)	^{232}Th (ppt)	Light Yield (PEs/keV)
Crystal-1	8.3	AS-B	3.20 ± 0.08	43.4 ± 13.7	<0.02	1.3 ± 0.4	14.9 ± 1.5
Crystal-2	9.2	AS-C	2.06 ± 0.06	82.7 ± 12.7	<0.12	<0.6	14.6 ± 1.5
Crystal-3	9.2	AS-WSII	0.76 ± 0.02	41.1 ± 6.8	<0.04	0.4 ± 0.2	15.5 ± 1.6
Crystal-4	18.0	AS-WSII	0.74 ± 0.02	39.5 ± 8.3		<0.3	14.9 ± 1.5
Crystal-5	18.3	AS-C	2.06 ± 0.05	86.8 ± 10.8		2.4 ± 0.3	7.3 ± 0.7
Crystal-6	12.5	AS-WSIII	1.52 ± 0.04	12.2 ± 4.5	<0.02	0.6 ± 0.2	14.6 ± 1.5
Crystal-7	12.5	AS-WSIII	1.54 ± 0.04	18.8 ± 5.3		<0.6	14.0 ± 1.4
Crystal-8	18.3	AS-C	2.05 ± 0.05	56.2 ± 8.1		<1.4	3.5 ± 0.3
DAMA			< 0.5	< 20	$0.7-10$	$0.5-7.5$	$5.5-7.5$

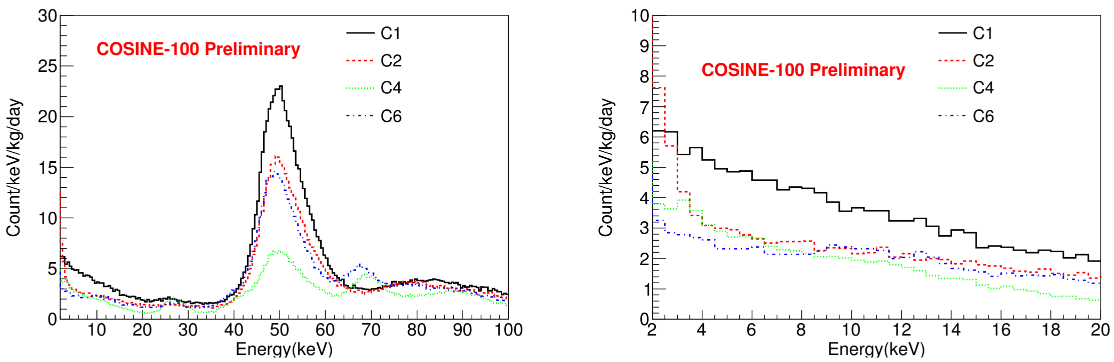

Figure 4: (left) Energy spectrum comparisons for four crystals from different powder samples. The peak near 50 keV reflects the ^{210}Pb contamination level in each crystal. Crystal-4 and Crystal-6 have been underground for less than one year and, so, they have cosmogenic peaks (e.g., ^{125}I at 67.8keV) (right) A zoomed plot to show the spectra for energies below 20 keV. The background levels are lowest for Crystal-4 and Crystal-6, which reflects their lower ^{210}Pb .and ^{40}K contamination levels. The spectra are made after all noise rejection criteria are applied.

4. Summary

The COSINE-100 experiment was constructed at Y2L and started data-taking since September, 2016. The main goal of the COSINE-100 experiment is to independently confirm or dispute the long-standing DAMA's annual modulation signature. The detector is composed of eight low-background NaI(Tl) crystals encapsulated by copper and encompassed by several layers of external radioactivity attenuators. Unlike the DAMA apparatus, the experiment is additionally equipped with the cosmic-ray muon panels and the liquid scintillator veto to tag events that may not originate from WIMP-induced interactions in the crystal. At the same time, various control and monitoring systems are in place collecting environmental records which can be used in correlation studies with the physics data. The detector has been running smoothly for more than 9 months. Initial data show a good performance and we expect to continue stable data-taking for the next two years before the next phase (COSINE-200) experiment is assembled.

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