Dark Matter Searches with the COSINE-100 Experiment

Adhikari Govinda,
Department of Physics, Sejong University, Seoul, South Korea
On behalf of the COSINE-100 collaboration
E-mail: adhikari.astro@gmail.com

Abstract. COSINE-100 is a direct dark matter detection experiment that aims to test DAMA/LIBRA’s claim of dark matter discovery using 106 kg of low-background NaI(Tl) detectors submerged in a 2-tonne liquid scintillator veto. The physics run of the experiment began in September 2016, and a 3.5 count/kg/day/keV background level within the 2-6 keV region of interest has been achieved. Several physics analyses, including WIMP searches and an annual modulation search, have been performed using a 2 keV energy threshold. Recently, this threshold has been lowered to 1 keV. In this talk, we describe the method used to lower the threshold to 1 keV and recent results with this lowered threshold.

1. Introduction
Various astronomical observation gives positive sign for the existence of dark matter comprising about 27% of the mass in the universe [1, 2, 3]. The DAMA/LIBRA experiment has been reporting a nonzero annual modulation for the last 15 years with a 12.3 σ significance which is the only strong evidence for dark matter model [4, 5, 6]. However, other experiments with different target materials but better sensitivity exclude the DAMA/LIBRA allowed signal region [7, 8, 9]. Additional independent experimental data using the same target material is necessary to understand the DAMA annual modulation signature. COSINE experiment is running at the Yangyang Underground Laboratory (Y2L) Yangyang, South Korea from September 2016 using the same NaI(Tl) target as DAMA used in order to confirm or refute the DAMA annual modulation search [10, 11].

The COSINE-100 collaboration publish spin-independent WIMP limits using the first 59.5 days of data and result of an annual modulation search with 1.7 years of the data, both with the 2 keV analysis threshold. COSINE 100 excludes DAMA/LIBRA phase 1’s interpretation with the spin-independent WIMP interaction with Standard Halo model in NaI (Tl) crystal [12]. The modulation amplitude and phase from COSINE best fit values are found to be 0.0092 ± 0.0067 Counts/day/kg/keV and 127.2 ± 45.9 days respectively. This result is consistent with both a null hypothesis and DAMA/LIBRA’s 2 - 6 keV best fit value with 68% CL [13]. Lowering the analysis threshold and more exposure will improve the sensitivity of COSINE experiment.

2. Lowering analysis threshold
Several experiment reported that NaI(Tl) detectors is suffer from non-linearity because of the fluorescence efficiency [14]. This non-linearity is more severe at low energy region, but COSINE-
100 has only six possible calibration points below 100 keV. Thus, an empirical calibration function is modeled based on the non-linearity response of NaI(Tl) detector data based on results from ref [14]. This empirical function is used to calibrate the COSINE detector and shows the proper alignments of the known isotopes and their corresponding energy scale from 0.8 keV ($^{22}\text{Na}$) upto 67.8 keV ($^{125}\text{I}$) peak.

In general, physics events caused by particles, energy deposit in a crystal to crystal have larger decay time than a typical PMT noise pulse. The signal shape profile of the scintillation events is determined from calibration run and the noise event shape profile is determined from background running. A logarithmic likelihood of the PMT pulses waveform for each event is compared with the reference signal shape profiles. A new parameter based on logarithmic likelihoods can be used to separate scintillation and noise equal like events at 1 keV as shown in figure 1.

![Signal/Noise template for likelihood analysis.](image)

**Figure 1.** Signal/Noise template for likelihood analysis.

### 2.1. Event selection

A multivariable Boosted Decision Tree (BDT) that accounts for correlation between the input variables is used to separate the scintillation signal and PMTs noise. The signal sample is prepared from the calibration run using likelihood and energy parameter space and noise sample is prepared from the normal background run for BDT training. The BDT weighted parameter from the WIMP search data shows good separation between signal and noise like events to as low as 1 keV shown in figure 2 until 1 keV. The event selection is optimized after modeling the BDT parameter between 1 to 1.5 keV energy region so that the noise contamination in signal region should be less than 1% level. The event selection efficiency is estimated by using the $^{60}\text{Co}$ calibration run and achieved more than 70% for each crystal.

### 3. Physics searches with COSINE data

The cosine detector has been running smoothly for the last 3 years and physics result from set1 (first 59.5 days data) and set2 (first 1.7 years of data) with 2 keV analysis threshold has been published [12, 13]. COSINE-100 lower down the analysis threshold to 1 keV and several physics searches are ongoing with a 1 keV threshold and a larger exposure of 153.7 kg.year. An improved background modeling based on Geant4 based simulation reproduces the background data and gives a better understanding of the detector’s background. The single and multiple hit spectrum are fitted above 6 keV and 1 keV respectively. The best fit models are extrapolated to the signal region of 1 to 6 keV. The dominant background in our signal region are $^{210}\text{Pb}$ from bulk and surface, cosmogenic isotopes of $^3\text{H}$, $^{109}\text{Cd}$ and $^{113}\text{Sn}$ . This background understanding constrains physics analyses like WIMP and annual modulation searches. The sensitivity of annual
Figure 2. Energy versus BDT weights for first two month of COSINE WIMP search data. The left band is populated for noise like events and right band is scintillating signal events.

modulation search using 153.7 kg.year exposure with 1 to 6 keV with an assumption of no modulation hypothesis as shown in figure 3.

Figure 3. COSINE 100 annual modulation sensitivity projection with 1keV energy threshold and an exposure of the 153.7 kg.year assuming null modulation hypothesis compared with DAMA [5] in an blue contour. The vertical green line is the phase of 152.5 days from standard halo-model.
4. Preparation for COSINE 200
Active R&D is ongoing for phase-2 of the COSINE experiment with the goal of getting lower background crystal’s. All the working procedure starting from powder purification, crystal growing, detector assembling and background measurements are well developed at the Center for Underground Physics (CUP), Daejeon Korea. The powder purification has already met the required goal and a few 1 Kg Tl doped NaI crystals has been grown in a small size grower. A rapid detector encapsulation and assembling system was developed that enables us to start the measurements within less than two weeks time after growing the crystal. The optical properties of the CUP-grown crystals meet the required criteria but some improvement still necessary to control the radio-purity of the crystals related $^{210}$Pb. COSINE 200 is planning to start their physics run by 2020.

5. Conclusion
COSINE-100 detector has been running smoothly for last 3 years and the detector response is well understood. Improved analyses with a lower threshold and larger exposure are under way. Low background crystal R&D demonstrates that, COSINE 200 can start in 2020 and will address the DAMA annual modulation signal in next the following few years.

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Nature 564 (2018) 83