Status of COSINE-100

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Abstract. The DAMA/LIBRA collaboration has claimed that an annual modulation signal which is consistent with signal induced by the dark matter interactions is observed by the NaI(Tl) crystal detectors. In order to test the DAMA/LIBRA collaboration’s claim, the COSINE experiment searches for interactions of Weakly Interacting Massive Particles (WIMPs) using the same target material. The COSINE-100 detector has been operating since September of 2016 in the 700-m-deep Yangyang underground laboratory. First annual modulation analysis based on the 2-keV energy threshold has been completed and several other analyses are in progress. In addition, studies for the 1-keV threshold have been on-going and analyses based on this threshold is underway. In this presentation, we report the detector design, performance, and recent results of COSINE-100 as well as plans for the next phase, COSINE-200.

1. Introduction

A great deal of astronomical observations have provided evidences of the existence of dark matter [1, 2]. Weakly Interacting Massive Particles (WIMPs), one of the popular candidates for dark matter [3, 4, 5], have been searched in a variety of ways, and to date there is no positive signs [6] except the DAMA/LIBRA’s results [7, 8, 9, 10, 11]. DAMA/LIBRA experiments to search annual modulation signals induced by dark matter have long claimed the observation of dark matter. DAMA/LIBRA experiment using NaI(Tl) crystals has accumulated data for over 20 years and recently published results from phase2 with upgraded detectors. The observation of annual modulation was also reported in phase2 and significance reached 9.5σ with 1-6 keV data. The significance of phases1 and phase2 is 12.9σ with 2-6 keV data, and the annual modulation signals are consistent with dark matter in terms of phase (145 ± 5 days) and period (0.999 ± 0.001 years) [11].

The results of DAMA/LIBRA have been the subject of ongoing debate because they conflict head-on with the exclusion limits of direct detection experiments [6]. Therefore, verification through experiments using the same target material, NaI(Tl), is essential, and several experiments using NaI(Tl) are in progress [12, 13, 14, 15, 16, 17, 18]. Among them, the COSINE-100, DM-Ice and KIMS joint effort, is an experiment to search for dark matter, aiming at verifying the DAMA/LIBRA’s claim with the same target material, NaI(Tl) crystal.
2. Experimental Site and Detector

The COSINE-100 experiment has performed at Yangyang underground laboratory (Y2L) which is next to the generator of Yangyang pumped-storage hydroelectric power plant in Yangyang in South Korea. There are two experimental halls, A5 and A6, and the COSINE-100 detector was installed at A5 which has about 700-m rock overburden. The detector room is located at the mid-sections of A5 tunnel which is maintained between 22°C and 25°C temperature and 60% to 70% relative humidity (RH). Electrical power supplied to the detector room is conditioned by uninterruptible power supply system and supplied voltages are monitored [18].

2.1. COSINE-100 detector

Eight low-background NaI(Tl) crystals with 106 kg in total are used as an active target. The U/Th/K level of the crystals is less than that of DAMA, but total α rate is higher than DAMA’s. As a result, total background of COSINE-100 is 2-3 times that of DAMA, but the crystals have higher light yield (∼15 p.e./keV), so it can make the threshold lower easily. Each crystal is encapsulated in copper and two 3-inch PMTs (Hamamatsu R12669SEL) are attached to each crystal [18]. Encapsulated crystals are contained in an acrylic tank with 2200-L LAB-based liquid scintillator (LS). 5-inch PMTs (Hamamatsu R877) are used for LS for veto [17]. The LS tank is surrounded by a 3-cm-thick copper box and the next layer is 20-cm-thick lead shielding against the external γs. One can see the detector design in the left plot of Fig. 1.

The outermost layer consists of a 4π muon detector using 37 plastic scintillator panels. One or two 2-inch PMTs (Hamamatsu H7195) are used for each panel [19]. There are two detectors for neutron monitoring system. One is a LS based detector for fast neutrons [20] and the other is a 3He gas detector for thermal neutrons. The physics run began in September 2016 and the environmental parameters being monitored are stable as shown in the right plot of Fig. 1. The temperature at crystals is 24.2±0.1°C and the humidity at the top of LS is smaller than 5% RH. The radon level measured in the detector room is 36±10 Bq/m³ [21]. Data taking is smooth with larger than 94% DAQ efficiency and the inefficiency is caused by calibration runs and power outages.

3. Data Analysis

In order to understand the detector response, the event selection of physical signals and background modeling via MC have been studied. For early dataset (SET1; 6303.9 kg-days exposure), we choose 2-keV analysis threshold and use the Boosted decision tree (BDT) to
Figure 2. COSINE-100 exclusion curves (90% CL) with the region allowed by DAMA/LIBRA (3σ) with DAMA (dotted) and new (solid) measurement of QFs. The used models are (a) isospin-conserving, (b/c) isospin-violating SI and (d) SD interaction in SHM (Details in Ref. [29]).

3.1 WIMP extraction analysis

The first physics analysis of COSINE-100 is searching canonical spin-independent (SI) WIMP-nucleon interaction in the Standard Halo Model (SHM) with SET1 data. Modeled background and SI-WIMP signal are fitted to data within the 2-20 keV energy range for this WIMP extraction analysis. The dominant systematic uncertainty is from selection efficiency, so the efficiency is verified via four separate analyses: 60Co calibration data, multiple-hit events, X-ray events from 40K and nuclear recoil events. In this analysis, COSINE-100 excludes the 3σ region allowed by DAMA/LIBRA-phase1, assuming the SI-WIMP interaction in the SHM [24].

Furthermore, WIMP search using updated quenching factors (QFs) has recently been performed. Recently, there are several measurements of QFs [25, 26, 27, 28], and we try to interpret DAMA/LIBRA’s result and COSINE-100 data with isospin-conserving/-violating SI and spin dependent (SD) WIMP-nucleon interaction in the SHM via those new QFs [29]. The allowed mass and cross-section are moved to higher using the new QFs, and COSINE-100 excludes the region allowed by DAMA/LIBRA for all cases as shown in Fig. 2.

3.2 Annual modulation analysis

DAMA/LIBRA’s claim is excluded by COSINE-100 under the assumption of specific models such as SI/SD WIMP-interaction in the SHM. However, the annual modulation signal of DAMA/LIBRA is model independent, so such analysis is also necessary. In order to search for the annual modulation signal, we use 1.7-years data (SET2; 97.7 kg-years exposure). The model which consists of background (offset+exponential function) and signal parts (sinusoidal function) is fit to data via likelihood ratio method.

The Feldman-Cousins method is also used for validation and the results are consistent as shown in the right plot of Fig. 3. The best fit values of DAMA/LIBRA and COSINE-100 are very close, but the current result agrees both with DAMA/LIBRA’s result and null hypothesis, due to the statistical limitation [21]. Analysis with more data and lowered threshold is ongoing. Besides, we tried to search for the dark matter via several models such as inelastic boosted dark matter [30], solar axions [31] and several effective field theories [32], but there are no positive signals of dark matter in all cases.
4. Plan for Next Phase

We have plans about the next phase, COSINE-200. The current background level of COSINE-100 is 2 to 3 times higher than that of DAMA/LIBRA, so we try to develop the pure crystals. For this, in-house systems for the entire process have been built such as purification system of NaI powder and full-size crystal grower. The responses and properties of NaI(Tl) crystals at low temperature has also been studied. The current COSINE-100 shield is designed to accommodate sixteen 12.5 kg crystals, so the shield structure can be used for next phase.

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