PROCEEDINGS OF SCIENCE

COSINE-100 experiment

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COSINE-100 is a direct search experiment for weakly interacting massive particles (WIMPs) using 106 kg of low-background NaI(Tl) crystal detectors. The experiment commenced its physics operation in September 2016 and concluded in March 2023. Its primary objective was either reproduce or refute the annual modulation signals observed by the DAMA experiment. However, initial three years of COSINE-100 data did not yield clear signals attributable to WIMP interactions and showed inconsistent results compared to DAMA's observations, assuming the canonical WIMP dark matter model. Nevertheless, the model-independent test of annual modulation has not yet reached a final conclusion. In this proceeding, we will discuss the recent progress made in the COSINE-100 experiment and outline future prospects.

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Since its first indications of an annual modulation signal in 1998 [1], the DAMA collaboration has consistently reported a positive signature from their annual modulation analysis for over 25 years, using a low-background NaI(Tl) detector array that can be interpreted as interactions between WIMPs and nuclei [2, 3]. However, no other experiment has detected any evidence of dark matter interaction, despite employing more advanced technologies and achieving lower cross-sectional limits for canonical WIMP dark matter models [4]. Therefore, it is imperative to obtain an unambiguous verification of the DAMA signal through an independent experiment using similar NaI(Tl) crystals.

The COSINE-100 experiment is aiming to reproduce or refute DAMA's results using the same NaI(Tl) crystals. This experiment operated with 106 kg of low-background NaI(Tl) crystals at the Yangyang underground laboratory [5]. An analysis of the initial 59.5 days of COSINE-100 data has revealed inconsistencies with the annual modulation signal reported by DAMA. This inconsistency arises when attempting to explain the signal using a spin-independent interaction between WIMPs and sodium or iodine nuclei within the framework of the standard halo model [6]. These findings have been further reinforced by 1.7 years of COSINE-100 data, which do not favor various dark matter interpretations of DAMA's observations [7], as depicted in Fig. 1.

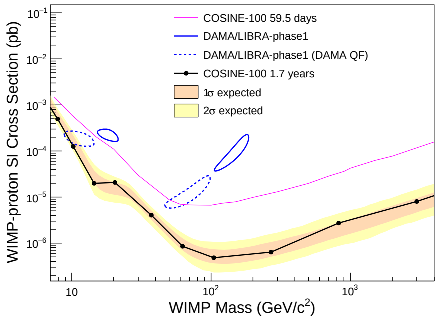

Figure 1: Exclusion limits on the WIMP-nucleon spin-independent cross section from the COSINE-100 1.7 years data.

Model-independent searches for an annual modulation signal using 1.7 years of data [8] as well as a 3-years updated analysis [9] have been reported. However, these searches were still not sensitive enough to conclusively challenge the DAMA observation. One interesting approach, adopting a similar analysis technique to DAMA, was applied to the COSINE-100 data and observed a significant annual modulation signal. This signal was attributed to an incorrect model of the time-dependent background, specifically a simple one-year average, but with an opposite modulation phase [10]. Simulated experiment for DAMA's data, assuming the same background composition as COSINE-100, surprisingly induced a consistent annual modulation amplitude, although the modulation phase was exactly opposite.

Ongoing efforts include improved data analysis targeting a reduced energy threshold and an increased dataset, which employs a multi-layer neural network for the discrimination of PMT-induced noise events. We have reached an eight number of photoelectrons (NPEs) threshold. Taking into account the nonproportional behavior of the NaI(Tl) crystals, an 8 NPE threshold corresponds to a 0.7 keV electron equivalent energy, assuming a 15 NPE/keV light yield at 60 keV energy. The detector nonproportionality has been measured in wide range of sub keV to 100 keV. We have also updated the calibration of nuclear recoil, denoted as the nuclear recoil quenching factor, particularly for the lowest energy point of 3.75 keV nuclear recoil energy. With a better understanding of the detector's nonproportionality, internal α background, and liquid scintillator veto counter, we have significantly improved our understanding of background spectra in the NaI(Tl) crystals over the extended energy ranges between 0.7 keV and 4,000 keV. These improvements will allow us to explore much lower mass dark matter in the lower cross-section regions in near future.

In addition to typical WIMP dark matter searches for elastic scattering, COSINE-100 performed extended searches for the dark sector particles. The search for WIMP-^{127}I inelastic scattering, which produce a 57.6 keV γ-ray accompanying the nuclear recoil, in the energy range of 35 keV–85 keV, did not yield any signals from 1.7 years of COSINE-100 data, resulting in world-best limits on the WIMP-proton spin-dependent interaction via inelastic scattering [11]. In the energy range of 10 keV–1000 keV, a search for excess signals due to bosonic super-WIMPs has been conducted with null results [12]. In this search, we included the Compton-like process for the first time in the world, leading to comparative limits for mass greater thant 200 keV, compared to the current best results from the GERDA experiment [13]. Further searches for higher energy signals caused by boosted dark matter have been conducted for both inelastic [14] and elastic [15] interactions, with null observations in the signal regions above 4 MeV. An annual modulation study due to the distance between the Sun and Earth was performed to search for solar bosonic dark matter [16].

The COSINE-100 experiment concluded in March 2023 at the Yangyang underground laboratory (Y2L), which had a rock overburden of 700 m. It will be relocated to Yemilab, a new underground laboratory in Korea, which boasts approximately 1,000 m of rock overburden, reducing muon flux by approximately four times compared to Y2L. Upgrades for the COSINE-100 detector are underway, primarily focusing on enhancing light yield. By machining 5-inch diameter collimators to 3-inch for both edges and directly attaching 3-inch PMTs to each end, we have achieved approximately a 45 % increase in light yield, from 14.9±0.5 NPE/keV to 21.6±0.6 NPE/keV, as demonstrated in the NEON experiment [17]. Additionally, we have prepared for −35°C operation, providing approximately a 10 % increase in effective light output, as well as improved pulse shape discrimination for nuclear recoil events [18].

Although interesting checks on DAMA's observation have been reported using COSINE-100 data, an unambiguous conclusion regarding DAMA's obsevation has not yet been reached due to the background levels of the crystals. As part of an effort to upgrade the ongoing COSINE-100 experiment to the next-phase COSINE-200 experiment [19], we have developed in-house technologies for low-background NaI(Tl) crystal growth. An initial chemical purification of raw NaI powder, based on a recrystallization method, has resulted in a sufficient reduction of K and Pb [20], and a large scale facility has already been assembled [21] and is in stable operation [22]. A proof of crystallization with sufficiently low levels of ^{40}K and ^{210}Pb has been demonstrated with a small crystal grower for approximately 1 kg-size crystal ingot [23, 24]. Crystallization for a 10 kg-size detector is currently under development.

Based on the improved light collection in the COSINE-100 upgrade detector and proof of a low-background crystallization technique, the next phase COSINE-200 experiment will verify the DAMA signal without any ambiguity. In addition to testing DAMA's signal, high light yield detector technology will provide world-competitive sensitivity for low-mass dark matter, especially

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for the spin-dependent WIMP-proton interaction, as one can see in Fig. 2. This could open up a new window of tonne-scale solid detectors using NaI(Tl) crystals, which are unique target materials for direct dark matter search experiments [19, 25].

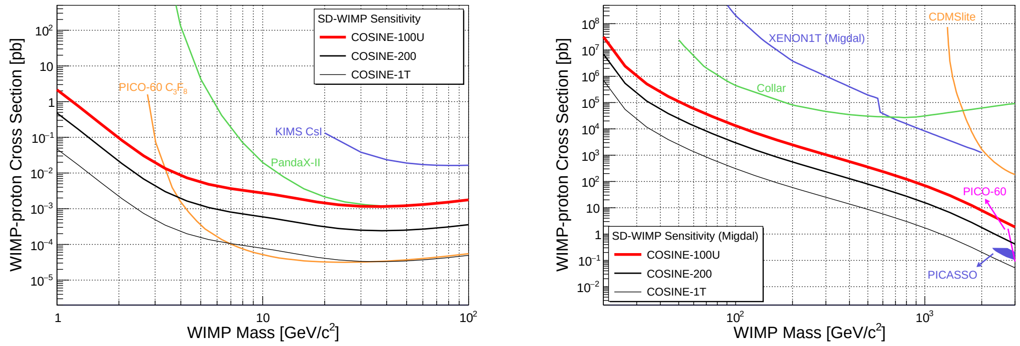

Figure 2: Sensitivities of future COSINE experiments on WIMP-proton spin-dependent interaction without Migdal effect (left) and with Migdal effect (right).

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