PROCEEDINGS OF SCIENCE

Dark matter search using NaI(Tl) at the COSINE-100 experiment

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The COSINE-100 is a direct WIMP search experiment that uses 106 kg of NaI(Tl) crystals as its target material. The experiment has started its data taking in September 2016, and has finished in March 2023, with exposure time ~6 years. Primary goal of the experiment is to test the dark matter signal observed by the DAMA/LIBRA experiment. The DAMA/LIBRA has claimed to observe annual modulation signal behavior of data, which is compatible with profile of WIMP signal. However, no other experiment has succeeded to find WIMP signal yet. COSINE-100 aims to directly test the DAMA/LIBRA, by using same target material. Here we present the summary of recent WIMP search result in COSINE-100, in terms of spectral analysis and time dependent modulation search analysis. In addition to this, upgrades on COSINE-100 detector for next phase experiment is also summarized.

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1. Introduction

Since the presence of dark matter has been first suggested to explain the rotational speed problem of the galaxy, many additional evidences are supporting the presence of the dark matter. However, despite of many evidences of dark matter, the identity of dark matter is still an nature mystery. There are many theoretical candidates for dark matter, and Weakly interacting massive particle (WIMP) is one of the most attractive scenario as an cold dark matter. In the Standard halo model of WIMP dark matter, it is expected that WIMP flux at the Earth frame changes with seasonal modulating behavior. This is because the relative speed of WIMP at the Earth changes according to the revolution. DAMA/LIBRA, which is the direct WIMP search experiment using NaI(Tl) crystals as target detector, has claimed to observe the annual modulation signal with 12σ confidence level. And the profile of this modulation signal was compatible with nature of WIMP dark matter [1], [2]. However, no other experiments has succeeded to find the dark matter signal in the cross section region inferred by the DAMA/LIBRA experiment[3]. One suggested solution about this mystery is that NaI(Tl) crystal, which is the scintillator used in DAMA/LIBRA, is somehow special for WIMP interaction. So the necessity of direct comparison using same target material has been required.

2. COSINE-100 experiment

COSINE-100 experiment, which is also a direct WIMP search experiment using NaI(Tl) crystal, aims to directly test the DAMA/LIBRA experiment by using same target material. The detector in COSINE-100 is consisted of 8 low-background NaI(Tl) scintillators, with total mass of 106 kg. Each crystal collects scintillation signal with two 3-inch photo multiplier tubes(PMTs) attached at both side. These crystals are immersed in 2200L liquid alkyl benzen (LAB) based veto scintillator, which is effective to reduce the background rate of crystals[4]. In addition to this, copper shield, lead blocks, and plastic scintiilators are installed to reduce external backgrounds including cosmic ray effects. The detector is located at the YangYang underground laboratory(Y2L) in Korea, with 700m rock overburdenn [5]. The experiment has collected its data from 30th, September, 2016 to 14th, March, 2023. Figure 1 shows an overview of COSINE-100 detector geometry.

3. WIMP spectral analysis

Although the experiment aims to search for a WIMP signature, the main source of the energy spectrum is derived from background isotopes. The WIMP spectrum, on the other hand, accounts for a very small or non-existent portion. For precise understanding of energy spectrum of the data, we have generated simulation spectrum of expected backgrounds. By using binned-likelihood method of simulation spectrum to data, we can get proper activities and spectral shape of background components. In this step, the WIMP region of interest (< 6 keV) is not included in the fitting region, so that there is no bias on residuals for WIMP spectrum[6]·[7]. After understanding background, a Bayesian statistical method has been used to test presence of WIMP in COSINE-100 data. So far, COSINE-100 experiment has released the spectral WIMP search result using 1.7 years data, and no WIMP spectral feature was found. As a result, spectral analysis with 1.7 years data has excluded DAMA/LIBRA's WIMP signal region (See Figure 2). This limit excludes the quenching

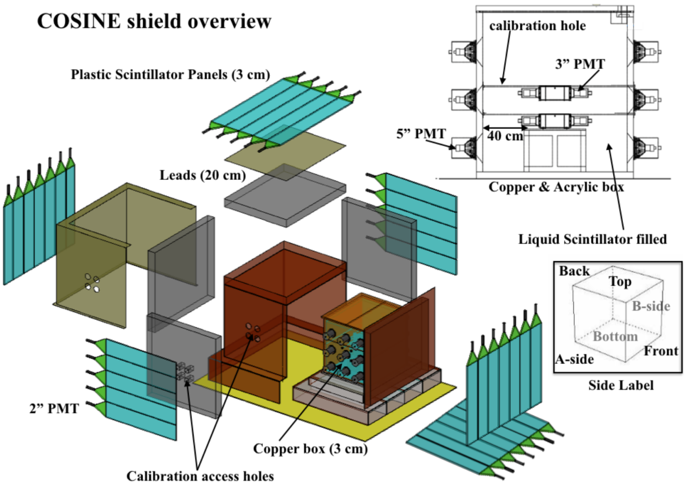

Figure 1: An overview of the COSINE-100 detector reveals its composition, comprising eight NaI(Tl) crystals. Crystal arrays are shielded using liquid scintillator veto, copper boxes, lead blocks, and plastic scintillator panels.

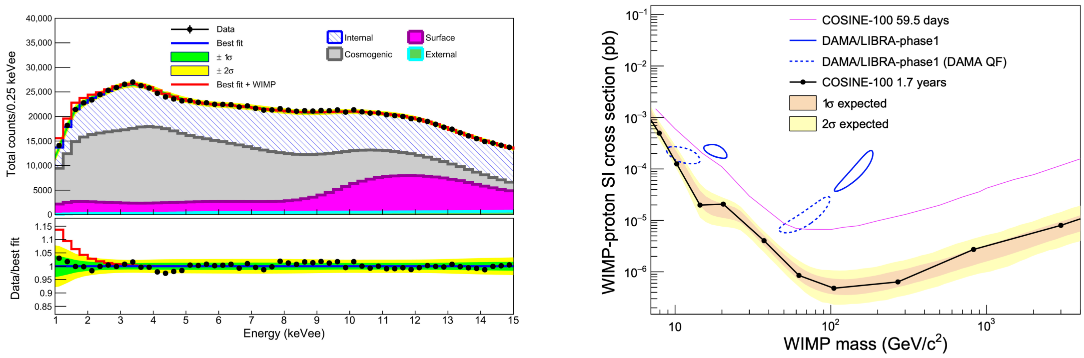

Figure 2: WIMP spectral analysis example in COSINE-100 1.7 years data with WIMP mass = 11.5 GeV/c^2 and coupling ratio f_n/f_p=0.76 case (Left), and WIMP-proton SI cross section upper limit (Right).

factor model not only measured from COSINE-100(blue solid line), but also the DAMA/LIBRA (blue dashed line) [8], [9].

4. WIMP modulation analysis

Although our spectral analysis has already excluded the DAMA/LIBRA allowed region in most models, we have conducted a time-dependent modulation analysis to mitigate any potential model dependency, using 2.82 years data. To interpret our data in terms of the equation about time, we have set the model to demonstrate both of exponentially decaying background isotopes and modulating behavior of WIMP.

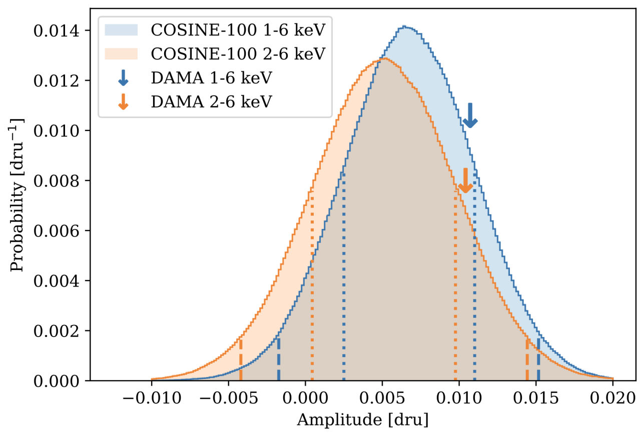

Figure 3: Posterior distribution of fitted modulation amplitude in the 1-6 keV and 2-6 keV energy range, with the phase fixed to 152.5 days. The dotted and dashed lines indicate the 68.3% and 95.5% confidence intervals, respectively. The arrow denotes the best-fit result obtained by DAMA/LIBRA.

$$R(t|S_m, \alpha^i, \beta^i_k) = \alpha^i + \sum_{k=1}^{N_{bkgd}} \beta^i_k e^{-\lambda_k t} + S_m \cos(w(t - t_0)). \tag{1}$$

In the Equation 1, rate of the ith crystal is expressed with 3 terms. First α term is the constant factor which represents background components with very long half life. Second term expresses sum of exponentially decreasing background with activity β and half life λ for kth isotope, over total N_{bkgd} backgrounds. And the last term express modulation of the WIMP, with amplitude S_m. To understand WIMP behavior better and reduce the bias from the wrong background understanding, we referred background activity from spectral analysis. The best fit result of time dependent fitting was $S_m = 0.0050 \pm 0.0047$ in the 2-6 keV region, and $S_m = 0.067 \pm 0.0042$ counts/(day·kg·keV) in the 1-6 keV region, with fixed phase 152.5 days. This result couldn't confirm or refute DAMA/LIBRA's modulation signal with amplitude 0.0105 ± 0.0011. Figure 3 displays this result compared to DAMA/LIBRA.

5. DAMA-like analysis in COSINE-100

The analysis strategy employed by COSINE-100 differs significantly from that of DAMA/LIBRA in several aspects. To ensure unbiased results, we also conducted an analysis using the same methodology as DAMA/LIBRA. To adapt the DAMA/LIBRA analysis to the COSINE-100 data, we made three methodological adjustments. Firstly, as DAMA/LIBRA did not have a liquid or plastic scintillator veto system, we did not utilize information from veto scintillators in our analysis. Secondly, DAMA/LIBRA employed different criteria to distinguish PMT-induced noise events within the region of interest. Typically, PMT noise waveforms exhibit a fast decay time of less than 50ns, whereas genuine scintillation events in NaI(Tl) crystals display a decay time of around 250ns. To exclude PMT noise, COSINE-100 implemented its own noise selection criteria utilizing a modern machine learning technique known as Boosted Decision Tree (BDT)[10]. Conversely, DAMA/LIBRA devised their own set of criteria referred to as the event selection (ES) parameter. In this DAMA-like

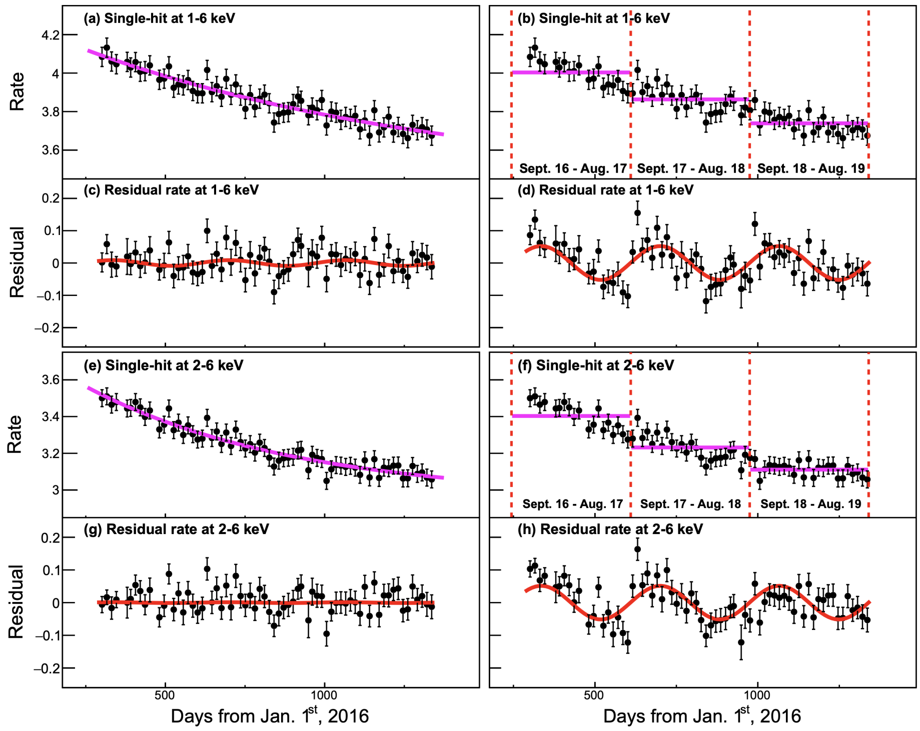

Figure 4: Comparison of COSINE-100 data fitting between exponential and yearly-averaged background rate model.

analysis, we also incorporated the ES parameter, making a slight adjustment to the cut value, in order to attain a signal selection efficiency comparable to that of DAMA/LIBRA[11],[12]. Finally, COSINE-100 and DAMA/LIBRA was using different approach to background understanding. As indicated in Equation 1, COSINE-100 is using exponentially decaying background rate model. In contrast, DAMA/LIBRA has claimed that background rate is constant over time, allowing for proper background reduction through the subtraction of the yearly averaged background rate.

In order to assess the potential impact of methodological differences, we conducted a comparative analysis between two fitting methods, namely the exponentially decaying and yearly averaged approaches. This analysis was performed while implementing both the "no veto scintillator" and "ES parameter noise rejection" methods. In Figure 5, (a) and (b) shows time-dependent modulation fitting of 1-6 keV energy range with different background rate assumption, single exponential and yearly-averaged each. After subtracting the fitted background rate, (c) and (d) gives time-dependent residual change according to each method. As a result, the observed residual amplitude was $S_m = 0.0048 \pm 0.0055$ and $S_m = -0.044 \pm 0.006$ for each (c) and (d), showing about ten times bigger amplitude in the yearly-averaged method. But the phase was negative in the yearly averaged method. This behavior is identical in the 2-6 keV energy region, with amplitude $S_m = 0.0048 \pm 0.0055$ and $S_m = -0.046 \pm 0.006$ for each (g) and (h).

Also to check the direct impact of this methodology difference in DAMA/LIBRA's result interpretation, we generated simulation data of DAMA-like background. In Figure 5, we could find that the time-dependent behavior of DAMA/LIBRA data is well explained by using background

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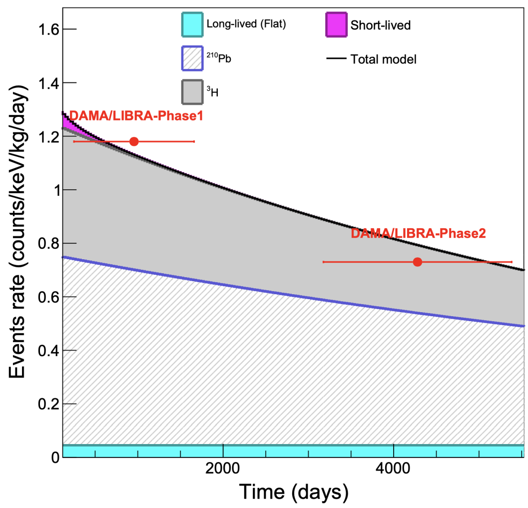

Figure 5: Background composition of COSINE-100 scaled to DAMA/LIBRA event rate.

components' fraction from COSINE-100 spectral analysis. So by assuming COSINE-100 like background composition and lowering overall background rate to be same with DAMA/LIBRA (~2.5 times smaller than COSINE-100), we have generated pseudo data of DAMA/LIBRA, while not including any WIMP signal. When we fitted this pseudo data with yearly averaged method, although no WIMP signal was generated, the residual from this simulation using the DAMA-like analysis showed apparent modulation behavior $S_m = -0.0098 \pm 0.0008$ over 12 σ significance. And this amplitude is similar value to DAMA/LIBRA's $S_m = 0.0105 \pm 0.0011$ but with a negative phase. Despite the opposite modulation phase, a consistent modulation amplitude value was observed in the DAMA-like method may be crucial for unveiling hidden phenomena in the DAMA/LIBRA experiment and its outcomes.

6. Next phase of COSINE-100

Official run of COSINE-100 is completed with exposure time ~6 years, and planning for the next step of the experiment. Upcoming next phase of the experiment is planned to be run in the new underground laboratory 'YemiLab' in Jeongsen, Korea. With new experimental site and some upgrades on the detector, there are several enhanced profiles in the next phase experiment. First, it is expected to have lower cosmic ray effect, with thicker rock over burden from Y2L's ~700m to YemiLab's ~1000m. Second, the detector is expected to be having enhanced detection efficiency. Originally, COSINE-100 was having light yield value ~15 photoelectrons(p.e.)/keV. In the next phase experiment, there is a modification in PMT attachment design, so that the scintillation to be collected more efficiently. And this new design is reported to bring ~50% enhancement in light yield value [13]. Third, the next phase of COSINE-100 is planned to be run in ~-35°C, and this condition is reported to bring enhancement not only in light yield, but also the quenching factors. Applying all these updates, next phase of COSINE-100 is expected to start its data taking in between late 2023 to early 2024. Furthermore to these upgrades, COSINE-100 collaboration is also doing research about in-house development of the entire crystal-making process, including

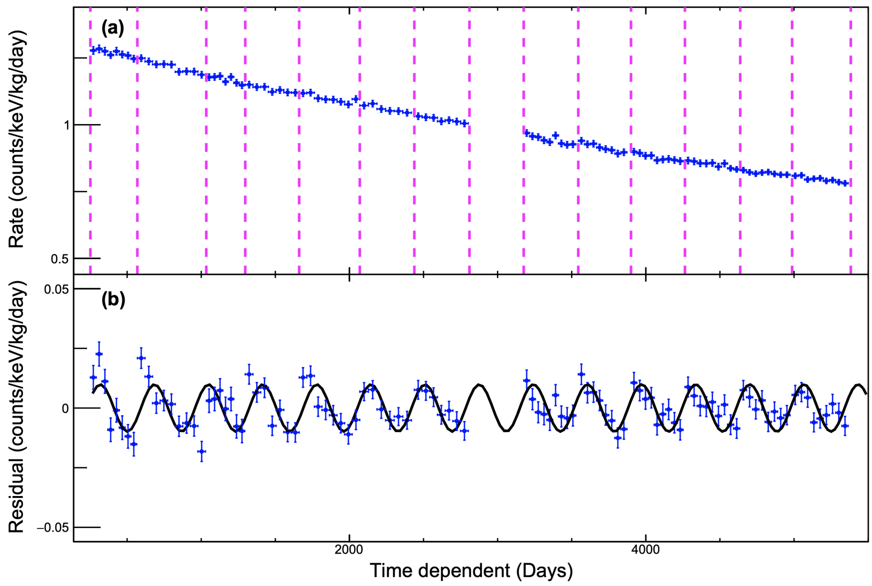

Figure 6: Simulation example of DAMA/LIBRA experiment in 2-6 keV region. (a) Simulation is generated using background understanding from the COSNE-100 experiment. The vertical dashed line indicates the start and end of each cycle in DAMA/LIBRA. (b) Residual(points) from DAMA-like analysis applied to simulation data, and its fit(solid line).

NaI purification, crystal growing, and detector assembly[14]·[15]. This new developed crystal is expected to bring lower background rate than DAMA/LIBRA and planned to be used more future experiment, named 'COSINE-200'.

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