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Search for a dark matter-induced annual modulation signal in NaI(Tl) with the COSINE-100 experiment


1Department of Physics, Sejong University, Seoul 05006, Republic of Korea
2Department of Physics and Wright Laboratory, Yale University, New Haven, CT 06520, USA
3Physics Institute, University of São Paulo, 05508-900, São Paulo, Brazil
4Department of Physics and Astronomy, Seoul National University, Seoul 08826, Republic of Korea
5Department of Physics, Bandung Institute of Technology, Bandung 40132, Indonesia
6Department of Physics and Astronomy, University of Sheffield, Sheffield S3 7RF, United Kingdom
7Center for Underground Physics, Institute for Basic Science (IBS), Daedeo 34126, Republic of Korea
8Department of Science Education, Ewha Womans University, Seoul 03760, Republic of Korea
9Department of Physics, Sungkyunkwan University, Suwon 16419, Republic of Korea
10Department of Physics and Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin-Madison, Madison, WI 53706, USA
11Department of Physics, Kyungpook National University, Daegu 41566, Republic of Korea
12IBS School, University of Science and Technology (UST), Daedeo 34113, Republic of Korea
13Korea Research Institute of Standards and Science, Daedeo 34113, Republic of Korea
14Department of Accelerator Science, Korea University, Sejong 30019, Republic of Korea
15Department of Physics, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA

We present new constraints on the dark matter-induced annual modulation signal using 1.7 years of COSINE-100 data with a total exposure of 97.7 kg-years. The COSINE-100 experiment, consisting of 106 kg of NaI(Tl) target, is designed to carry out a model-independent test of DAMA/LIBRA’s claim by searching for the same annual modulation signal using the same NaI(Tl) target. The crystal data show 2.7 counts/keV/kg/day background rate on average in the 2–6 keV energy region of interest. Using a chi-squared minimization method we observe best fit values for modulation amplitude and phase at 0.0092±0.0067 counts/keV/kg/day and 127.2±45.9 days, respectively.

Keywords: COSINE, dark matter, sodium iodide, WIMP, direct detection, annual modulation

Cosmological observations give strong evidence that 27% of the energy content of the Universe exists in the form of non-luminous dark matter [1], unaccounted for by the standard model of particle physics [2]. One theoretically favored model of dark matter postulates the existence of weakly interacting massive particles (WIMPs) [3, 4] that interact only through the gravitational and weak scale forces and have a mass on the GeV to TeV scale [5, 6]. Within the context of the standard halo model, there will be an annual modulation in the dark matter-nucleon interaction rate with a period of one year [7–9]. One experiment, DAMA/LIBRA observes annual modulations in the detected event rate with a significance exceeding 12σ which they attribute to the presence of dark matter [10–12]. DAMA/LIBRAs observation is inconsistent with other experiments under most well-motivated WIMP dark matter models [13–21]; however, none of these other experiments have used the same target material as DAMA, thallium-doped sodium iodide (NaI(Tl)) scintillating crystals. Thus, these comparisons are necessarily dependent on the particular model of WIMP-nucleus scattering and assumed WIMP halo structure.

The COSINE-100 experiment aims to resolve this tension in the field by performing a model-independent test of DAMA’s observation using the same detector material, NaI(Tl), as DAMA. Previously, we have performed a model-dependent test of DAMA and found that DAMA’s observed annual modulation cannot be explained by spin-independent WIMP-nucleus scattering in the context of standard halo model [22]. Additionally, there are several other experiments aimed at performing model-independent tests of DAMA, including DM-Ice17 [23], KIMS [24], SABRE [25], and ANAIS-112 [26, 27], which has recently reported their first result.

COSINE-100 is located at the Yangyang underground laboratory (Y2L) in South Korea, with >700 m of rock overburden. It consists of eight NaI(Tl) crystals with a total mass of 106 kg immersed in 2200ℓ of liquid scin-
tillator (LS) that reduces internal and external backgrounds [28]. Each NaI(Tl) crystal is optically coupled to two photomultiplier tubes (PMTs), each of which detects scintillation photons with the signals recorded as 8 µs waveforms [29]. These eight crystals are referred to as Crystal-1 (C1) to Crystal-8 (C8). C1, C5, and C8 are excluded from this analysis due to their high background (about twice that of the other crystals), high noise rate (C1), and low light yield (C5 & C8), for a total effective mass of 61.3 kg. The detector is surrounded by passive and active shielding that include, starting from the inside, copper plates of 3 cm in total thickness, 20 cm of lead, and 3 cm of 37 plastic scintillator panels for cosmic ray muon tagging [30]. More details of the experimental apparatus are presented in Ref. [31].

Data taking for COSINE-100 began in September 2016, and the analysis presented here covers 1.7 years' exposure, spanning October 21, 2016 to July 18, 2018. Several datasets from C2 and C7 are excluded due to excessive noise levels. The total exposure used in this analysis corresponds to 97.7 kg-year.

The overall stability of the detector is closely monitored to ensure that neither environmental nor detector effects can create an artificial dark matter signal [31]. Humidity and temperature of the detector room are maintained at 40.0±3% RH (Relative Humidity) and 23.5±0.3°C, respectively. Gas boil-off from liquid nitrogen is purged into the space above the liquid scintillator inside the inner copper chamber at a rate of 3 liters/minute to keep out radon and prevent contact with oxygen and water as well as to maintain a high light yield of the LS. The humidity inside the shielding structure is kept at <5% RH and the high heat capacity helps to keep the temperature within the liquid stable at 24.2±0.1°C. The radon level in the detector room is measured at 36±10 Bq/m³. The time dependence of temperature, humidity, radon, and cosmic ray muons [30] is shown in Fig. 1. The spikes in Fig. 1(a) are due to power outages or A/C failure, and those periods are excluded from the data. The effects of temperature and radon level on the pulse shape, light yield, and overall performance of the NaI(Tl) detectors and of the full detector were reported in Ref. [32]. A monitoring of fast neutrons inside the detector room has recently started in Summer 2018 [33].

The gain of the PMTs is monitored by measuring the position of the 46.5 keV peak from 210Pb decays that occur in the NaI(Tl) crystal bulk. The gain is tracked and modeled as a piece-wise linear function of time and corrected for the observed gain drift over time in each PMT. After correction, the 46.5 keV peak is stable to within 0.1% on average. We assess the efficacy of this gain correction method within the 2–6 keV region of interest by measuring the position of the 3.2 keV decay peak from 40K over time; the position of the decay peak is stable to within <2% on average in the dataset used in the analysis.

Events that trigger more than one crystal, pulses with pulse shapes that are inconsistent with a NaI(Tl) scintillation signal, e.g. PMT related noise, are rejected [24, 31, 34]. We use two boosted decision tree multivariate analysis algorithms (BDTs) [35] to remove PMT-related and other noise events, which we call BDT1 and BDT2. BDT1 is used to remove PMT-induced noise and is based on the amplitude-weighted average time of a pulse, the ratios of the leading- and trailing-edge charge sums relative to total charge, and the difference of deposited charges between the two PMTs [36]. It is trained with a sample of signal-rich, energy-weighted events from a 60Co calibration run for signal, and single-hit events from the WIMP-search physics-run data for noise, with the latter mostly triggered by PMT noise events. The second BDT, BDT2, includes weighted higher-order time moments and eliminates intermittent PMT discharge-triggered events that have slower pulse decay times. The event selection technique and criteria are described more in detail in

![FIG. 1. COSINE-100’s environmental parameters as a function of time. (a) Detector room and near-crystal temperature. (b) Relative humidity for the detector room and the top volume of acrylic box, on top of the LS. Note that the measurement for the top of the LS started around 450 days later. (c) The radon level in the detector room air. (d) Total muon rate the muon detector is shown in panel with 30 days bin.](image-url)
FIG. 2. Efficiency-corrected and time-integrated energy spectra for the five crystals used in this analysis between 2–20 keV (top panels) and signal selection efficiency evaluated using $^{60}$Co calibration data (bottom panel). The efficiencies at 2 keV are >60% for all crystals. The primary sources of background in the crystals are $^{210}$Pb and $^{40}$K, which are lower for Crystal-6 and Crystal-7. These spectra are obtained using the full data set considered in this analysis.

The same BDT selections were applied to the Compton-scattered low energy events from a $^{60}$Co calibration run to estimate the event selection efficiency. The efficiency is the ratio of events that survive the selection to the total number of signal events. Errors are of binomial statistics. Figure 2 shows the event selection efficiency as a function of energy, along with the efficiency-corrected, 2–20 keV spectra of the five crystals used in this analysis. The spectra are well-modeled with a Geant4-based simulation [37–39]; the 3.2 keV $^{40}$K peak is clearly visible in C2 and C4, whereas the overall background levels in C6 and C7 are lower than in other crystals because of their lower $^{210}$Pb and $^{40}$K contamination levels.

In order to confirm our background understanding and account for possible systematic effects that could appear over time, we investigated a control sample of multiple-hit events in the 2–20 keV energy region with statistics comparable to that in the ROI. These are events in which multiple NaI(Tl) crystals are triggered or a single crystal is triggered along with the LS and, thus, cannot be attributable to typical WIMP dark matter interactions. They comprise 20% of the total signal event sample.

We also consider the possibility that certain event types that are removed during event selection could cause a modulation signal. The noise events observed in the COSINE-100 detector are systematically categorized and studied to understand how their removal affects the signal region counting rate over time. The study showed the removed events have negligible impact on the modulation of signal events.

The event rate as a function of time are modeled as:

$$\text{Rate} = C + p_0 \cdot \exp\left(-\frac{\ln2 \cdot t}{p_1}\right) + A \cdot \cos\left(\frac{2\pi(t - t_0)}{T}\right),$$

where $C$ is a constant offset constrained by backgrounds as described in Ref. [39], and $p_0$ and $p_1$ are amplitude and
FIG. 4. The COSINE-100 best fit and 68.3%, 95.5%, and 99.7% C.L. contours as a function of modulation amplitude (counts/keV/kg/day) and phase relative to January 1, 2015, for period fixed at 365.25 days. A Feldman-Cousins technique is used to cross-check and the result of 68.3% C.L. is shown. The amplitude and phase reported by DAMA/LIBRA in the 2–6 keV energy interval with statistical uncertainties (blue cross) and the phase expected from a standard halo model (June 2nd) are overlaid for comparison. Top and side panels show the dependence of $\Delta \chi^2$ as a function of phase and amplitude, respectively, along with two-sided significance levels.

decay times for an exponentially decaying background as a model for cosmogenically activated backgrounds. The modulation is described by $A$, $T = 365.25$ days, and $t_0$ as its amplitude, period, phase, respectively.

The data from all crystals was fit simultaneously with a single set of modulation amplitude, phase, and period but with a separate set of constant offset and exponential decay. Figure 3 shows the COSINE-100 event rates for the 2–6 keV ROI, where recorded 670 events/day on average, i.e. 2.7 counts/keV/kg/day, in the crystals used for the analysis. We performed chi-squared minimization fits for the modulation amplitude with the period fixed at 365.25 days with the phase as a free parameter and, also, with it fixed at the 152.5 days halo-model expectation and the 145 days DAMA/LIBRA value. The best fit to the 2–6 keV range has a modulation amplitude of $0.0092 \pm 0.0067$ counts/keV/kg/day with a phase of $127.2 \pm 45.9$ days. A log-likelihood parameter estimation of the annual modulation with amplitude and phase as free parameters shows that the current data from COSINE-100 is consistent with both the DAMA/LIBRA annual modulation result and the null hypothesis at the 68.3% C.L. A Feldman-Cousins method [40] was also used to cross-check the result, and returned a consistent C.L.

Table I summarizes the result of the various fitting scenarios used for the 2–6 keV energy interval. The period is fixed at 365.25 days (1 year) for all scenarios, whereas the phase is either floated freely or fixed at 152.5 days as expected from the standard halo model. COSINE-100 is the only NaI(Tl) experiment with a LS veto surrounding the crystals providing additional capabilities for rejection of external background. As a cross-check, we show the fit results to the annual modulation with and without the LS veto. The LS veto removes backgrounds and improves the uncertainties on the annual modulation amplitudes by 7%.

The best fit modulation amplitudes as a function of energy with 1 keV energy bins are shown in Fig. 5. These fits were performed with a fixed period of one year and the phase fixed at 152.5 days.

In summary, we report the results from the search for a dark matter-induced annual modulation signal in NaI(Tl) based on 1.7 years of COSINE-100 data. A fit to the 2–6 keV energy range returns a modulation amplitude of $0.0092 \pm 0.0067$ counts/keV/kg/day with a phase of $127.2 \pm 45.9$ days. At 68.3% C.L., this result is consistent with both a null hypothesis and DAMA/LIBRA’s 2–6 keV best fit value. We expect approximately $3 \sigma$ coverage of DAMA region using the same target within five years of data exposure. Future searches with COSINE-100 will utilize a larger dataset and lower energy threshold of 1 keV and are expected to reduce the required exposure for $3 \sigma$ coverage.

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TABLE I. Summary of fit results for the modulation and null hypotheses for the 2–6 keV energy region in COSINE-100. Detector rates were fit to Eq. (1), with the period fixed at 365.25 days. Results with phase floated and fixed at 152.5 days are listed. The result without using the LS veto is presented as a cross-check. DAMA/LIBRA results [12] and the ANAIS-112 2019 result [27] are also shown.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$\chi^2$</th>
<th>d.o.f.</th>
<th>p-value</th>
<th>Amplitude (counts/keV/kg/day)</th>
<th>Phase (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COSINE-100</td>
<td>175.3</td>
<td>174</td>
<td>0.457</td>
<td>0.0092±0.0067</td>
<td>127.2±45.9</td>
</tr>
<tr>
<td>DAMA/LIBRA (Phase1+Phase2)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.0096±0.0008</td>
<td>145±5</td>
</tr>
<tr>
<td>COSINE-100</td>
<td>175.6</td>
<td>175</td>
<td>0.473</td>
<td>0.0083±0.0068</td>
<td>152.5 (fixed)</td>
</tr>
<tr>
<td>COSINE-100 (Without LS)</td>
<td>194.7</td>
<td>175</td>
<td>0.143</td>
<td>0.0024±0.0071</td>
<td>152.5 (fixed)</td>
</tr>
<tr>
<td>ANAIS-112</td>
<td>48.0</td>
<td>53</td>
<td>0.67</td>
<td>-0.0044±0.0058</td>
<td>152.5 (fixed)</td>
</tr>
<tr>
<td>DAMA/LIBRA (Phase1+Phase2)</td>
<td>71.8</td>
<td>101</td>
<td>0.988</td>
<td>0.0095±0.0008</td>
<td>152.5 (fixed)</td>
</tr>
</tbody>
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* Present address: Department of Physics, Carleton University, Ottawa, Ontario, K1S 5B6, Canada
  jayhyun.jo@yale.edu