Snowmass2021 - Letter of Interest

COSINE-200: A Next-Generation NaI(Tl) Experiment

Thematic Areas: (check all that apply □/■)

■ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
□ (CF7) Cosmic Probes of Fundamental Physics
□ (Other) *[Please specify frontier/topical group]*

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Abstract:
We propose COSINE-200, a next-generation dark matter experiment that will use ultra-low background thallium-doped sodium iodide (NaI(Tl)) detectors. As the successor to COSINE-100, COSINE-200 will feature several improvements over its predecessor, mostly focusing on improvements to the NaI(Tl) detectors. These advances are enabled by the in-house manufacture of detectors by members of the collaboration, which has shown promising initial results. In-house manufacturing has allowed us to produce detectors with significantly lower levels of ^{210}Pb, the primary background component in COSINE-100, than has been achievable with our industry partners. It has also enabled the development of novel encapsulation designs, with the goal of doubling detector light yield compared to COSINE-100. Owing to these improvements, COSINE-200 will have world-leading sensitivity among NaI(Tl)-based dark matter searches. These advances are also significant for DM-Ice200, as the use of COSINE's in-house crystals will increase its physics reach compared with a deployment of industry-supplied detectors. COSINE-200 will definitively confirm or refute the DAMA collaboration's claim of dark matter discovery. Also, the spin-dependent WIMP-proton coupling is of particular interest, as we expect to achieve sensitivity comparable to or exceeding that of liquid xenon-based experiments. Based on these advances, sodium iodide-based dark matter detectors will be an important entry in the portfolio of next-generation direct dark matter searches.

Introduction: Despite the fact that cosmological observations indicate 27% of our Universe is made up of dark matter[1], only a single experiment, DAMA/LIBRA [2], has claimed a positive detection of a dark matter signal. This signal comes in the form of a dark matter-induced annual rate modulation observed at a level of 12.9σ for nearly two decades.

DAMA's results are in direct conflict with null results from other direct detection experiments within most dark matter models [3–7]; however, until recently a direct test of DAMA's results has not been possible, as they were the only experiment utilizing thallium-doped sodium iodide-based (NaI(Tl)) detectors. For the past four years, the COSINE collaboration has been operating COSINE-100, a 106-kg NaI(Tl)-based WIMP dark matter detector. Originally, the COSINE collaboration was formed as a joint effort of the DM-Ice and KIMS dark matter searches, with the goal of performing a model-independent test of DAMA's claim of dark matter discovery by searching for the same dark matter-induced annual modulation. If DAMA's claim of dark matter discovery is correct, COSINE-100 expects to confirm their observation at 5σ with 5 years of data, assuming stable operation. In the absence of a dark matter signal, COSINE-100 and ANAIS-112, a sister experiment, are likely to exclude DAMA's claim of discovery at 3σ within the next few years [8, 9].

In addition to the annual modulation search, COSINE-100 has also engaged in several other analyses searching for different models of dark matter. Most notable out of these is our search for spin-independent (SI) WIMP-nucleus scattering, a model often used as the standard benchmark between different direct detection experiments. COSINE-100 has excluded SI WIMP-nucleus scattering as the origin of DAMA's signal, setting the most stringent constraints on WIMPs with a sodium iodide detector to date [10]. In this Letter of Interest, we outline the physics that can be explored with COSINE-200 and highlight the progress and implications of our R&D efforts that will make this upgrade more than just an increase in fiducial mass.

Physics Reach: The main goal of COSINE-100 is to perform a model-independent test of DAMA's claim of dark matter discovery. It is likely that COSINE-100 and ANAIS-112 will exclude the DAMA-observed modulation at 3σ within a few years, assuming the absence of a dark matter signal; however, it is unlikely that either COSINE-100 or ANAIS-112 will be able to independently exclude the DAMA-observed modulation at 5σ within the next several years. Thus, COSINE-200 will provide the definitive test of DAMA's claim of dark matter discovery. If COSINE-100 observes an annual modulation consistent with DAMA's observation, COSINE-200 will be essential in investigating this result with higher precision.

Along with searching for an annual modulation, COSINE-200 will have world-leading sensitivity among NaI(Tl)-based experiments to several dark matter interactions, such as SI and spin-dependent (SD) WIMP-nucleus scattering. The lowered energy threshold of COSINE-200, enabled by the promising results we have seen in developing detectors with higher light yields (see Research and Development section), will allow us increased sensitivity compared with existing sodium iodide experiments, especially to WIMP masses below 10 GeV. Of particular interest is the SD WIMP-proton cross section. As we use sodium iodide detectors, both the constituent isotopes have non-zero nuclear spins, with J=3/2 for ^{23}Na and J=5/2 for ^{125}I. Additionally, both isotopes contain an odd number of protons, increasing sensitivity to this cross section. With the low energy threshold of COSINE-200, we expect to have sensitivity to the SD WIMP-proton cross section comparable to liquid xenon experiments [11–13].

Research and Development: The primary focus of COSINE's R&D efforts towards COSINE-200 has been on the development of ultra-low background, high light yield NaI(Tl) detectors. For the development of the detectors used in COSINE-100 the collaboration partnered with Alpha Spectra Inc., an industry supplier of sodium iodide detectors. Through this partnership we were able to attain detector background levels comparable to, though slightly higher than, DAMA's achieved levels [14]. COSINE-200 will feature NaI(Tl) detectors with significantly lower background levels and higher light yields than those used in COSINE-100 [15]. The development of ultra-low background, high light yield detectors ($\leq$0.5 counts/day/kg/keV in the 1-6 keV region of interest) will increase the sensitivity of COSINE-200 by more than an order of magnitude when compared with COSINE-100. Increasing the light yield of the detectors will also allow greater sensitivity to low mass dark matter. To create detectors of our desired radiopurity and light yield, COSINE-200 will use sodium iodide detectors produced by the collaboration in-house. In addition, we are exploring the possibility of deploying these newly developed detectors in DM-Ice200.

The Center for Underground Physics (CUP) at the Institute for Basic Science in South Korea has created a facility specifically for the development, and eventual production, of high light yield, ultra-low background sodium iodide detectors. One major area of focus has been on designing a new encapsulation design and procedure for the NaI(Tl) crystal. In most standard NaI(Tl) detector designs, a cylindrical crystal is housed within a copper encapsulation to protect the crystal both mechanically and from moisture, which can dissolve the intensely hydroscopic crystal. The ends of the encapsulation feature quartz light guides to which a PMT is coupled. Though this is a robust design for industrial applications, the total light yield is decreased by the quartz window. In our new encapsulation design, the quartz window is eliminated, allowing the PMT to more directly couple to the crystal. The detectors employed in COSINE-100 have a light yield of 15 photoelectrons/keV (pe/keV), typical of what Alpha Spectra can reliably produce. Initial results [16] indicate that the first crystals we have encapsulated using this technique achieve a light yield of 22 pe/keV. Further refining this technique, the most recently encapsulated crystal achieves a light yield of 30.1 ± 0.4 pe/keV, a 200% higher light yield than achieved by DAMA, and 100% higher than achieved by COSINE-100. Encouraged by this result, we have set a goal of using crystals with a 30 pe/keV light yield in COSINE-200, enabling energy thresholds of less than 0.5 keV.

In addition, several studies on how to increase the radiopurity of the detectors is underway. Another major driver behind refining the encapsulation procedure is to reduce the level of ^{210}Pb contamination in the crystal, which is the primary background within COSINE-100's region of interest. ^{210}Pb contamination is caused by exposure of the crystal and encapsulation components to ^{222}Rn. ^{210}Pb can also be introduced to the crystal during the growth process. Techniques to reduce this contamination are currently being studied. In our most successful attempt, we achieved a ^{210}Pb level of 0.01 ± 0.02 mBq/kg [17]. This is one-third the contamination level achieved by the SABRE experiment [18], though in a smaller detector. Reducing ^{40}K contamination is also of interest, and this occurs mostly through the purification of NaI powder used to grow the crystals and the liquid scintillator veto system, which is able to tag and veto 70% of ^{40}K background events [15]. Cosmogenic radionuclides are also of concern; in particular, tritium is the second-largest contributor to the background within the ROI in COSINE-100, requiring its mitigation in COSINE-200. A dedicated study to measure cosmogenic production rates in NaI(Tl) is currently underway using crystals that have been cosmogenically activated at the Los Alamos Neutron Science Center.

Lastly, DM-Ice200 also stands to benefit from the development of state-of-the-art NaI(Tl) detectors at CUP in the form of increased sensitivity compared with industry-supplied detectors. As the entirety of the detector R&D process has been funded by the South Korean government, deploying these new detectors in DM-Ice200 would allow the American physics community to capitalize on this new detector technology while incurring only the relatively small marginal cost of DM-Ice200. DM-Ice200 is further detailed in a Letter submitted to this same topical group.

Summary: With the development of high light yield, ultra-low background NaI(Tl) detectors, COSINE-200 will have world-leading sensitivity among sodium iodide-based dark matter searches. Though COSINE-100 is expected to test the DAMA/LIBRA claim of dark matter discovery at a 3σ level, the increased radiopurity of COSINE-200 will enable a test at the 5σ level. Additionally, the increased light yield will permit searches for SD WIMP-proton scatters with sensitivity comparable to liquid xenon experiments. Lastly, in-house development of NaI(Tl) detectors is an advance that will benefit other experiments utilizing NaI(Tl) detectors, such as DM-Ice200. The results of our research and development demonstrate the feasibility and importance of including NaI(Tl) detectors in the portfolio of next-generation dark matter searches.

References

[1] P.A.R. Ade *et al.* (Planck Collaboration), Astron. Astrophys. **594**, A13 (2015).

[2] R. Bernabei *et al.* (DAMA/LIBRA Collaboration), Nucl. Phys. At. Energy **19**, 307 (2018).

[3] D.S. Akerib *et al.* (LUX Collaboration), Phys. Rev. Lett. **118**, 021303 (2017).

[4] E. Aprile *et al.* (XENON Collaboration), Phys. Rev. Lett. **119**, 181301 (2017).

[5] X. Cui *et al.* (PandaX-II Collaboration), Phys. Rev. Lett. **119**, 181302 (2017).

[6] R. Agnese *et al.* (SuperCDMS Collaboration), Phys. Rev. Lett. **112**, 241302 (2014).

[7] C. Amole *et al.* (PICO Collaboration), Phys. Rev. Lett. **118**, 251301 (2017).

[8] G. Adhikari *et al.* (COSINE-100 Collaboration), Phys. Rev. Lett. **123**, 031302 (2019).

[9] J. Amaré *et al.* (ANAIS Collaboration), Phys. Rev. Lett. **123**, 031301 (2019).

[10] G. Adhikari *et al.* (COSINE-100 Collaboration), Nature (London) **564**, 83 (2018).

[11] C. Fu *et al.* (PandaX-II Collaboration), Phys. Rev. Lett. **118**, 071301 (2017).

[12] D.S. Akerib *et al.* (LUX Collaboration), Phys. Rev. Lett. **116**, 161302 (2016).

[13] E. Aprile *et al.* (XENON Collaboration), Phys. Rev. Lett. **119**, 181301 (2017).

[14] P. Adhikari . *et al.* (COSINE-100 Collaboration), Eur. Phys. J. C **78**, 490 (2018).

[15] P. Adhikari . *et al.* (COSINE-100 Collaboration), Eur. Phys. J. C **78**, 107 (2018).

[16] J.J. Choi *et al.*, Submitted to Nucl. Instrum. Methods A, arXiv:2006.02573.

[17] B.J. Park *et al.*, Accepted in Eur. Phys. J. C, arXiv:2004.06287.

[18] B. Suerfu, M. Wada, W. Peloso, M. Souza, F. Calaprice, J. Tower, and G. Ciampi, Phys. Rev. Research **2**, 013223 (2020).