Snowmass2021 - Letter of Interest

DM-Ice200: Search for a Dark Matter Modulation Signal with NaI(Tl) in the Southern Hemisphere

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 DM-Ice200 as a new dark matter direct detection experiment using NaI(Tl) scintillation detectors deployed deep in the South Pole Ice. This experiment is currently being planned based on the experience and knowledge gained from the predecessor experiments, DM-Ice17 and COSINE-100. This project complements dark matter search efforts in the Northern Hemisphere and will investigate the observed annual modulation in the DAMA/LIBRA experiment.

Introduction:

Astrophysical evidence suggests that 27% of the Universe is made up of cold dark matter [2], but the properties of dark matter remain largely unknown. The Weakly Interacting Massive Particle (WIMP) is a theoretically favored candidate for dark matter [22, 37]. Many direct detection dark matter experiments are underway worldwide [27] to search for evidence of WIMP-nucleon elastic scattering [28, 32].

The WIMP interaction rate in terrestrial detectors is expected to modulate annually due to the Earth's motion relative to the galactic WIMP halo [29, 30]. DM-Ice and COSINE experimental programs grew out of the need to verify the DAMA Collaboration's claim that they have detected dark matter [19–21] by observing such annual modulations. To add to the confusion, several other experiments saw hints of a modulation signal, most of which have since been attributed to unforeseen backgrounds or are currently undergoing more stringent testing [1, 10, 16]. Thus, DAMA/NaI and its successor, DAMA/LIBRA, stand as the only two experiments to claim a direct detection of dark matter. Several experiments have failed to reproduce DAMA's observation; in fact, larger, more sensitive experiments such as XENON-1T, LUX, CDMS, DarkSide, and PANDA-X have ruled out "vanilla" WIMPs as the culprit behind DAMA's modulation signal [11, 13, 17, 26]. Several sources of backgrounds have been proposed as the the origin of DAMA's observed modulation, but none are able to satisfactorily explain the signal.

The DM-Ice program was conceived when the direct detection community came to the IceCube community to discuss the possibility of deploying a direct detection dark matter experiment, ideally also made of NaI(Tl), along with IceCube at the South Pole. The central idea behind deploying a detector at the South Pole is that if the DAMA-observed modulation is due to dark matter, an experiment in the Southern Hemisphere would expect to observe a modulation with the same phase and amplitude. If the modulation is due to a seasonal environmental background, it will be 180° out of phase between the two hemispheres.

DM-Ice17 is the first phase of the DM-Ice program, consisting of 17 kg of NaI(Tl) target material. It demonstrated for the first time that low-background scintillation detectors can be remotely calibrated and operated under the ice at the South Pole, with the excellent environmental conditions, including temperature stability, provided by the ice [18, 23, 24]. COSINE-100 is a joint effort between the DM-Ice and KIMS collaborations, located at Yangyang Underground Laboratory in South Korea. It consists of 8 NaI(Tl) crystals with a total mass of 106 kg, submerged in a $\approx$2000 liters of liquid scintillator veto [4–6, 36]. With the initial 60 days of data, COSINE-100 excluded spin-independent WIMP-nucleon interactions as the source of the DAMA modulation [3, 8]. For the model independent test of DAMA, an annual modulation analysis was also performed with 1.7 years of data, which showed consistent result with both the null hypothesis and DAMA's signal due to limited statistics [7]. COSINE-100 has also carried out many studies of exotic dark matter searches [9, 33]. COSINE-100 is still taking data, and expects to soon release the results from the second set of analyses with an increased exposure.

DM-Ice200:

DM-Ice and COSINE-100 revived the competition in NaI community; ANAIS112, located at Canfranc laboratory with 112 kg of NaI(Tl), showed their first annual modulation search found no signal yet [15]. SABRE is currently developing ultra-low NaI(Tl) crystals, and planning to start to install the crystals at locations in both Northern and Southern Hemisphere [31]. Other novel NaI researches are also underway, including a study of un-doped NaI at cryogenic temperature [34].

Even with current efforts from COSINE and ANAIS-112, DAMA's result still has not been fully tested. With IceCube deploying seven new detector strings for its upgrade, there is an opportunity to install NaI(Tl) crystals along with the strings, just like with DM-Ice17. With the successful runs of DM-Ice17 and COSINE-100, the DM-Ice collaboration gained a better understanding of both South Pole operation as well as general operation of NaI(Tl) detectors. Operating a full-scale NaI(Tl) detector at South Pole will be able to help the scientific community by providing a definitive test of DAMA, complementary to existing and planned

NaI(Tl) experiments.

Conceptual Design:

We are planning to deploy two to four modules, each attached to a separate IceCube string. Each module will comprise a grade-5 titanium pressure vessel that will encase 50–100 kg of NaI(Tl) crystals instrumented by 3-inch PMTs, and an IceCube main board. These modules will deployed at the bottom of new IceCube strings [35]. The IceCube strings usually are attached with 250 kg weights at the bottom, but for these two strings, the DM-Ice modules will serve as the weight. The depth of the modules will be approximately 2600 m.

The pressure vessels need to withstand pressures of up to ≈10,000 psi while also having a low radioactive background and being light-weight enough for the IceCube infrastructure. Grade-5 titanium was chosen to meet this criteria. Vessels of an appropriate dimension for even the largest crystal options come in at a reasonable dry weight of 215 kg. A background simulation using GEANT4 [12, 14] indicates the pressure vessel will contribute a ≈0.6 counts/day/kg/keV background in 2–6 keV region of interest in the NaI(Tl) detector, which is much lower than the intrinsic detector background. Along with the crystal, PMTs, and other supporting structures, the module mass of the largest detector option is expected to be ≈340 kg, which meets IceCube's weight requirement.

The data acquisition will use the same main board as IceCube, mDOM, for easier power supply, data transfer and storage. mDOM is a multi-PMT digital optical module for the next generation IceCube experiment [25]. The mDOM ADC runs at 100 MHz sampling rate, but we plan to split the PMT signal into two channels with the two ADCs 180 degrees out of phase to increase the effective trigger rate to 200 MHz. This doubled sampling rate will increase the low energy noise event separation power with pulse shape discrimination.

We plan to use the same Hamamatsu R12669-SEL 3-inch photomultiplier tube (PMT) that are used in COSINE-100, as their performance has been thoroughly characterized and is well understood. The PMTs utilize low radioactive background glass with a quantum efficiency of greater than 32%. We have tested this PMT model with the mDOM and found them to be compatible.

Each DM-Ice200 detector module will contain one or more 15 to 50 kg NaI(Tl) crystal(s) coupled on each end to 3-inch PMTs. The NaI(Tl) crystals will be ultra-low background (internal background < 2 counts/day/kg/keV in 2–6 keV), or even lower. Each crystal will be encapsulated with diffusive reflector and copper casing. It is vital to operate with such low background and high light yield crystals to increase the sensitivity, and our collaborator at the Center for Underground Physics at the Institute for Basic Science in South Korea are currently in development of such crystals at their facility.

Summary:

In spite of all the efforts from various experiments, the DAMA's claim of dark matter discovery at 5σ is still yet to be tested definitively, and it is important to resolve this tension with the same target medium. Along this effort, performing the search for annual modulation signal in the Southern Hemisphere will be able to deepen our understanding of the nature of the DAMA's result. DM-Ice200 will be built off from experience with DM-Ice17 and COSINE-100 with support from the IceCube collaboration, and will be able to provide rich physics result to the dark matter community.

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