PROCEEDINGS OF SCIENCE

# Results from the DM-Ice17 Dark Matter Experiment at the South Pole

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DM-Ice is a phased experimental program using low-background NaI(Tl) crystals with the aim to unambiguously test the claim of dark matter detection by the DAMA experiments. DM-Ice17, consisting of 17 kg of NaI(Tl), has been continuously operating at a depth of 2457 m in the South Pole ice for over five years, demonstrating the feasibility of a low-background experiment in the Antarctic ice. Studies of low and high energy spectra, an annual modulation analysis, and a WIMP exclusion limit based on the physics run of DM-Ice17 are presented. We also discuss the plan and projected sensitivity of a new joint physics run, COSINE-100, with upgraded detectors at the Yangyang Underground Laboratory in Korea.

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## 1. Introduction

Astrophysical and cosmological observations provide strong evidence that the dark matter constitutes nearly a quarter of the Universe [1, 2]. The weakly interacting massive particle (WIMP) is a theoretically favored to explain this dark matter [3]. One method of detecting WIMP is to measure the annual modulation of a WIMP signal caused by the Earth's motion in galactic rest frame, with period of one year. Only the DAMA/NaI and DAMA/LIBRA experiments, located at Laboratori Nazionali del Gran Sasso in Italy, claim to have observed an annual modulation of dark matter accurate to 9.3 $\sigma$ [4, 5], which is in conflicts with several experiments [6].

The DM-Ice experiment aims to resolve this tension by operating an experiment in the Southern Hemisphere using the same target material, thallium-doped sodium iodide (NaI(Tl)) scintillating crystals. While the expected dark matter modulation has the same phase everywhere on Earth, any other modulating environmental backgrounds will have 180° out of phase between the Northern and Southern Hemisphere. By operating at the South Pole, we expect that DM-Ice can disentangle the dark matter phase from seasonal variations.

## 2. DM-Ice17 Detector

As the first stage of the DM-Ice experimental program, DM-Ice17 was built to demonstrate the feasibility of performing low background measurements in the Antarctic ice [7]. DM-Ice17 consists of two 8.47 kg NaI(Tl) detectors, referred to as Det-1 and Det-2, which were deployed 2450 m into the South Pole ice in December 2010 [8]. The physics run started on June 2011 and ended on January 2015 with a total exposure of 60.8 kg·yr. The detectors have continued stable operations since.

## 3. Results of DM-Ice17

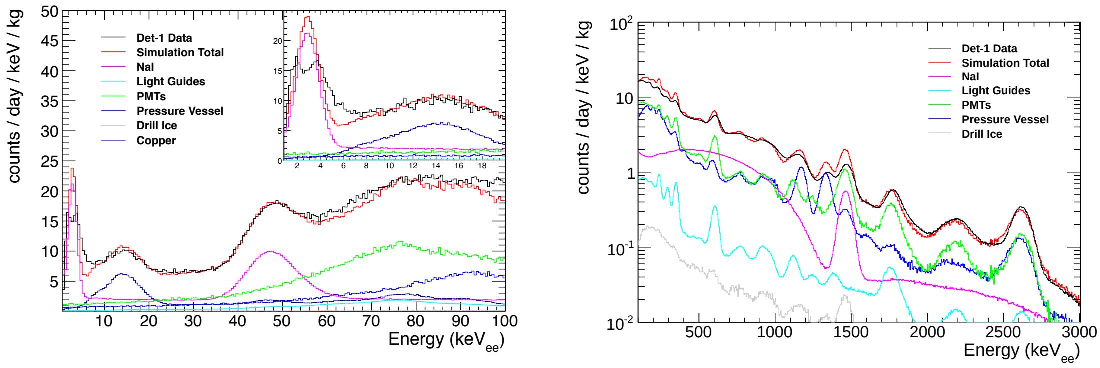


Figure 1: DM-Ice17 Det-1 background data at low (left) and high (right) energies. Detector components with main contaminations are simulated. Background peaks are used for energy calibrations.

DM-Ice17 is calibrated with intrinsic and cosmogenic backgrounds, such as $^{210}$Pb and $^{125}$I, respectively. Calibration measurements were performed separately within the low and high energy regions, due to non-linear NaI light responses. Despite inability to use external calibration sources, the $^{125}$I cosmogenic peak confirms the calibration by identifying both its energy and the decay time, with the expected half-life of 59.4 days.

Simulated background model produced with Geant4 are consistent with the data from DM-Ice17, as shown in Fig. 1 [8]. At the extreme end of the low energy region, below 4 keV, simulation does not agree with the data, mainly due to the efficiency of signal retention during noise removal. Thus, an analysis threshold for Det-1 and Det-2 was set to 4 keV and 6 keV, respectively.

As confirmed by simulations, the dominant sources of contamination are from the $^{40}$K, $^{238}$U and $^{232}$Th chains in the crystals, PMTs, and pressure vessels. The 3 keV peak is due to Auger electrons and x-rays from $^{40}$K decays in the crystals. A broad peak at 14 keV can be attributed mostly to surface contamination of the $^{238}$U-chain in the copper encapsulation, which has been observed previously in other NaI(Tl) experiments [9]. The flat background of the crystal reaching to 30 keV is dominated by contributions from $^{210}$Pb and $^{40}$K.

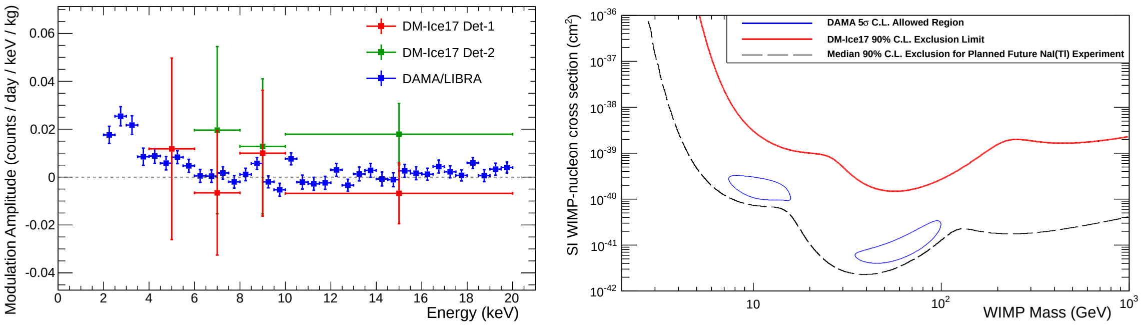


Figure 2: Left: Det-1 (red) and Det-2 (green) modulation amplitudes of each energy bin compared to the values from DAMA/LIBRA. Right: WIMP exclusion limit at 90% C.L. from the 60.8 kg·yr DM-Ice17 physics dataset (red), with DAMA preferred 5$\sigma$ C.L. contour (blue) for comparison.

Maximum likelihood fits of the background subtracted event rates for 4 different energy bins (4–6, 6–8, 8–10, and 10–20 keV) have been performed within the DM-Ice17 annual modulation analysis. When modulation amplitudes of each energy bin are compared to the values from DAMA/LIBRA with period and phase fixed to that of an expected dark matter signal (1 year and 152.5 days, respectively), as shown in Fig. 2 (left), it reveals that the data from DM-Ice17 are consistent with both the null hypothesis and DAMA/LIBRA signal under the limitations of the detector [10]. However, the result provides the strongest limit in the Southern Hemisphere by a direct detection dark matter search (See Fig. 2 (right)).

## 4. Prospect: COSINE-100

DM-Ice17 is limited by small exposure and high backgrounds, and targeted R&D programs have been ongoing to overcome this limitation [11, 12]. Cleaner crystals with more mass can be accessible with a new crystal vendor[1] and newer PMTs with lower background and higher quantum efficiency are needed.

[1] http://www.alphaspectra.com

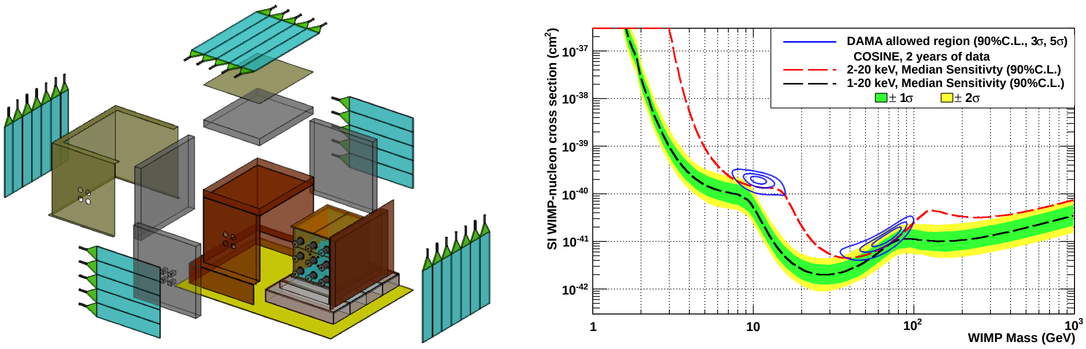


Figure 3: Left: COSINE-100 shielding structure. Right: Projected sensitivity for COSINE-100 with 1 keV (2 keV) threshold in black (red) with 2 years of data.

DM-Ice and KIMS-NaI have formed a new collaboration, COSINE-100, located at Yangyang underground laboratory in South Korea. COSINE-100 consists of 8 NaI(Tl) crystals with a total mass of 106 kg and a 2000 liter liquid scintillator veto, to help reduce low energy backgrounds by tagging $^{40}$K events. Figure 3 (left) shows the shielding structure of COSINE-100 which includes 3 cm of copper, 20 cm of lead, and 3 cm of 37 plastic scintillator panels for cosmic ray muon tagging. Data taking for COSINE-100 began in September 2016.

Figure 3 (right) shows projected sensitivity of COSINE-100, assuming 2–4 counts/day/keV/kg flat background, depending on crystal powder type. It is expected that within two years of running, COSINE-100 will achieve a sensitivity to test DAMA's result.

## 5. Conclusion

DM-Ice17, the only dark matter detector in the Southern Hemisphere, is operating successfully under Antarctic ice and established the South Pole as a site for underground low-background experiments. The DM-Ice17 physics run data, taken over 3.6 years for a total exposure of 60.8 kg·yr, shows no evidence of an annual modulation in the 4–20 keV energy range. Results give the strongest exclusion limit in the Southern Hemisphere, but are consistent with both the null hypothesis and DAMA's results as DM-Ice17 is limited by exposure time and intrinsic background rates.

COSINE-100 will utilize more massive NaI(Tl) crystals with lower intrinsic backgrounds with the aid of a liquid scintillator veto. COSINE-100 has been taking data since September 2016 and two years of data will be able to test DAMA's assertion for the detection of dark matter.

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