6 DAMIC: search for dark matter using CCD detectors

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DAMIC (Dark Matter in CCDs) is an experiment designed to provide the highest sensitivity to dark matter with mass around 5 GeV. The dominant contribution of matter in the universe is dark matter (DM) as has been determined through its gravitational effects and through its influence on the structure of the cosmos being five times more prevalent than expected from the known matter [1–4]. The earth is expected to be traversing a galactic halo of non-relativistic DM particles with a density of 0.3 GeV/cm^3 and a rigorous program to identify possible particle interactions of DM is a major focus of particle physics experiments. If DM particles interact weakly, earth-based experiments should be able to directly detect them through their nuclear recoils with detector material.

Most current and proposed DM direct-detection experiments are optimized for detecting DM particles with masses on the order of 100 GeV, which is the most natural scale for Weakly Interactive Massive Particles (WIMPs) theorized by supersymmetry [5]. This is appealing because the electroweak cross-section for producing 100-GeV to 1-TeV scale particles is such that the correct abundance of DM in the universe would freeze out as the universe cooled after the big bang. While this scenario is still a strong possibility, direct searches for supersymmetry at the LHC are increasingly ruling out the most natural versions of supersymmetry, reducing the parameter space available for a WIMP DM candidate. There is, however, another natural mass scale for DM motivated by another coincidence. The DM and baryon abundances are similar, $\rho_{DM}/\rho_B \sim 5$, which suggests a theoretical correlation between them [6]. This relationship can arise naturally when the DM has an asymmetry in the number density of matter over anti-matter similar to that of baryons:

$$n_\chi - n_{\bar{\chi}} \simeq n_b - n_{\bar{b}},$$

where n_χ and $n_{\bar{\chi}}$ are the DM and anti-DM densities, and n_b and $n_{\bar{b}}$ are the baryon and anti-baryon densities.

Since $\rho_{DM}/\rho_B \sim 5$, this suggests that the mass of the DM particle $m_\chi \sim 5 \times m_p \simeq 5$ GeV. Therefore, the proton mass scale sets the DM mass scale. This possibility has the added benefit that the the difference between the DM mass scale and the baryon mass scale arises from the relationship between the weak scale and the QCD confinement scale. Many new asymmetric DM theories originating from [7] have been hypothesized in the last few years exploring this possibility. In addition to the theoretical interest in low mass DM, there are now four direct DM detection experiments [8–11] with excesses in the 5-10 GeV DM mass region, with DAMA/Libra reporting a significance of more than 8 σ [8].

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6.1 First results

The main challenge in searching for low mass DM is measuring the low energy deposit of the associated nuclear recoils in the detection material. DAMIC uses CCDs with an electronics noise of σ=7.2 eV. This leads to a 5σ=36 eV threshold, which is the lowest of any current DM detector. CCD detectors are silicon pixel detectors that shift charge from the capacitor of one pixel to the next by generating potential wells until reaching a charge amplifier which converts the charge to voltage (see Fig. 6.1). The DAMIC CCD detectors were fabricated by Lawrence Berkeley

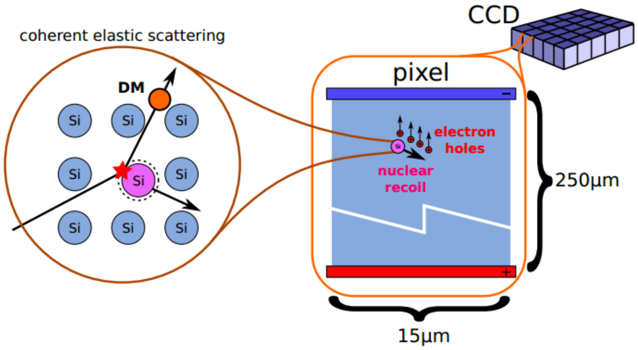

FIG. 6.1 – DAMIC detection principle: hypothetical dark matter particles scatter coherently off silicon nuclei, producing a nuclear recoil that is recorded as charge on pixels in the CCD.

National Laboratory [1] originally for the Dark Energy Camera (DECam) [2, 3]. Each CCD has up to 16 million 15 μm x 15 μm pixels and is read by two amplifiers in parallel. The electronic gain is $\sim$ 2.5 μV/e. The signal is digitized after correlated double sampling (CDS) and the noise performance improves by reducing the readout speed. The lowest noise, $\sigma < 2e^-$ (R.M.S.) per pixel, was achieved with readout times of 50 μs per pixel [5].

The second major feature that makes the DECam CCDs [4] good candidates for a DM search is their relatively large thickness (ten times thicker than usual), which directly affects the detection efficiency.

First results were obtained with a single 0.5 g CCD, installed ≈100 m underground in the NuMI [6] near-detector hall at Fermilab. Data were collected during 11 months in 2011. Standard techniques were used to interpret the results as a cross section limit for spin-independent DM interactions [7], and parameterizations were used allowing the direct comparison with other limits on low mass DM particles. The DAMIC limit constituted the best constraint on DM particles with mass below 4 GeV.

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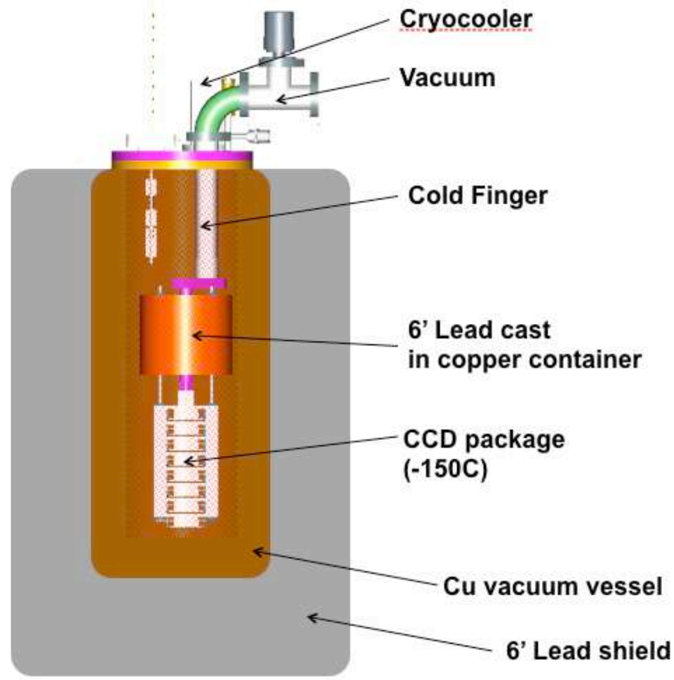

FIG. 6.2 – Schematic of the DAMIC-100 vacuum vessel with copper and lead shielding.

6.2 DAMIC-100

Our next experiment is DAMIC-100, which will begin collecting data in the summer of 2014. The experiment moved deep underground to Snolab, where prototypes of newly designed CCDs for DAMIC-100 have been running since December 2012. A schematic of the new setup is shown in Fig. 6.2. The CCDs, with a total mass of 100 g, are installed inside a copper box cooled to -150°C to reduce dark current. The cold copper also shields the detectors against infrared radiation. A closed cycle helium gas refrigerator is used to maintain the low temperature. The detector is connected through a readout cable to the preamplifiers located outside the lead shield. The detector package is housed in a cylindrical vacuum vessel fabricated with oxygen-free copper, and maintained at 10^{-7} Torr with a turbo molecular pump. Lead and polyethylene shield against γ-rays and neutrons. Fig. 6.3 shows existing parts. The projected DAMIC-100 sensitivity region is shown in Fig. 6.4 together with results from the previous DAMIC search and other experiments.

6.2.1 Calibration and testing

Energy calibration of a DM detector is factorized in (i), the ionisation energy calibration as determined from direct X-rays and carbon and oxygen fluorescent X-rays from a Fe^{55} source and (ii), the signal quenching observed for

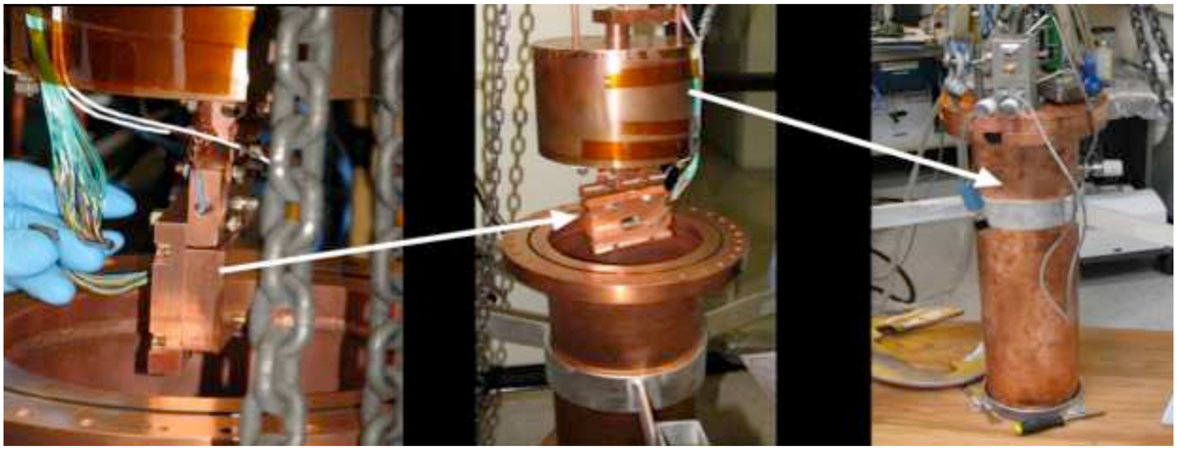

FIG. 6.3 – Vacuum vessel with copper IR shield. Above the IR shield there is a lead shield. Not shown is an outer polyethylene shield.

highly ionizing nuclear recoils. The quenching factor has been measured in Si for recoil energies above 4 keV [1], showing good agreement with the Lindhard model [2, 3].

We have helped design and test an experimental set up at the Tandem Van der Graaf of the University of Notre Dame in which monochromatic neutrons are scattered off a silicon target and the scattering angle and neutron time-of-flight are used to determine the nuclear recoil energy. The scattered neutrons are detected with a set of 20 scintillating bar counters placed at the small angles that correspond to the low recoil energies of interest (down to an unprecedented 1 keV). We are currently studying the signals and achievable timing resolution of the bars and hope to have results in summer 2014.

We are building a copy of the DAMIC detector (see Sec.19) which will be studied with X-rays and neutrons from the 2.5 MeV neutron beam at our institute. We will use the apparatus to measure the noise components of the CCD detectors. Our group has characterized the CCD noise signals and determined the optimal settings minimizing the noise. We will also measure the lateral pixel diffusion of recoil signals resulting in neighboring pixels sharing the recoil energy. The effect can be reduced by increasing the voltage applied to the silicon substrate.

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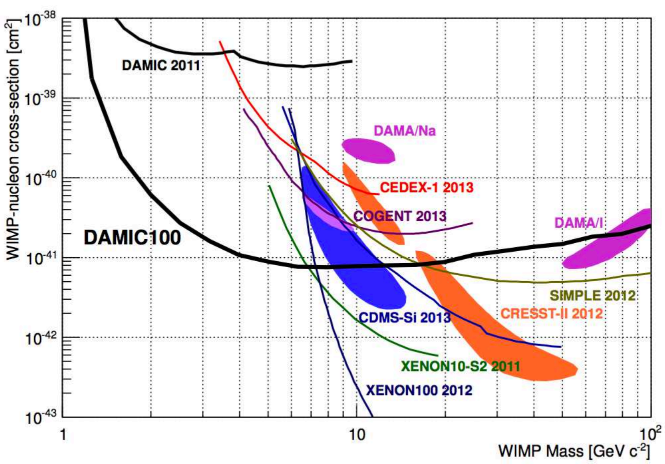

FIG. 6.4 – Signal regions (colored areas) and exclusion boundaries (colored lines) from direct DM searches. Limits from DAMIC 2011 and projected sensitivity for DAMIC-100 are shown as well.

6.2.2 Monitoring and data analysis

To reach the projected sensitivity of DAMIC-100 shown in Fig. 6.4 we will need to understand the noise, dark current, energy response, backgrounds, map of dead and hot pixels for each CCD, and calibrate them with optical light and X-ray sources. Our group has developed a monitoring system which records temperature, voltage, and pressure inside the detector cryostat, and correlates this information with dark current, RMS detector noise, X-ray radio-impurities of each individual CCD. For each of the thousands of exposures expected in one year of data taking, this monitoring software will determine the data quality and usability in the final analysis. There is an web page interface to visualize the information in real time, and store everything for offline usage. We will study the selection criteria optimizing the signal efficiency versus background rejection. First results for DAMIC-100 are expected towards the end of 2014, but of course, more time would be needed to demonstrate an annual modulation of a DM signal resulting from the earth's orbit through the galactic DM halo.