The DAMIC-100 dark matter detection experiment with CCDs at SNOLAB

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The DAMIC (Dark Matter in CCDs) experiment uses the fully depleted silicon of CCDs (Charge Coupled Devices) as a target for galactic dark matter. The ionization energy threshold for detecting nuclear recoils of dark matter reaches down to 50 eV_{ee}, resulting in better sensitivity to dark matter with mass below 5 GeV than other direct dark matter detection experiments. Installation of the DAMIC-100 experiment at SNOLAB is ongoing and we present our expected sensitivity, which will extend the reach to low-mass dark matter cross sections within a year of operation.

1 Introduction

The mass and interaction type and strength of dark matter particles is yet unknown. It has been suggested that, to explain why the dark matter density is so similar to the baryon density, the lepton-baryon asymmetry was transferred to dark matter in the early universe, resulting in a natural mass of the dark matter particle of $5 \cdot M_{proton} \sim 5$ GeV [2, 3, 4]. This dark matter particle would interact weakly with matter, and could therefore be detected through its nuclear recoil with the target of a low-background detector. Several experiments searching for dark matter have reported statistically significant excesses consistent with this expected signal [5, 6].

DAMIC (Dark Matter in CCDs) uses the fully depleted silicon of CCDs (charge-coupled devices) [1] as a target for coherent dark-matter nucleus elastic scattering. Due to the low electronics noise (2e-) of its minimalistic readout scheme, the CCD is an ideal detector for searching for the low energy recoil expected from dark matter with mass ~ 5 GeV. Improvements in the resistivity of silicon substrates have allowed scientific CCDs to achieve thicknesses of 675

μm [7], more than 30 times that of commercial CCDs, resulting in improved near-infrared light detection for telescope imaging [8], and more massive targets for direct dark matter detection.

First results for DAMIC were reported in Ref. [9]. The experiment used a shallow underground site (350' deep) and one 0.5-gram CCD detector developed for DECam, and with 107 g-days total exposure, achieved the best upper limits on the cross-section for weakly interacting dark matter particles below 4 GeV. Subsequently, DAMIC has been moved to SNOLAB (6800' deep), and the construction of the next phase of the experiment, DAMIC-100 is underway. More information about DAMIC-100 can be found in Ref. [10].

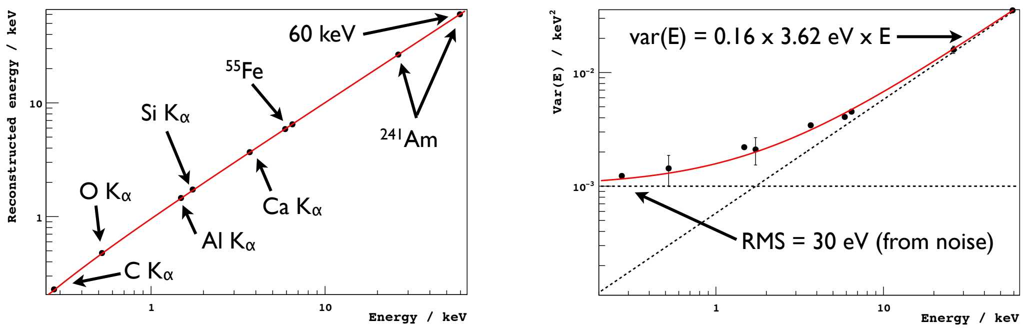
DAMIC CCDs were originally designed and fabricated at the Lawrence Berkeley National Laboratory MicroSystems Lab for the Dark Energy Survey (DES) camera (DECam) [7]. They make use of a three-phase, triple poly-silicon gate structure with a p-channel implant to collect holes from the fully depleted n-type silicon substrate which has a resistivity of 10–20 kΩ cm. A CCD has up to 16 Mpixels, each with a transverse size of $15\,\mu\text{m} \times 15\,\mu\text{m}$, and a thickness of at least 250 μm. CCDs are fully depleted with a 20 (50) V substrate voltage for 250 (675) μm thickness which causes ionization produced from nuclear recoils in the active region to be accelerated toward anode gates on the backside of the CCD, where charge is collected near a p-n junction. The substrate voltage also controls the level of lateral diffusion of the charge carriers as they drift the thickness of the CCD. The depth of an interaction inside the CCD can be determined from a measurement of the lateral sharing of charge among the pixels which record charge from the interaction.

DAMIC-100 CCDs are operated at 133 K, resulting in a dark current due to thermal excitations in the silicon substrate of $\sim$1 e^-/pix/day. The RMS noise in each pixel measurement is $\sim$1.9 e^- which corresponds to 7 eV energy. Pixels are measured by shifting charge row-by-row, column-by column to a low capacitance output gate via phased potential wells generated by the three-phase gate structure. Charge is converted to an output voltage of $\sim$ 3 μV/e- that is compared to the pedestal value for each pixel in order to determine the signal level. High frequency electronics noise is reduced by increasing the integration time of each readout, so that pixels are read out at $\sim$1 Mpixels per minute. Long exposure times ($>$ 10 hours) are used to reduce the total number of times the readout noise is incurred per dataset. DAMIC does not have timing resolution, and therefore cannot veto background events through timing coincidence with supplemental detectors as in other experiments.

Calibrations of the CCDs with fluorescence X-rays from a Kapton target exposed to the ^{55}Fe source or αs from ^{241}Am were performed. Figure 1(a) demonstrates the linearity of the CCD in the measurement of ionization energy, while Figure 1(b) quantifies the energy resolution of the CCD. For these calibrations the CCD was illuminated from the back, which, due to charge diffusion, leads to a larger dynamic range and worse energy resolution than if the CCD had been illuminated from the front.

The ionization efficiency of nuclear recoils is a fraction of that of electrons. Previous measurements have been done down to energies of 3–4 keV$_\text{r}$ [11], yielding results in agreement with Lindhard theory [12]. From this, DAMIC's nominal 50 eV$_{ee}$ threshold corresponds to $\sim$0.5 keV$_\text{r}$. Given the significant uncertainty in the extrapolation, and the importance of precise nuclear recoil scale calibration for dark matter searches, we are undergoing a series of experiments to measure this value down to the threshold [10].

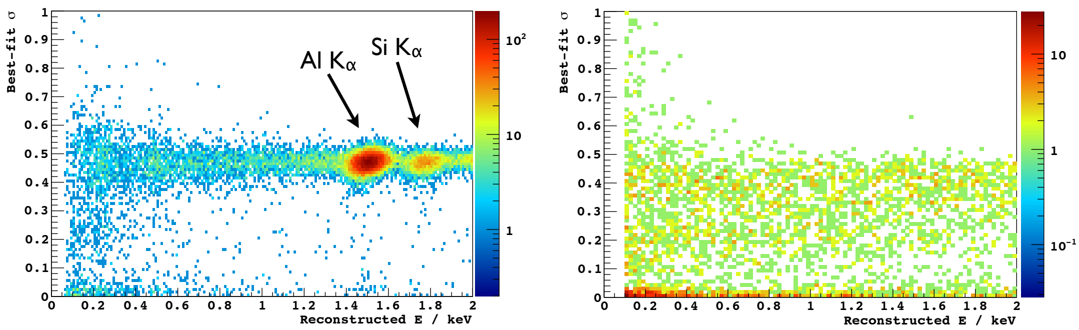
DAMIC-100 consists of eighteen, 675 μm thick, 16 Mpixel LBNL CCDs with a total mass of 100 g in a vacuum vessel with copper, lead, and polyethylene shielding at SNOLAB. The CCDs will be installed on high-purity silicon supports, immediately surrounded by OFHC copper. The radioactive background from the CCD packaging is expected to be $\ll$1 events/(keV$_{ee}$$\cdot$kg$\cdot$d)



(a) Linearity of the ionization energy scale

(b) Energy resolution

Figure 1: a) Reconstructed energy of X-ray lines compared to true energy from ^{55}Fe and ^{241}Am sources. The labeled K_α markers are fluorescence lines from elements in the Kapton target and other materials in the CCD setup. Linearity is demonstrated from 0.3 keV$_{ee}$ to 60 keV$_{ee}$. b) Variance of X-ray lines as a function of energy yielding a Fano factor of 0.16 typical for a CCD [1]. The resolution of 30 eV$_{ee}$is for maximal diffusion since the calibration was performed on the backside of the detector.



(a) Low energy X-rays from the back

(b) ^{252}Cf source (uniform)

Figure 2: The RMS size of pixel clusters (in pixels) as a function of energy from (a) fluorescence X-rays from a Kapton target exposed to a ^{55}Fe source and (b) fast neutrons from a ^{252}Cf source. X-rays are absorbed in $<10\,\mu$m of the back side, resulting in large lateral diffusion, and an RMS of about 0.5 pixels or 7.5 μm. The neutron interaction length is much larger than the thickness of the CCDs, resulting in a uniform depth of interaction, as is expected for dark matter.

and the count rate should be dominated by Compton scattering from external γ-rays, at a predicted rate of 0.5 events/(keV$_{ee}$·kg·d). Operation of the new detector should start early 2015. We use an MCNP simulation to model the backgrounds and a possible signal expected in the CCD detectors based on measurements of the radioactivity of the limiting backgrounds in the experiment. Fig. 3 shows the expected reach of DAMIC-100 and the magnitude of the possible signal from the light WIMP scenario suggested by CDMS-Si [5].

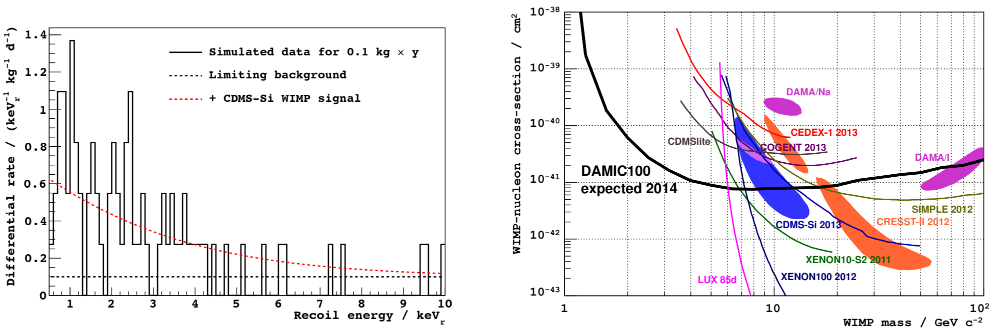


Figure 3: a) Simulated energy spectrum of DAMIC-100, considering a dark matter candidate with the mass and interaction cross-section of the best-fit to the CDMS-Si signal (M_χ=8.6 GeV and $\sigma_{\chi\mathrm{N}}$=1.9×10^{-41} cm^2) [5], standard halo parameters (ρ_χ=0.3 GeV/cm^3, v_0=220 m/s, v_E=232 m/s, v_{esc}=544 m/s) and a 0.1 kg·y exposure. The expected limiting background of 0.5 events/(keV$_{ee}$·kg·d) corresponds to 0.1 events/(keV$_r$·kg·d) due to the assumption of an ionization efficiency of 0.2. b) We present an expected 90% exclusion plot which would result in the best limits on spin-independent WIMP-nucleon elastic scattering for M_χ<6 Gev.

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