Status of the DAMIC direct dark matter search experiment

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The DAMIC experiment uses fully depleted, high resistivity CCDs to search for dark matter particles. With an energy threshold \(~50\) eV\textsubscript{ee}, and excellent energy and spatial resolutions, the DAMIC CCDs are well-suited to identify and suppress radioactive backgrounds, having an unrivaled sensitivity to WIMPs with masses \(<6\) GeV/c\textsuperscript{2}. Early results motivated the construction of a 100 g detector, DAMIC100, currently being installed at SNOLAB. This contribution discusses the installation progress, new calibration efforts near the threshold, a preliminary result with 2014 data, and the prospects for physics results after one year of data taking.

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1 Introduction

A variety of astrophysical and cosmological observations provide strong evidence supporting the existence of non-baryonic, cold dark matter [1, 2, 3]. Theoretical models proposing weakly-interacting massive particles (WIMP) with masses in the range of 1-15 GeV/c^2 [4] have gained interest motivated by recent experimental results [5, 6].

The goal of the DAMIC (Dark Matter in CCDs) experiment is to use high-resistivity charge-coupled Devices (CCDs) as detectors for the direct search for light dark matter particles. The low threshold and low background of CCDs, and the relatively small mass of the Si nucleus will allow the experiment to explore new regions of the WIMP parameter space.

The potential of CCDs to perform a WIMP search was successfully demonstrated in 2011 during a short test run at a shallow depth [7]. This promising result prompted the DAMIC collaboration to install a larger detector in the SNOLAB laboratory in Canada. The collaboration is well on its way to installing a 100 g version of the experiment, DAMIC100, which should begin operations during the first half of 2016.

2 CCDs as particle detectors

The DAMIC CCDs have 8 to 16 million pixels, with sizes of 15 µm × 15 µm, and thicknesses of several hundred µm. They have a three-phase polysilicon gate structure with a buried p-channel, and an active region made of high resistivity n-type silicon, whose low donor density (∼ 10^{11} cm^{-3}) allows for fully depleted operation at low bias voltages (40 V for a 675 µm-thick CCD). Holes produced by ionization (3.62 eV per e^- and hole) diffuse as they drift towards the gates attaining a lateral spread that can be used to reconstruct the z-coordinate of point-like interactions [8].

Charge collected over multiple hour exposures (∼ 8 hr) is read out row by row through a serial register on one side of the CCD. The pixel charges are measured in a low capacitance output node with a typical RMS noise of ∼ 2 e^-/pix (or ∼ 7 eV/pix). At the operating temperature of 100 K the dark rate is < 0.01 e^-pix^{-1}day^{-1}. The nominal DAMIC pixel threshold of ∼50 eV_{ee} is defined by the condition that a pixel value be 7σ above the noise. Figure 1 shows various particle tracks in a DAMIC CCD (left), and illustrates the WIMP detection principle (right).

Energy calibrations from exposures to X-rays from a ^{55}Fe source and light-element fluorescence, and α particles from a ^{241}Am source, have demonstrated the excellent linearity and energy resolution of the DAMIC CCDs [8, 9]. Alpha spectroscopy and studies of spatial β−β coincidences have been used to set stringent constraints on the radioactive contamination in the CCDs [10]. DAMIC’s threshold to nuclear recoils corresponds to roughly ∼0.5 keV_{r}. This estimation has large uncertainty as it is based on the extrapolation of the Lindhard model [11] of the ionization efficiency of
nuclear recoils, for which measurements exist only down to 3-4 keV, [12, 13].

3 Progress towards DAMIC100

DAMIC was installed at SNOLAB in November 2012. Details of the initial installation can be found elsewhere [8, 9]. Each CCD is epoxied to a high-purity Si support piece fitted to a copper bar, which facilitates the handling of the packaged CCD and its insertion into a slot of an electropolished copper box cooled to 100 K inside a copper vacuum vessel (10^{-6} torr), see figure 2. The CCDs are connected to a vacuum interface board (VIB) through Kapton flex cables running along the side of an 18-cm-thick lead block hanging from the vessel flange, which shields the CCDs from radiation produced at the VIB. The cables are glued to the support piece and covered with copper frames. The vacuum vessel sits inside a 21 cm-thick lead castle to shield from ambient γ-rays. The innermost inch of lead comes from an ancient Spanish galleon and has negligible content of 210Pb, strongly suppressing the background from bremsstrahlung γs produced by 210Bi decays. A 42 cm-thick polyethylene shield is used to moderate and absorb environmental neutrons.

In December 2014, preparations for the deployment of DAMIC100 were started. A major modification was the installation of a new copper box with improved grounding, as shown in figure 2(a), suited to house up to eighteen 4k×4k (16 Mpix), 5.8 g, 675 µm-thick CCDs with a new package design. At that time, three 675 µm 2k×4k (8 Mpix) CCDs were installed, pending packaging and testing of the 16 Mpix versions. The background event rate level with this setup was measured to be ∼50 dru (1 dru = 1 kg^{-1}day^{-1}keV_{ee}^{-1}), two orders of magnitude lower than in the original setup.

A series of R&D efforts aimed at identifying the source of the observed limiting background have been carried out: a pressurized N₂ box was installed in order to reduce the radon in the setup. The outer copper vessel was chemically etched to remove any contaminants that may have accrued since the time of the installation. Radioactivity tests performed by placing ancient lead and copper shields with different
surface treatments around the CCDs demonstrated problems with the electropolished copper. Wafers with a total of twenty-four 16 Mpix CCDs to be used for DAMIC100 have been acquired and are in the process of being packaged and tested. At the time of this writing one 4k×4k 16 Mpix CCD with mass of 5.9 g has already been installed at SNOLAB and preliminary tests have shown a background count rate of < 5 dru, approaching the DAMIC100 goal.

4 Near-threshold response to γ-rays and neutrons

The response of a DAMIC CCD to γ-rays and fast neutrons has been studied in a vacuum chamber at The University of Chicago. These studies have been done for the calibration of the CCD with 24 keV neutrons produced by γ-rays from a $^{124}\text{Sb}$ source impinging on a $^9\text{Be}$ target. The configuration of the source allows to characterize the γ-ray background by replacing the beryllium with an aluminum target, which does not produce any neutrons. Figure 3(left) shows the energy spectrum from the background γ-rays. Steps are visible corresponding to the K-shell (1.8 keV$_{ee}$) and L-shell (0.15 keV$_{ee}$) electron binding energies. These correspond to the minimum energy deposited by γ-rays when scattering on electrons from the different atomic shells. The magnitude of the vertical drops is approximately proportional to the number of electrons in each shell. This demonstrates the capability of the detectors

*At the time of writing this report, the collaboration has pinned down the source of background to impurities embeded in the copper used for the box and package holders, possibly during the electropolishing process.
Preliminary studies with the $^{124}$Sb-$^9$Be neutron source have provided evidence of the CCD’s ability to measure Si recoils with a maximum energy of 3.2 keV$_{ee}$. This can be seen in figure 3(right), where the red histogram shows the spectral excess observed with the beryllium target in place, containing the signal from neutrons in addition to the $\gamma$-ray background.

5 Preliminary dark matter result with 2014 data

A search for dark matter was performed using data from 36 days of exposure with two 500 µm-thick (2.2 g each), and one 675 µm-thick (2.9 g), plus an additional 7 days of exposure with the 675 µm-thick CCD (total exposure of 0.27 kg·day).

WIMP candidate events are expected to deposit energies $\lesssim 10$ keV and form diffusion-limited hits $[$8$]$. These events were searched for by performing a 2D Gaussian fit to the charge distribution in a moving 7×7 pixel window with the following parametrization: $N_e \times \text{Gauss}(x, y \mid \mu_x, \mu_y, \sigma) + c_{\text{ped}}$. Here, $x$ and $y$ are the pixel coordinates, and the five fit parameters are the total number of ionized electrons $N_e$ (in e$^-$), the event width $\sigma$ (in pixels) due to lateral diffusion, the mean position of the charge distribution $\mu_x$ and $\mu_y$ in each direction, and a residual local pedestal $c_{\text{ped}}$. The difference between negative log-likelihood (LL) of the best fit, and that obtained from a fit to only a local pedestal, $\Delta LL = LL_{bf} - LL_{ped}$, was used as discriminant.

†Thinned astronomical CCD’s with indium-tin oxide (ITO) coating.
‡Un-thinned CCD without ITO coating.
Figure 4: Left: Exposures as a function of energy for the CCDs used in the dark matter search analysis. Right: ΔLL distributions for events with $E < 0.25 \text{ keV}_{ee}$ in a 30 ks real exposure, blank exposures (no physical events), and uniformly distributed events simulated on the blank exposures.

Figure 4(left) shows the exposures of the CCDs used in the analysis. Figure 4(right) shows the ΔLL distribution from a 30 ks exposure, and compares it to the distribution from data blanks (containing no physical events), and that from simulated events with uniform energy distributed evenly throughout the data blanks.

An unbinned likelihood fit of a standard dark matter halo model [14] was performed over the data events with energies $< 10 \text{ keV}_{ee}$, letting also float a flat level background. The model assumed a local WIMP density of 0.3 GeV/cm$^3$, halo dispersion velocity of 220 km/s, Earth velocity of 232 km/s, and escape velocity of 554 km/s. The detector response simulation used the efficiencies extracted from the data shown in figure 4(left), and assumed the Lindhard model [11] to calculate nuclear recoil energies.

Figure 5(left) shows the energy spectrum of the data events used in the fit (black line), and the predicted best-fit spectrum (red line). The resulting best fit parameters are $M_\chi = 26 \pm 46 \text{ GeV}/c^2$, $\sigma_\chi = 7 \pm 16 \times 10^{-4} \text{ pb}$, and $c_{bg} = 67 \pm 13 \text{ dru}$, consistent with the absence of a dark matter signal. The best fit had a negative log-likelihood minimum of $-\log L_{bf} = -396.5$, consistent with the value from a fit to the NULL hypothesis ($c_{bg} = 74 \pm 5 \text{ dru}$, $-\log L_{NULL} = -396.1$). The 90% C.L. limit on the WIMP parameters is shown in the right-hand side plot in figure 5.

6 Expectations for DAMIC100

The full deployment of DAMIC100 will consist of eighteen 4k×4k (16 Mpix) CCDs 675 μm-thick for a total Si mass of ~ 100 g in the current vessel and shielding at SNOLAB. The radioactive background event rate from the CCD packaging is expected to be $\ll 1 \text{ dru}$ leading to a limiting background dominated by Compton scattering of
Figure 5: Left: Energy spectrum of data events used in the dark matter search (black histogram) compared to the best fit energy spectrum (red line). Right: Extracted 90% C.L. limit (solid black line). Also shown is the projected sensitivity for DAMIC100 (black long-dash line) with a 36.5 kg·day exposure, assuming a limiting background of 0.5 kg$^{-1}$·day$^{-1}$·keV$^{-1}$, and a threshold of 0.5 keV$_r$. Several other results are shown for comparison.

external $\gamma$-rays at a predicted rate of $\sim$ 0.5 dru. Figure 5(right) shows the expected DAMIC100 sensitivity (long-dash black line) after one year of operation assuming this level of background, and a 0.5 keV$_r$ threshold. The physics run with this new detector should begin during the first half of 2016.

7 Conclusions

The DAMIC collaboration has demonstrated the potential of CCDs to perform a competitive search for light WIMPs. A preliminary result from a short exposure of $\sim$ 0.3 kg·day at SNOLAB has been presented. A novel method for the characterization of the CCD response to low energy $\gamma$-rays exploiting the atomic structure of silicon has been developed. Recent studies with neutron sources suggest that the detectors should be able to measure Si recoils with energies near the 50 eV$_{ee}$ threshold.

The installation of DAMIC100 is well underway. The detectors are in the process of being packaged in new low radioactive assemblies for subsequent testing. Radioactivity tests of the new CCD package have shown that the experiment will be able to achieve a limiting background rate close to $\sim$ 0.5 dru required to reach the projected sensitivity. The experiment should begin data taking during the first half of 2016.

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