DAMIC at SNOLAB

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\textbf{Abstract.} This report presents the past results, current status and future plans for DAMIC: a search for low-mass dark matter particles with low-noise CCDs. We summarize the extensive laboratory efforts on the characterization of the CCDs and the calibration of their response to potential dark matter signals and radioactive backgrounds. Recent results include exclusion limits on the spin-independent scattering of WIMPs with silicon nuclei and on the absorption of eV-scale hidden-photon dark matter by valence electrons. A 40 g 7-CCD array started operation in February 2017 and data acquisition is ongoing, with results expected in 2018. We outline the future plans for DAMIC-1K, a 1 kg 50-CCD array with an ionization threshold of \(2 e^-\).

1. Introduction
The DAMIC experiment at SNOLAB \cite{1} employs the bulk silicon of scientific-grade charge-coupled devices (CCDs) as a target for interactions of particle dark matter from the galactic halo. By virtue of the low readout noise of the CCDs, DAMIC is particularly sensitive to the small ionization signals from recoiling nuclei or electrons following the scattering of low-mass dark matter particles.

The relatively low mass of the silicon nucleus allows for particularly good sensitivity to the coherent elastic scattering of weakly interacting massive particles (WIMPs) \cite{2, 3, 4} with masses in the range 1–10 GeV \(c^{-2}\), which would induce nuclear recoils of keV-scale energies. In addition, the low leakage current provides sensitivity to dark matter-electron interactions that would deposit sufficient energy to overcome the band gap of silicon and ionize a single electron. For example, DAMIC is sensitive to the absorption of hidden photons \cite{5, 6, 7, 8}, massive vector bosons with a weak kinetic mixing with ordinary photons, with masses as small as 1.2 eV \(c^{-2}\).

The current version of the DAMIC CCDs are 16 Mpixel devices with a pixel size of 15×15 \(\mu m^2\) (Fig. 1). Each CCD is epoxied onto a silicon backing, together with a flex cable that is wire bonded to the CCD and provides the voltage biases, clocks and video signals required for its operation. These components are supported by a copper frame to complete the CCD module. The modules slide into slots of a copper box that is cooled to \(\sim130\) K inside a vacuum chamber. Details of the DAMIC infrastructure at SNOLAB can be found in Refs. \cite{1, 9}.

The bulk of the devices is high-resistivity (10–20 k\(\Omega\) cm) silicon with a thickness of 675 \(\mu m\), which is fully depleted by the application of a substrate bias of 40 V. Ionization charge produced in the substrate is drifted along the direction of the electric field (\(z\) axis) and collected on the pixel array (\(x-y\) plane). Because of thermal motion, the ionized charge diffuses transversely with respect to the electric field direction as it is drifted, with a spatial variance that is proportional to the transit time. Hence, there is a positive correlation between the lateral diffusion of the
collected charge on the pixel array and the depth of the interaction, which is used to reconstruct in three dimensions \((x,y,z)\) the location of energy deposits in the bulk of the device. This allows to efficiently reject surface backgrounds, which arise from low-energy photons and electrons emitted by radioactive decay on surfaces or radiated by the surrounding materials.

The pixel array is read out after exposure times defined by the user, typically \(\sim 8\) h, which are not affected by image saturation or pile-up thanks to the low background rates at SNOLAB \((\sim 1\ g^{-1}\ \text{d}^{-1})\). Each pixel value is read with an uncertainty of \(\sim 2\ e^{-}\). Fig. 2 shows an image segment from an exposure acquired in the surface laboratory, which depicts a variety of observed particle tracks. The characteristics of the pixel clusters readily identify the nature of the ionizing particles, providing important information on their origin.

2. CCD response

The response of DAMIC CCDs to ionizing radiation was thoroughly characterized in the laboratory. The linear response of the amplifier was demonstrated with optical photons for ionization signals as small as \(10\ e^{-}\) [1], and with monoenergetic x- and \(\gamma\)-ray sources for energies in the range \(0.5\text{–}60\kev\) (where \(3.8\keve=1\ e^{-}\), as an electronic recoil loses, on average, \(3.8\ eV\) of kinetic energy for every electron-hole pair produced) [10]. These radioactive sources, together with cosmic minimum-ionizing particles [1], were used to validate the relation between the depth \((z)\) of the interaction and the lateral spread of the charge collected on the pixel array.

A direct measurement of the Compton spectrum at the lowest energies was performed with \(^{241}\text{Am}\) and \(^{57}\text{Co}\) \(\gamma\)-ray sources, which demonstrated the capability of the CCDs to reliably resolve spectral features down to the current energy threshold of \(60\ eV_{ee}\) [10]. Furthermore, this was a direct measurement of the dominant background expected in DAMIC at SNOLAB: the low-energy electronic recoils from small-angle Compton scattering of external \(\gamma\) rays.

The ionization efficiency of nuclear recoils, i.e., the amplitude of the ionization signal produced by a nuclear recoil of a given kinetic energy, was directly measured down to the current energy threshold by comparing the observed and predicted nuclear-recoil energy spectra in a CCD.
from a low-energy $^{124}\text{Sb}\text{,}^9\text{Be}$ photoneutron source ($E_n \leq 24$ keV) [11]. This result was confirmed by a complementary measurement using the time-of-flight technique at a pulsed fast-neutron beam with a silicon drift detector (SDD) [12]. The measured ionization efficiency (Fig. 3) shows significant deviation from the extrapolation of Lindhard theory to low energies [13], which is commonly used to estimate the sensitivity of WIMP searches.

3. Results from DAMIC at SNOLAB

The DAMIC Collaboration has been operating CCD detectors at SNOLAB since 2013. The first efforts focused on the mitigation of radioactive backgrounds to achieve a level $<10$ keV$_{ee}^{-1}$ kg$^{-1}$ d$^{-1}$ at low energies, necessary for a competitive dark matter search. These efforts included the study of the radioactive contamination of the CCDs [9], in particular, the first measurement of the rate of $^{32}\text{Si}$ decays in detector-grade silicon of $80^{+110}_{-65}$ kg$^{-1}$ d$^{-1}$ (95\% C.L.). A long-lived natural isotope of silicon, $^{32}\text{Si}$ cannot be removed by chemical purification. In this analysis, the $\beta$ decays of $^{32}\text{Si}$ and its daughter, $^{32}\text{P}$, were identified by the spatial correlation between the start points of the tracks of the emitted $\beta$ particles. Although $^{32}\text{P}$ has a relatively long half-life (14 d), the expected number of accidental pairs was strongly suppressed by the extremely high spatial resolution of the CCD. The identification with high efficiency of individual $^{32}\text{Si}$-$^{32}\text{P}$ decay sequences also allows the vetoing of $^{32}\text{Si}$ and $^{32}\text{P}$ decays that may fall in the dark matter search energy region, reducing this potential background by a factor $>10^2$. Beside $^{32}\text{Si}$ and $^{210}\text{Po}$ $\alpha$ decays from surface contamination, no other radioactive backgrounds were observed. This result confirmed that the radioactive contamination in the bulk and surfaces of the DAMIC CCDs will not be the limiting background for the upcoming run at SNOLAB.

Throughout the year 2015, DAMIC acquired R&D data with 8 Mpixel CCDs. An exposure of 0.6 kg d was selected to perform a search for WIMP dark matter [1]. This work established the low-noise, stable performance of the devices over month-long periods, allowing for the efficient selection of low-energy ionization events in the bulk of the silicon target. The energy spectrum of the observed events was consistent with the expected background from Compton scattering of environmental $\gamma$ rays. A spectral analysis led to the exclusion limit on the WIMP-nucleon elastic-scattering cross section shown in Fig. 4, which directly probed, with the same nuclear target, parameter space corresponding to the signal excess in the CDMS-II silicon experiment [14].
Figure 5. Distribution of pixel values in a 6.25 d exposure of DAMIC. The distribution is consistent with the null-hypothesis (blue line). Dashed lines show the expected distortion from the absorption of hidden-photon dark matter.

Figure 6. Exclusion limits for the hidden-photon kinetic mixing $\kappa$ as a function of hidden photon mass $m_V$ from different experiments. The blue line presents the result from DAMIC in Ref. [15]. Limits from direct searches for dark matter are labeled “DM.”

The remarkably low leakage current of the CCDs at a level of $4 e^- \text{mm}^{-2} \text{d}^{-1} \left(10^{-21} \text{A cm}^{-2}\right)$ allows DAMIC to place experimental constraints on dark matter interactions that deposit as little as 1.2 eV in the target, improving by an order of magnitude the ionization threshold over previous dark matter searches. A search for the absorption of hidden-photon dark matter was carried out with 6.25 d of data acquired in January 2016 with a 16 Mpixel CCD [15]. The analysis studied the noise profile of the CCD images, searching for deviations in the distribution of pixel values that could arise from the absorption of hidden photons. Fig. 5 shows the observed pixel distribution, consistent with the expected distribution of leakage current convolved with a white pixel readout noise of $1.9 e^-$. This result allowed us to set the most stringent direct-detection constraints on hidden-photon dark matter in the galactic halo with masses 3–12 eV (Fig. 6).

4. Status of DAMIC at SNOLAB

Seven 16 Mpixel CCDs with a total mass of 40 g have been running at SNOLAB since February 2017. Stable operation was achieved since the start of data acquisition and the CCD performance is consistent with what was shown in Refs. [1, 15]. The raw event rate (i.e., before any background discrimination) at low energies varies between CCDs and was measured to be in the range $5\text{--}15 \text{keV}_{ee}^{-1} \text{kg}^{-1} \text{d}^{-1}$. So far, an exposure of 6 kg d has been accrued, and the CCD array is expected to acquire data at SNOLAB throughout calendar year 2018. Fig. 7 shows the expected sensitivity of DAMIC at SNOLAB to the spin-independent scattering of WIMPs with nuclei after a 13 kg d exposure.

5. Prospects for DAMIC-1K

DAMIC-1K, a 50-CCD detector array of 1 kg target mass, is the next step in the DAMIC program. It capitalizes on the DAMIC experience at SNOLAB and, at the same time, takes a giant leap forward in sensitivity by radically innovating the detector technology. Its 36 Mpixel CCDs will be the most massive ever built, 20 g each. The implementation of a novel “skipper” readout will result in the high-resolution detection of a single electron. Together with the remarkably low leakage current of $<10^{-21} \text{A cm}^{-2}$ — a combination unmatched by any other dark matter experiment — DAMIC-1K will feature a threshold of 2 or 3 $e^-$. 
In the skipper readout, a series of repetitive, uncorrelated measurements of the charge collected by each pixel are performed. The pixel noise is significantly decreased by averaging over the large number of samples. The single-electron resolution of the skipper readout was already demonstrated with a 200 μm-thick 3.6 Mpixel CCD in Ref. [16], where a readout noise of 0.07 e− was achieved with 4000 samples per pixel.

To maximize the science reach of DAMIC-1K, a decrease of the radiogenic background to \( \sim 0.1 \text{ keV}_c \text{ee}^{-1} \text{ kg}^{-1} \text{ d}^{-1} \) will also be necessary. This will require improvements in the design of the detector array and in the handling and packaging of the devices to mitigate surface backgrounds from \(^{210}\text{Pb}\). Also, careful selection of construction materials and procedures, in order to minimize the exposure of the components to cosmic rays, will be implemented; a main concern is the activation of \(^3\text{H}\) in the silicon target, which is expected to be the dominant background.

DAMIC-1K will search for low-mass dark matter in a broad range of masses from 1 eV \( c^{-2} \) to 10 GeV \( c^{-2} \). In addition to progress in the search for GeV-scale WIMP dark matter (Fig. 7) and hidden-photon dark matter (e.g., Fig. 2 in Ref. [17]), DAMIC-1K will break new ground in the search for dark matter with masses 1 MeV \( c^{-2} \) to 1 GeV \( c^{-2} \) by improving by orders of magnitude the sensitivity to the ionization signals from the scattering of dark matter particles with valence electrons (e.g., Fig. 2 in Ref. [18]). The science reach of DAMIC-1K together with the prospects for other direct detection experiments, was compiled in Section IV of Ref. [19].

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