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Dark Matter Search Results from DAMIC

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Dark Matter Search Results from DAMIC

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Abstract. We present the current status of DAMIC at SNOLAB: a search for low-mass dark matter (DM) particles with low-noise CCDs. A 40 g 7-CCD array started operation in February 2017 and DM search data was acquired throughout 2017–2019. We summarize recent results on the search for few-e^- ionization signals induced by electronic recoils from the scattering of DM particles with masses $\sim$MeV c^{-2} or the absorption of hidden photons with masses 1–10 eV c^{-2}. We report on the status of the search for ionization signals greater than 15 e^- from recoiling silicon nuclei following the scattering of DM particles with masses $\sim$GeV c^{-2}.

1. Overview

The DAMIC experiment at SNOLAB [1] employs the bulk silicon of scientific-grade charge-coupled devices (CCDs) as a target for interactions of particle DM 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 electrons or nuclei following the interactions of low-mass DM particles.

The low leakage current provides sensitivity to DM-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 scattering of DM particles with masses as small as 0.5 MeV c^{-2} [2] and the absorption of hidden photons [3, 4, 5, 6] with masses as small as 1.2 eV c^{-2}. In addition, the relatively low mass of the silicon nucleus allows for particularly good sensitivity to the coherent elastic scattering of weakly interacting massive particles (WIMPs) [7, 8, 9] with masses in the range 1–10 GeV c^{-2}, which would induce nuclear recoils of keV-scale energies.

The current version of the DAMIC CCDs are 16 Mpixel devices with a pixel size of $15\times15\ \mu\mathrm{m}^2$. Each CCD is packaged into a copper module that slides into slots of a copper box. A flex cable is used to connect the module to the electronics that drive and read out the CCD. The copper box is cooled to $\sim$130 K inside a vacuum chamber, which is shielded from all sides by $\sim$20 cm of lead and $\sim$40 cm of polyethylene to stop environmental γ and neutron radiation, respectively. Details of the DAMIC infrastructure at SNOLAB can be found in Refs. [1, 10].

The bulk of the devices is high-resistivity (10–20 kΩ cm) silicon with a thickness of 675 μm, which is fully depleted by the application of a substrate bias of 70 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 (Fig. 1). Hence, there is a positive correlation between the lateral spread

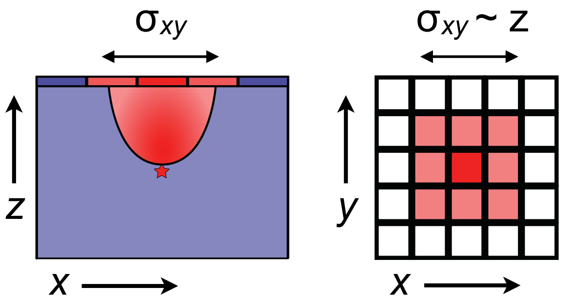

Figure 1. Charge distribution on the pixel array from an ionization event in the bulk of a CCD. The ionization charge diffuses laterally as it is drifted to the pixel array by the applied electric field. The observed pattern is a two-dimensional Gaussian with spread σ_{xy} positively correlated with the z coordinate of the interaction.

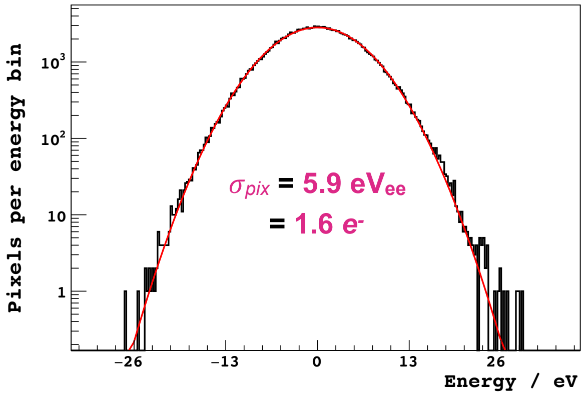

Figure 2. Pixel value distribution for a short exposure (no ionization events) acquired with DAMIC. The pixel noise is well-described by a Gaussian function with standard deviation $\sigma_{\rm pix}$ of 1.6 e^-.

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.

DAMIC data are images that contain all ionization events occurring within an exposure, typically ~8 h long. The CCDs are read out by measuring the charge collected by every pixel individually or by measuring the total charge collected in column segments that are 100-pixels high. In either case, the uncertainty in a single charge measurement is $<2\,e^-$ (Fig. 2). When the CCDs are read out in column segments, information on the spatial distribution of the charge along the y dimension is lost but a better signal-to-noise ratio is obtained for the total charge collected in the column segment, which improves the energy resolution. The depth of the event can still be reconstructed from the spread of the charge in the x dimension. Details on the readout of DAMIC CCDs can be found in Ref. [1].

2. Constraints on DM interactions with electrons

The remarkably low leakage current of the CCDs at a level of $\sim 2\,e^-\,\mathrm{mm}^{-2}\,\mathrm{d}^{-1}$ ($10^{-21}\,\mathrm{A\,cm}^{-2}$) allows DAMIC to place experimental constraints on DM interactions that deposit as little as 1.2 eV in the target. A search for low-energy DM interactions was carried out by studying the observed distribution of pixel values in a 200 g-d exposure of the four CCDs with the lowest leakage current [11]. The presence of a DM signal, e.g., few ionized e^- from the scattering of light DM particles with electrons or the absorption of hidden photons, would lead to a distortion of the pixel distribution toward higher values. Statistical tests between the noise-only hypothesis and templates that also include DM signals were performed. Exclusion limits on the amplitude of a DM signal were extracted for different model assumptions, e.g., the type of DM particle and its mass. At present, these results represent the world's strongest limits on the scattering of DM particles with masses $<5\,\mathrm{MeV}\,c^{-2}$ and on the absorption of hidden photons with masses 1–9 eV c^{-2}. For example, Fig. 3 shows the 90% C.L. exclusion limits for the DM-electron scattering cross-section (σ_e) as a function of DM mass (m_χ) where the DM scattering form factor F_{DM}=1.

3. Status of WIMP Search

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 detector

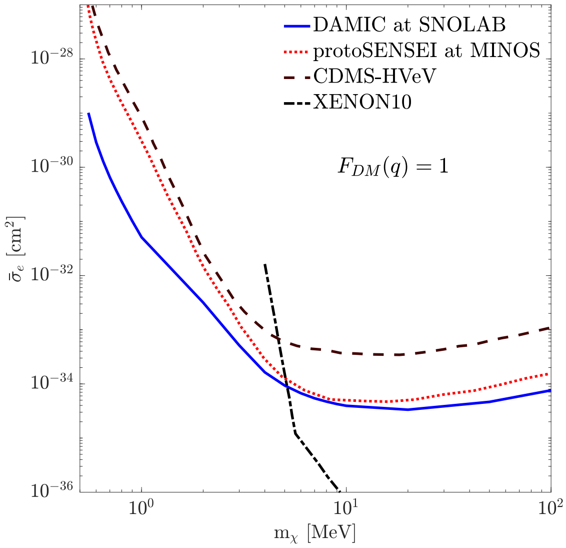

Figure 3. Exclusion limits (90% C.L.) from DAMIC and other experiments [12, 13, 14] on the existence of DM particles with masses 0.5–100 MeV c^{-2} that scatter with electrons.

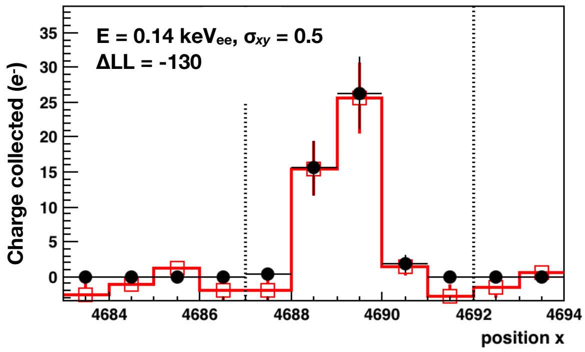

Figure 4. Example low-energy ionization event observed in the WIMP search data set of DAMIC at SNOLAB. The red points are the measured pixel values along a row and the black points are the best-fit result with a Gaussian distribution of charge. The event is classified as occurring deep in the bulk of the CCD.

performance improved since the first WIMP search results with a previous deployment of 8 Mpix CCDs [1]. Readout noise is now 1.6 e^- (or 5.9 eV$_{\rm ee}$ because an electronic recoil loses, on average, 3.8 eV of kinetic energy for every electron-hole pair produced), and the total event rate is 5–15 keV$_{\rm ee}^{-1}$ kg^{-1} d^{-1}, depending on CCD. Throughout 2017–2018, DM search data was acquired with CCD readout in column segments 100-pixels high to optimize the detection efficiency for low-energy deposits in the target. We select ionization events with 10% efficiency at the 50 eV$_{\rm ee}$ threshold up to full efficiency for events with energy >100 eV$_{\rm ee}$, while the acceptance for events from noise is negligible. The analysis of a 13 kg-day exposure with this data set is being finalized. The expected sensitivity to WIMPs with masses $\sim$GeV c^{-2} is at least an order of magnitude better than our previous result [1].

Fig. 4 shows an event of energy E=140 eV$_{\rm ee}$ from the WIMP search data set. Note the $<2\,e^-$ baseline noise and the high statistical significance of the event. The spread of the charge is reconstructed as σ_{xy}=0.5 pix, which corresponds to an energy deposit well within the bulk of the device, away from its surfaces. The WIMP search analysis is based on an unbinned-likelihood fit to the E-σ_{xy} distribution of low-energy (E<6 keV$_{\rm ee}$) events with signal and background templates (probability distribution functions). The generation of the background template is based on a full Monte Carlo simulation of the detector that produces the E-σ_{xy} distribution of events from many radioactive contaminants in different parts of the detector. The overall background template comes from a two-dimensional binned-likelihood fit to the events in the data with E>6 keV$_{\rm ee}$—where no DM signal is expected [15]—with different background components. The amplitude of the different components is constrained with additional knowledge of the radioactive contaminants in the detector, e.g., from materials screening. The best-fit overall template is extrapolated to low energies for the WIMP search.

The response of DAMIC CCDs to ionizing radiation was thoroughly characterized with optical photons, cosmic rays, X rays [1], γ rays [16] and neutrons [17]. Of particular relevance for the WIMP search is the calibration of the CCDs to low-energy nuclear recoils with a ^{124}Sb-^{9}Be photoneutron source [17]. Primary γ rays from ^{124}Sb interact with a ^{9}Be target to produce 24 keV neutrons that are then slightly moderated on their way to the CCD by a lead shield necessary

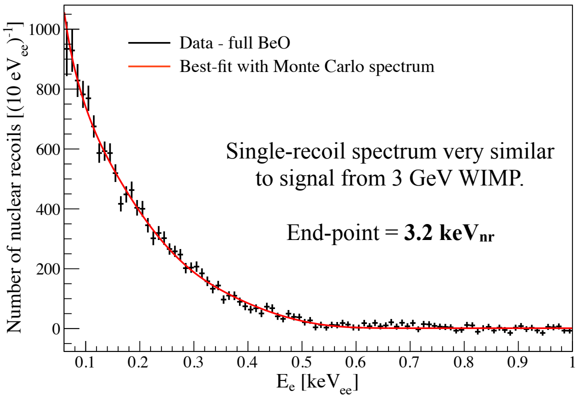

Figure 5. Energy spectrum of ionization events from a ^{124}Sb-^{9}Be photoneutron source. A fit to the data with the simulated nuclear-recoil spectrum was used to extract the ionization efficiency in silicon.

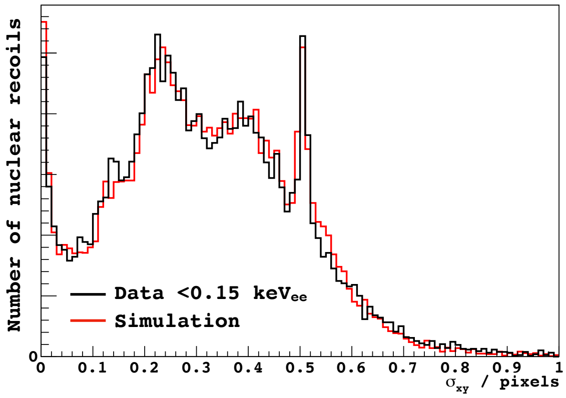

Figure 6. Distribution of the spread σ_{xy} of low-energy clusters in the ^{124}Sb-^{9}Be photoneutron calibration data compared to simulation, which includes the charge diffusion model.

to stop the primary γ rays. The energy spectrum and spatial distribution of the nuclear recoils in the CCD is very similar to the expected signal from a 3 GeV c^{-2} WIMP (Fig. 5). From the comparison between the observed and simulated energy spectra, we extracted the nuclear-recoil ionization efficiency, i.e., the amplitude of the ionization signal produced by a nuclear recoil of a given kinetic energy, down to 60 eV$_{ee}$. The measured ionization efficiency is inconsistent with the extrapolation of Lindhard theory to low energies [18], which is commonly used in the absence of calibration data to interpret the results from other searches for GeV c^{-2}-scale WIMPs [19, 20].

The ^{124}Sb-^{9}Be photoneutron source was also used to validate the charge diffusion model implemented in our simulation, which determines the accuracy of our depth reconstruction and consequently the discrimination against surface backgrounds in our fit to the WIMP search data. Fig. 6 shows the agreement between data and simulation in the reconstruction of σ_{xy} for low-energy events ($E<150$ eV$_{ee}$).

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