PROCEEDINGS OF SCIENCE

Confirmation of the excess of ionization events in DAMIC at SNOLAB with skipper CCDs

Michelangelo Traina[a,*] **on behalf of the DAMIC, DAMIC-M and SENSEI collaborations**

[a] *Center for Experimental Nuclear Physics and Astrophysics, University of Washington, Seattle, WA, United States*

E-mail: mtraina@uw.edu

We present results from a 3.2 kg-day target exposure of two 24-megapixel skipper charge-coupled devices (CCDs) deployed in the DAMIC setup at SNOLAB. With a 10× reduction in pixel noise, we investigate the excess population of low-energy bulk events previously observed above expected backgrounds. We address the dominant systematic uncertainty of the previous analysis through a depth fiducialization designed to reject surface backgrounds on the CCDs. The observed energy spectrum and spatial distribution of ionization events with electron-equivalent energies <500 eV confirm the presence of a bulk excess compatible with previous findings. This measurement establishes the existence of a prominent source of low-energy events in the CCD target with characteristic rate of ~7 events per kg-day, and energies ~80 eV, whose origin remains unknown.

XVIII International Conference on Topics in Astroparticle and Underground Physics (TAUP2023)
28.08-01.09.2023
University of Vienna

[*] Speaker

https://pos.sissa.it/

PoS(TAUP2023)059

1. DAMIC at SNOLAB Skipper Upgrade

DAMIC (Dark Matter in CCDs) at SNOLAB is a low-background experiment installed beneath 2 km of granite in the Vale Creighton Mine near Sudbury, Canada [1], using thick, silicon Charge-Coupled Devices (CCDs) to detect light dark matter ($m_\chi < 10$ GeV$/c^2$).

The DAMIC at SNOLAB apparatus was upgraded in late 2021 [2], decommissioning seven CCDs with conventional readout to install two 24-Mpixel CCDs with skipper readout, which enables sub-electron resolution. Minor modifications were made to rest of the apparatus, which features the same copper, lead and polyethylene shielding as the previous installation. The skipper upgrade of DAMIC at SNOLAB was commissioned for operations with a sub-electron noise of 0.2 e^-, leakage current of $\sim 10^{-3}$ e^-/pix/day, and background rate of ~ 10 keV^{-1} kg^{-1} day^{-1} compatible with the previous apparatus [1]. The factor of 10 reduction in readout noise enables lower energy threshold (previously 50 eV$_{\rm ee}$) and better spatial reconstruction of ionization events. Following detector commissioning, we conducted a science data run using both skipper CCDs to investigate the statistically significant excess of low-energy events (E < 0.5 keV$_{\rm ee}$) previously observed above expected backgrounds [1]. We acquired 10124 CCD images amounting to 4.8 kg-day of target exposure throughout 2022. The cluster search was performed using a likelihood clustering algorithm [3], where the likelihood ratio $\Delta LL = -\mathcal{L}_g/\mathcal{L}_n$ is computed for the hypotheses that the charge in a 5×5 pixel window comes from an ionization event and noise ($\mathcal{L}_g$), and from noise only ($\mathcal{L}_n$). For each cluster of pixels found with a soft cut on ΔLL, a stricter, charge-dependent cut is applied to efficiently discriminate noise accidentals from ionization events for cluster charge ≥ 6 e^-. Figure 1 illustrates the clustering procedure (left) and a candidate low-energy ionization event (right).

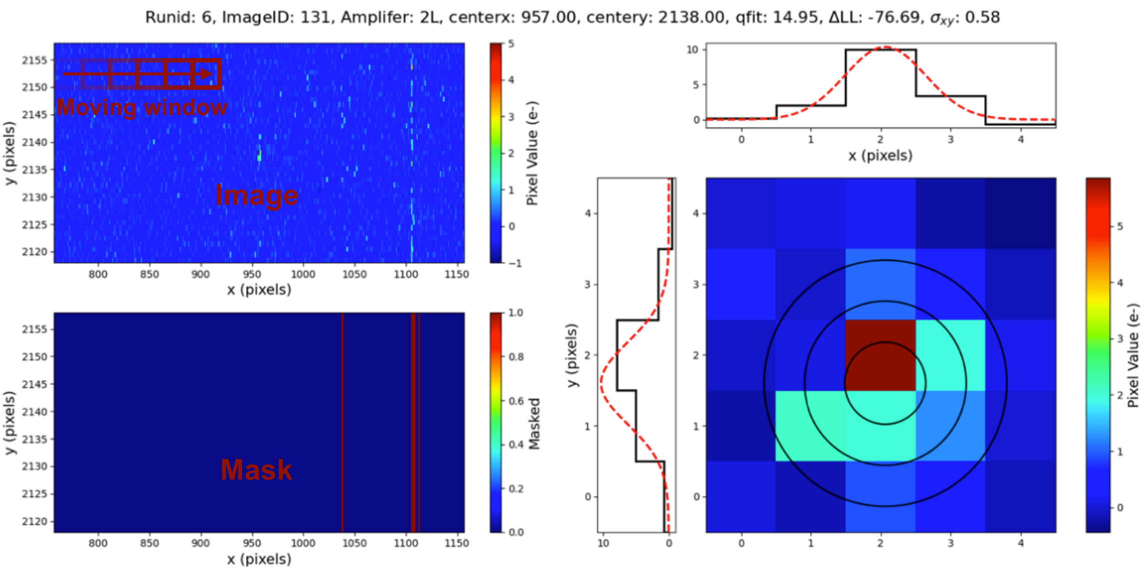

Figure 1: Left: DAMIC at SNOLAB science image with illustration of likelihood clustering pixel window (top) and pixel mask (bottom) devised to reject high charge leakage in the CCD (red pixels are masked). Clusters within windows containing masked pixels are ignored. Right: candidate low-energy ionization event within the clustering window. The event has 2D Gaussian topology as expected for ionization events. Run, image and amplifier IDs, as well as spatial metrics (window center coordinates centerx and centery, Gaussian fit standard deviation σ_{xy}), ΔLL value and total charge (qfit) of the cluster are reported in the header.

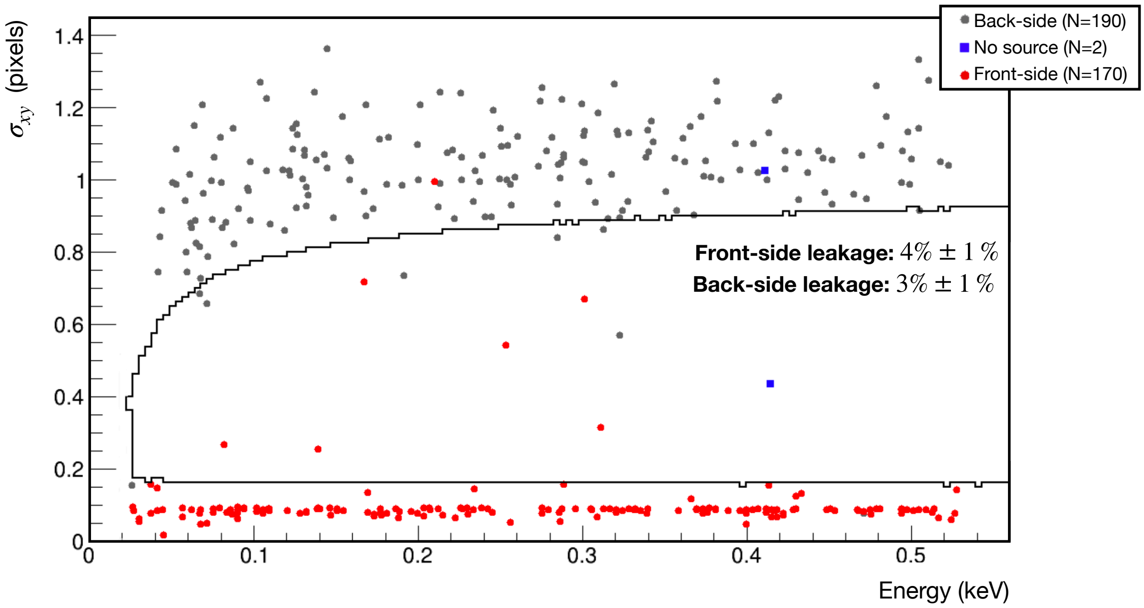

Figure 2: Distribution of ^{14}C calibration event clusters in energy vs. σ_{xy} space. Gray and red (blue) data points correspond to events occurring during exposure of the back- and front-side of the CCDs to the ^{14}C source (no-source), respectively. The black curve delimits the surface region (large and small σ_{xy} values) from the bulk fiducial region (intermediate σ_{xy} values). The no-source data was acquired to account for the contribution of no-source events to the front- and back-side datasets. The estimated front- and back-side leakage values are consistent with the projected 95.4% surface rejection efficiency.

To address the dominant systematic uncertainty of the previous analysis—the detector response to CCD surface events—we fiducialized the bulk of the CCDs leveraging the depth dependence of the lateral spread of pixel clusters (σ_{xy}) associated to ionization events. The charge diffusion across the bulk silicon of the CCD was calibrated on muon surface data.[1] Energy-lateral spread selections were subsequently designed to reject 95.4% (2σ) of events occurring in the front- and back-side surfaces of the CCD. The rejection efficiency of these selections was validated experimentally at the University of Washington, by exposing the front and back sides of a 24-Mpixel skipper CCD to a ^{14}C beta source (Q_β = 156.5 keV, $\bar{E}_\beta$ = 49.5 keV). Figure 2 summarizes this validation study. The functional form of our diffusion model was previously validated for bulk events in the CCD by means of low-energy (<24 keV) neutrons and γ rays [4].

To confirm that the previously constructed background model [1] retained its validity, we analyzed the measured ionization spectrum between 0.5 keV$_{ee}$ and 20 keV$_{ee}$. The total (bulk) background rate in the 1–6 keV$_{ee}$ energy range of 9.7 ± 0.8 (4.4 ± 0.6) keV^{-1} kg^{-1} day^{-1} was found to be comparable to the previous installation. A detailed spectral analysis revealed the anticipated cosmogenic tritium spectrum within the CCDs bulk (Q_β = 18.592 keV), accompanied by a steady contribution from Compton scattering of external γ rays. These contributions are expected to dominate at lower energies. We thus assumed a flat background model below 0.5 keV$_{ee}$. This is a conservative assumption, given the non-increasing nature of the tritium and Compton [5] spectra

[1]Cosmic muons cross CCDs from top to bottom and thus provide complete depth information on charge diffusion in the CCD.

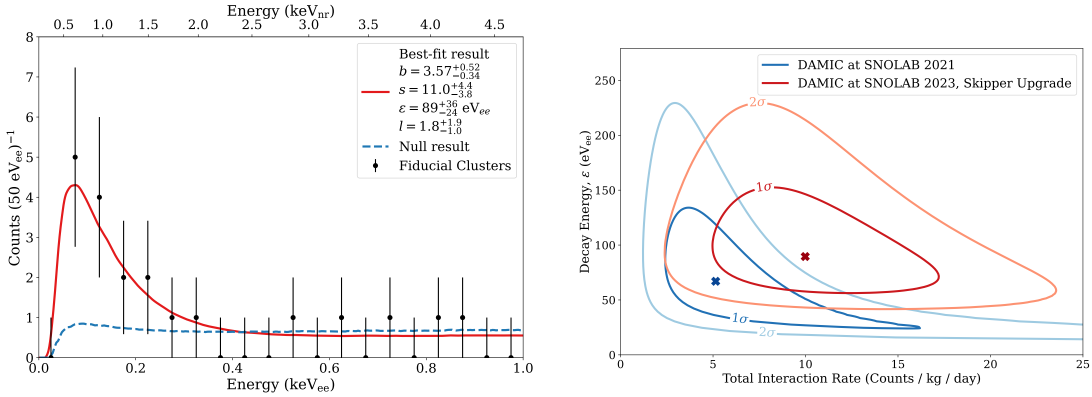

Figure 3: Left: result of the fit to fiducial clusters with the exponential excess plus flat background (red) and the background-only (blue dashed) hypotheses. The fit prefers a low-energy exponential component. Counts in the legend are reported for $E < 0.5$ keV. The upper horizontal axis reports the nuclear recoil energy scale from [6]. Right: comparison of the allowed parameter space of the bulk excess measured in this work and the previous 11 kg-day analysis [1].

below 0.5 keV$_{ee}$. We find it leads to a (up to) 25% decrease of the background rate below 0.2 keV$_{ee}$ and would thus enhance any excess of events above the background model.

We performed an extended unbinned likelihood fit to the energy spectrum of fiducial events with a flat background component and an exponentially decaying spectrum, which suitably parametrized the observed excess in the previous analysis. The fit takes into account the leakage of surface events expected into the fiducial region. The leakage was constrained to the expected value within uncertainty using a smooth, asymmetric penalty, and assumed to contribute to the flat and exponential components in the same proportions as the spectrum of fiducial events below 0.5 keV. The free parameters in the fit are the integrated counts in the background (b), leakage (l) and excess (s) spectra, and the decay energy (ε) of the exponential. Spectra were corrected for the bulk event efficiency and the fit was performed between 0 and 6 keV$_{ee}$. Below 0.5 keV, the fit finds $s = 11.0^{+4.4}_{-3.8}$ excess events with $\varepsilon = 89^{+36}_{-24}$ eV$_{ee}$, and $b = 3.57^{+0.52}_{-0.34}$ background events. A likelihood-ratio test between the null hypothesis ($s = 0$, b and l free) and the best-fit results in a p-value of 7.73×10^{-4}. Left-hand side figure 3 shows best-fit and null results for fiducial clusters below 1 keV$_{ee}$. The new excess population was found to be statistically compatible with DAMIC at SNOLAB previous finding [1]. This is shown in right-hand side figure 3. Combining the two results leads to a characteristic rate of ~7 events per kg-day and electron-equivalent energies of ~80 eV. As an additional check, we performed a 2D fit in the (E, σ_{xy}) parameter space, with different depth regions of the CCD (bulk, front and back) as different fit components, each modeled as a flat background plus a decaying exponential in energy. The σ_{xy} distribution of events was found to be consistent with the three distinct populations from bulk, front and back surfaces (p-value = 0.73), which further disfavors a surface leakage interpretation as the source of the excess population. Figure 4 reports the σ_{xy} projection of the data along with the fit result, the overall spectrum is broken down into front, back and bulk depth components.

This result confirms with high significance (>3σ) the presence of an excess population of low-energy events above our background model [2]. The observed excess ionization events likely

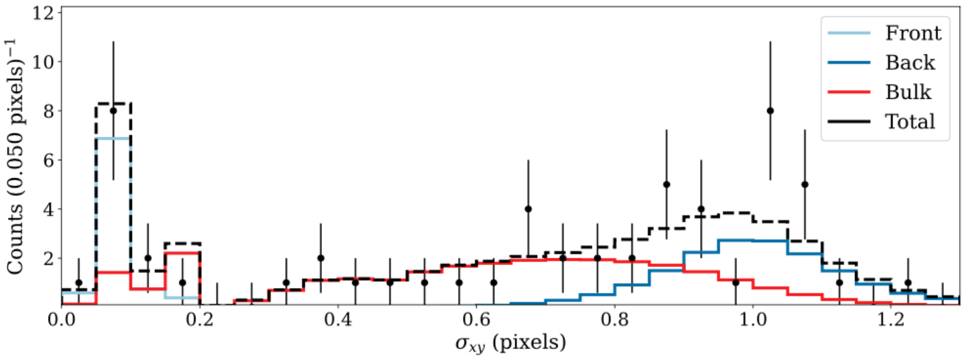

Figure 4: Energy-lateral spread fit projection in σ_{xy}, for E < 400 eV$_{ee}$. The overall spectrum (dashed black) is broken down into three depth components (front, back and bulk). The distribution of events is consistent with three distinct populations from CCD bulk, front and back surfaces.

arise from a source of radiation in the DAMIC detector or from the environment, which is common to the two experiments. As such, this excess is distinct from the excess of phonon signals reported in cryogenic calorimeters, which likely stems from stress release in the crystal [7]. The only established physical process that could give rise to the observed excess spectrum are neutron interactions with silicon nuclei in the bulk of the CCDs. Scattering from neutrons with energies up to 17 keV and a flux of ~0.2 cm^{-2} day^{-1} could produce the observed excess spectrum. No such source of neutrons has been identified. The bulk excess spectrum is well described by nuclear recoils from interactions of weakly interacting massive particles (WIMPs). For spin-independent WIMP-nucleus coherent elastic scattering with standard galactic halo parameters, the corresponding WIMP would have mass ~2.5 GeV/c^2 and WIMP-nucleon scattering cross section ~3×10^{-40} cm^2. This interpretation is excluded by results from DarkSide-50 [8] and CDMSlite [9]. Attempts to find an alternative interpretation, consistent with null results from these experiments are explored in [10].

The DAMIC-M detector [11], a 0.7 kg skipper-CCD array with a radioactive background rate of $\mathcal{O}(0.1)$ dru, will start operations at the Modane underground laboratory (LSM) in late 2024. If the bulk excess is detected in DAMIC-M, a high-statistics, high-resolution spectral measurement, time evolution studies of the excess, and investigations of its dependence on detector configuration and operating parameters will be possible to better understand its origin.

References

[1] *Results on Low-Mass Weakly Interacting Massive Particles from an 11 kg-day Target Exposure of DAMIC at SNOLAB*, A. Aguilar-Arevalo et al. (DAMIC Collaboration), Phys. Rev. Lett. 125, 241803 (2020), arXiv:2007.15622 [astro-ph.CO]. *Characterization of the background spectrum in DAMIC at SNOLAB*, A. Aguilar-Arevalo et al. (DAMIC Collaboration), Phys. Rev. D 105, 062003 (2022), arXiv:2110.13133 [hep-ex]. *Results on Low-Mass Weakly Interacting Massive Particles from an 11 kg-day Target Exposure of DAMIC at SNOLAB*, M. Traina et al. (DAMIC Collaboration), PoS ICRC2021, 539 (2021), arXiv:2108.05983 [astro-ph.CO].

[2] *Confirmation of the spectral excess in DAMIC at SNOLAB with skipper CCDs*, A. Aguilar-

Arevalo et al. (DAMIC, DAMIC-M, SENSEI Collaborations), (2023), arXiv:2306.01717 [astro-ph.CO].

[3] *Search for low-mass WIMPs in a 0.6 kg day exposure of the DAMIC experiment at SNOLAB*, A. Aguilar-Arevalo et al. (DAMIC Collaboration), Phys. Rev. D 94, 082006 (2016), arXiv:1607.07410 [astro-ph.CO].

[4] *Dark Matter Search Results from DAMIC*, A. E. Chavarria (DAMIC Collaboration), J. Phys. Conf. Ser. 1468, 012024 (2020). *Measurement of low energy ionization signals from Compton scattering in a CCD dark matter detector*, K. Ramanathan et al., Phys. Rev. D 96, 042002 (2017), arXiv:1706.06053 [physics.ins-det].

[5] *Precision measurement of Compton scattering in silicon with a skipper CCD for dark matter detection*, D. Norcini et al. (DAMIC-M Collaboration), Phys. Rev. D 106, 092001 (2022), arXiv:2207.00809 [physics.ins-det].

[6] *Ionization efficiency for nuclear recoils in silicon from about 50 eV to 3 MeV*, Y. Sarkis, A. Aguilar-Arevalo, and J. C. D'Olivo, Phys. Rev. A 107, 062811 (2023).

[7] *A Stress Induced Source of Phonon Bursts and Quasiparticle Poisoning*, R. Anthony-Petersen et al., (2022), arXiv:2208.02790 [physics.ins-det].

[8] *Search for low-mass dark matter WIMPs with 12 ton-day exposure of DarkSide-50*, P. Agnes et al. (DarkSide-50 Collaboration), Phys. Rev. D 107, 063001 (2023), arXiv:2207.11966 [hep-ex].

[9] *Search for Low-Mass Dark Matter with CDMSlite Using a Profile Likelihood Fit*, R. Agnese et al. (SuperCDMS Collaboration), Phys. Rev. D 99, 062001 (2019), arXiv:1808.09098 [astro-ph.CO].

[10] *The DAMIC excess from WIMP-nucleus elastic scattering*, A.E. Chavarria et al., (2023), arXiv:2308.12176 [astro-ph.CO].

[11] *The DAMIC-M Experiment: Status and First Results*, I. J. Arnquist et al. (DAMIC-M Collaboration), SciPost Phys. Proc. 12, 014 (2023), arXiv:2210.12070 [hep-ex].

PoS(TAUP2023)059