First data from the full CCD array of DAMIC at SNOLAB

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(Photo image: particle tracks in a DAMIC CCD)
DAMIC @ SNOLAB

675 μm thick, 16 Mpix CCD, 6 g

Copper module
Kapton signal cable

Lead block
Kapton signal cable

Cu box with CCDs

Cu vacuum vessel

VIB

Lead

Poly-ethylene

6 cm
exquisite spatial resolution

50 pixels = 7.50 µm

Energy / eV

5 10 15 20 25 30

σ = 5.9 eV
= 1.6 e⁻

pixel charge distribution

σxy ≈ Z : fiducial volume definition

particle identification and background characterization

extremely low noise and dark current

lowest dark current ever measured in a silicon detector:
5x10⁻²² A/cm² (at 140 K)

(improved wrt R&D phase where σ = 2 e⁻ and current = 10⁻²¹ A/cm² at 100 K)
Selected results

WIMP DM

Hidden photon DM

radioactive bkg in the silicon bulk
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nuclear recoil calibration

electron recoil calibration

Calibration down to 60 eVee.

Numerical results
Current status

- Seven CCDs in stable data taking; 40 g detector
  One CCD sandwiched in ancient lead
- A data set (7.6 kg day) collected with full spatial resolution (1x1 binning), optimized for background characterization and measurement ($^{32}$Si, $^{210}$Pb)
- A second data set being collected (so far 4.7 kg day) with best energy threshold (1x100 binning)

Binning: charge of several pixels are added before readout

Some loss of spatial resolution but improved signal to noise (same readout noise but more charge in a binned pixel)
Event selection

- A search window is moved across the CCD array
- A ML fit is performed to a gaussian signal plus noise hypothesis: fit provides event position, energy, spatial $\sigma$ and $L_s$ value
- A ML fit is performed to only noise hypothesis, fit provides $L_N$
- The likelihood difference is calculated, $\Delta LL = L_N - L_s$, which is used to select candidate events

$E = 10$ keV \hspace{1cm} $\sigma = 1.0$ pix

$\Delta LL = -184000$
• $\Delta LL < -25$ required (from distribution of “blanks”, images with zero exposure which only have noise)

• Rejection of surface events by requirements on spatial $\sigma$

surface background

fiducial region for bulk events

$0.3 < \sigma < 0.8$

surface background

Cu fluorescence and Pb x rays visible
• Backgrounds: on front and back surfaces of CCDs, in the bulk

• Data compared with background model 50/25/25 bulk/front/back (estimated from high energy data)

• Acceptance for energy deposit in the bulk estimated from MC simulations; threshold at 50 eV$_{ee}$
Energy spectrum above 2 keV

≈ 5 dru in fiducial region, consistent between CCDs

a factor of ≈ 3-4 lower than our previous background level

≈ 2 dru for lead sandwiched CCD
Low energy data

- We are analyzing the data from 50 eV to 2 keV, which provide most sensitivity to low mass WIMPs. Some examples of candidates.

- **NOTE**: CDMS II silicon potential signal obtained with a 7 keV$_{nr}$ threshold ($\approx 2$ keV$_{ee}$)

  We are exploring for the first time the silicon target with a much lower threshold of 0.6 keV$_{nr}$ ($\approx 0.05$ keV$_{ee}$)

  Our results will be relevant for SuperCDMS Si and DAMIC-1K
On-going background measurements

- **Cosmogenic $^{32}$Si**

Search for spatially correlated beta decays. Sensitivity with current data is few Bq/kg

\[
^{32}\text{Si} \ (T_{1/2}=150 \text{ y, } \beta) \rightarrow ^{32}\text{P} \ (T_{1/2}=14 \text{ days, } \beta)
\]

\[
E_1 = 51.0 \text{ keV}
\]

\[
\Delta t = 29.1 \text{ days}
\]

Candidate $^{32}$Si - $^{32}$P in the new data set

- **Bulk and surface radiogenic backgrounds**

\[
^{210}\text{Pb} \ (T_{1/2}=22.3 \text{ y, } \beta) \rightarrow ^{210}\text{Bi} \ (T_{1/2}=5.0 \text{ days, } \beta) \rightarrow ^{210}\text{Po} \ (T_{1/2}=138 \text{ days, } \alpha)
\]

- **Cosmogenic tritium sensitivity**

Sensitivity to activation rate down to few tens of tritium atoms/kg/day
DAMIC-1K at the LSM

- Proposals submitted for a kg-size detector at the Laboratoire Souterrain de Modane
- CCDs with skipper readout for sub-electron noise

- Large size Skipper CCDs (6k x 4k) for DAMIC-1K development will arrive at UW in May/June 2018.

SENSEI R&D at Fermilab

\[ \sigma = 0.06 \text{ e}^- \]

University of Chicago, University of Washington, Pacific Northwest National Laboratory, SNOLAB, Laboratoire de Physique Nucléaire et de Hautes Energies (LPNHE), the Laboratoire de l'Accélérateur Linéaire (LAL) and the Laboratoire Souterrain de Modane/Grenoble (LSM), University of Zurich, Niels Bohr Institute, the University of Southern Denmark, University of Santander, Universidad Federal do Rio de Janeiro, Centro Atomico Bariloche
DAMIC-1K sensitivity

WIMP DM

DM-electron scattering via ultra-light hidden photon

DS-50 (yesterday)
Outlook

• DAMIC is collecting high quality data - few dru background and 50 eV threshold - with a 40 g CCD detector at SNOLAB. We will reach $\approx 15$ kg day in 2018.

• These data will provide essential information for the next generation of silicon detectors (DAMIC-1K, SuperCDMS):
  - explore spectrum below 2 keV$_{ee}$ in silicon
  - measure cosmogenic and radiogenic backgrounds in silicon
  - measure CCD dark current at the lowest temperatures

• Next stage is a kg-size DAMIC detector to be installed at the LSM in France. Large-size skipper CCDs will be characterized this year. We will continue to profit from the current setup at SNOLAB in this development stage
Backup
CCD principle

Metal-Oxide-Semiconductor capacitor

Metal gate
Si oxide (insulator)
n-type Si (buried channel)

p-type Si

electron-hole pairs generated by a photon or ionizing particle

Moving charge from pixel to pixel

φ1
φ2
φ3

Charge motion
“vertical clocks”

Output amplifier

“horizontal clocks” (faster)

Charge motion

readout time

Correlated Double Sampling

pixel i-2 pixel i-1 pixel i pixel i+1

sig

ref,
DAMIC-1K features

- A kg-size DAMIC built with the existing technology

Silicon wafer

- Background
  - from a few dru to a fraction of dru.
  - 
    - external bkg.: improved design, materials (e.g. electroformed copper), strict procedures (silicon storage underground, radon, surface contamination)
    - internal bkg.: cosmogenic $^{32}$Si and tritium

Dalisa has confirmed the feasibility to fabricate these larger and thicker CCDs

6k x 6k pixels, 1 mm thick
≈ 20 g / CCD
≈ 50 CCDs / 1 Kg

E-formed copper vessel at PNNL
DAMIC-1K sub-e⁻ noise

- Skipper readout

a novel charge readout approach which results in *single electron resolution*

Non-destructive measurement of the charge!

Measure the charge fast (kill $1/f$ noise) and $N$ times (noise $\approx 1/\sqrt{N}$)