Dark Matter In CCDs (DAMIC)

Radomir Smida
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Silicon (A=28), the average electron-hole ionization energy 3.77 eV

Suitable for scattering of low mass DM particles (nuclear or electron recoil) or absorption of hidden photons

Nuclear recoil energy of 1 GeV DM on Si nucleus equals to \(\approx 20 \text{ eV} (= 5 \text{ e}^-)\)
Charge-coupled device (CCD)

Advantage of using CCDs:
- Developed in 1969, significant improvements since then
- Commercial product (fabrication chain)
- Microelectronics (clean environment)
- Mega-pixel size (spatial resolution)

But, the absorption length of visible light <10 µm in silicon

Astronomical telescopes requirements:
- >100 Mpx in total (sky area)
- Near-infrared sensitivity (cosmology)
  => thicker CCDs >100 µm
- Low noise (SNR increase)
CCDs developed at LBNL

- High-resistivity (>10k Ωcm) n-type Si
- 675 μm thick, fully depleted
- Leakage current ≈ 5x10^{-4} e/px/day (=5x10^{-22} A/cm^2) at 140 K
- Low noise 2 e- RMS
- Charge transfer inefficiency ≈ 10^{-6}
- Pixel pitch 15 μm (spatial resolution)

Dark Energy Survey

4k x 2k
(6 cm x 3 cm)

unthinned 675 μm
2.33 g/cm^3

Target for DM particles

or ionization

coherent elastic scattering

arXiv:1506.02562

Holland+, IEEE-56 (2009)

thinned to 250 μm
Particle tracks – exposure on the ground

Exposure 1 s
readout ca. 840 s

\(^{55}\text{Fe}\) calibration run

1/2 of 8 M image
Particle tracks – exposure on the ground

- Electrons
- Muon
- δ electron
- X rays 5.9 keV

Diffusion → depth

Particles identification

X-ray? n, WIMP?

Diffusion limited

Front

μ

Back

α

e

50 pixels

Energy measured by pixel / keV

5 10 15 20 25 30

arXiv:1506.02562

Pixels 4σ above noise → Energy in eVee

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CCD – energy resolution and linearity

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The setup for Compton-scattering measurement of $^{57}$Co 122 keV γs

Stainless steel vacuum chamber

$\sigma_E^2 = (12 \text{ eV})^2 + (3.8 \text{ eV})FE$, where $F = 0.13$

55 eV / 6400 eV = 0.9%

Using optical photons and X rays

Linear within 5% down to 40 eV$_{ee}$ (10 e$^{-}$)

arXiv:1607.07410

arXiv:1706.06053

$57$Co $4 \times 4$ Data

- Gaussians + Offset

$\text{Cr K}_\alpha$ $\text{Mn K}_\alpha$ $\text{Fe K}_\alpha$ $\text{Fe K}_\beta$ $\text{Ni K}_\alpha$ $\text{Cu K}_\alpha$

Num. of events [(10 eV)$^{-1}$]

E [keV]

Fano Best Fit $\Rightarrow F = 0.128(2)$

σ [eV]

arXiv:1706.06053
CCD – nuclear recoil and ionization energy conversion

CCD measures ionization energy

\[ E_e [\text{keV}_{ee}] \]

\[ 1 \]

\[ 10^{-1} \]

\[ E_r [\text{keV}_{nr}] \]

\[ 1 \]

\[ 3 \]

124Sb-9Be (neutrons of 24 keV)

Dougherty (1992)

Gerbier et al. (1990)

Zecher et al. (1990)

Lindhard, k=0.15

Consequence to Si detectors

arXiv:1608.00957

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6010 m w.e. with <0.3 muons/m²/day

DAQ since the middle 2017

7 CCDs (4k x 4k pixels, 5.6 g) or 112 Mpx DM telescope

Total target mass of 40 g

2 e⁻ RMS pixel noise (i.e. ≈7.5 eV uncertainty in deposited energy)

Background 5 dru (events/keV/kg/day)
DAMIC@SNOLAB – Shielding

- Lead shielding
- Lead bricks
  - 2.5 cm ancient (inner)
  - 18.5 cm modern (outer)
- Copper box
- Vacuum vessel
- Electronics
- 42 cm polyethylene
CCD exposure at SNOLAB (6010 m w.e.)

Exposure 30k s (8.3 h)

4k x 4k pixels
Background $\beta$ decay
(We use it to investigate the contamination level)
**32Si decays in the bulk**

**Origin**: Spallation of $^{40}$Ar by cosmic ray protons $\rightarrow$ fall down from the atmosphere due to precipitation $\rightarrow$ accumulate in sand, half-life **150 y**

**Double $\beta$ decay**

$^{32}$Si $\rightarrow^{32}$P + $\beta^-$ with $\tau_{1/2} = 150\text{ y}$, $Q -$ value $= 227\text{ keV}$

$^{32}$P $\rightarrow^{32}$S + $\beta^-$ with $\tau_{1/2} = 14\text{ d}$, $Q -$ value $= 1.71\text{ MeV}$

**Spatial coincidence of two events with $E_1 < 230\text{ keV}$ and $E_2 < 1.8\text{ MeV}$ within $\Delta t < 5\tau_{1/2} = 70\text{ d}$**

$E_1 = 114.5\text{ keV}$

$(x_o, y_o)$

$\Delta t = 35\text{ days}$

$E_2 = 328.0\text{ keV}$

arXiv:1506.02562
Bulk and surface decay rates

<table>
<thead>
<tr>
<th>Analysis method</th>
<th>Isotope(s)</th>
<th>Tracer for</th>
<th>Bulk rate $\text{kg}^{-1} \text{d}^{-1}$</th>
<th>Surface rate $\text{cm}^{-2} \text{d}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$ spectroscopy</td>
<td>$^{210}\text{Po}$ \ $^{234}\text{U} + ^{230}\text{Th} + ^{226}\text{Ra}$ \ $^{224}\text{Ra} – ^{220}\text{Ra} – ^{216}\text{Po}$</td>
<td>$^{210}\text{Pb}$ \ $^{238}\text{U}$ \ $^{232}\text{Th}$</td>
<td>&lt;37 \ &lt;5 (4 ppt) \ &lt;15 (43 ppt)</td>
<td>0.011±0.004, 0.078±0.010</td>
</tr>
<tr>
<td>$\beta$ spatial coincidence</td>
<td>$^{32}\text{Si} – ^{32}\text{P}$ \ $^{210}\text{Pb} – ^{210}\text{Bi}$</td>
<td>$^{32}\text{Si}$ \ $^{210}\text{Pb}$</td>
<td>11.5±2.4 (Preliminary)</td>
<td>–</td>
</tr>
</tbody>
</table>

$^{238}\text{U}$ and $^{232}\text{Th}$ decay chains in the bulk and on surfaces:

- Ongoing analysis of measured data
- Decay rates are used in our background model
- The coincidences allow to veto these backgrounds
- Guidance how to minimize backgrounds

LBNL simulations
Liquid crystal displays with touch screen technology

- Capacitive touch sensors
- Resistive touch sensors
- Surface acoustic wave (SAW) touch sensors
Low mass DM and hidden photons

Dark matter particle, particularly low mass DM

Hidden photon (absorption by a valence $e^-$ leads to ionization)

Finishing analysis of the data:
- Exposure $>10$ kg day
- Updated reconstruction and quality cuts
- Comprehensive background model
- Geant4 simulations (radioactive and dark current backgrounds, detailed CCDs structure, inputs from various assays, etc.)

@ summer conferences

WORK IN PROGRESS
COMING SOON!
At the Modane underground laboratory (LSM) in France (4800 m w.e., 4 muons/m²/day, radon ≈15 Bq/m³)

- 50 CCDs (1 kg year exposure)
- Most massive CCDs ever built (36 M pixels, mass 20 g)
- Sub-electron resolution (a skipper technique)
- Negligible dark current
- Background reduction to ≈0.1 dru (events/keV/kg/day)
- Funded by ERC and NSF (2018 – 2023)

Institutions:
The University of Chicago, University of Washington, Pacific Northwest National Laboratory (PNNL), SNOLAB, Laboratoire de Physique Nucleaire et des Hautes Energies (LPNHE), Laboratoire Souterrain de Modane (LSM), Laboratoire de l’Accélérateur Linéaire (LAL), CENBG Bordeaux, SUBATECH Nantes, University of Zurich, Niels Bohr Institute, University of Southern Denmark (SDU), Instituto de Física de Cantabria, Universidade Federal do Rio de Janeiro, Centro Atómico Bariloche

DAMIC at Modane (DAMIC-M)
Cosmogenic activation of tritium in silicon

Production rate ca. $100\ 3^\text{H}/\text{kg/d}$

Three CCDs irradiated by a neutron beam at LANSCE (similar to the CR flux)

Talk by R. Saldanha on Monday

Exposure to cosmic rays

Exposure <2 months (shielding, no flights)

Annealing wafers?
Other background mitigation efforts

Electroformed copper

For Majorana @ SURF

- Inner parts of the detector
- Clean (U/Th chain)
- Low cosmogenic activation (Co, Mn)
  Grown underground at PNNL

Dedicated assaying of materials

Clean materials and surface cleaning

Assembling in a clean room underground at LSM

Limited exposure to air (radon & dust)

e tc.

Goal: to \( \approx 0.1 \text{ dru} \) (events/keV/kg/day)
Conclusions

- CCD highly advanced technology
  - Spatial and depth determination
  - Energy resolution and linearity
  - Low energy threshold
  - Particle identification
  - Veto of radioactive decays

- Suitable target for low mass DM and dark photons

- Finishing analysis of DAMIC@SNOLAB data (to be presented at summer conferences)

- DAMIC-M goals
  - Detector at the Modane Underground Laboratory
  - 1 kg year exposure
  - Background ≈0.1 dru (events/keV/kg/day)
  - Single e- counting (sub-eV readout noise)
  - Commissioning in the middle 2023

http://damic.uchicago.edu/