Performance of the prototype DEPFET-RNDR device for direct dark matter detection in DANAE

Hexi Shi
HEPHY ÖAW
Preparation

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DANAE (DANAË)
Direct dArk matter search using DEPFET with repetitive-Non-destructive-readout Application Experiment
OeAW funding for innovation in detector technology

Collaboration

“Danae” by G. Klimt
Over 80% of the mass in the universe is invisible dark matter

“WIMP” as a dark matter candidate:
- weakly interacting with matter
  \[<\sigma_{\text{WIMP}} \cdot v> \sim G_F^2 \cdot m_X^2 \sim 1/\Omega_X\]
- fits the Hubble constant and “relic” density of dark matter

predicts dark matter WIMP mass between 2 GeV and 120 TeV

WIMPs dominated the direct detection experiments until recently
WIMP direct detection method

look for nuclear recoils from WIMP-nucleus scattering

Energy deposit in target material in forms of:
- light
- phonon
- electric charge

Detection limitation:
energy deposit from nucleus recoil
\[ E_{NR} \sim 2\mu x, N^2 \cdot v_x / m_N \]

\[-\text{ for } 100 \text{ MeV } m_x, E_{NR} \sim 1 \text{ eV } * \]

plus quenching factors and noise level of the detectors

typical DM velocity \( v_x \lesssim 800 \text{ km/s} \)
*for silicon
DM-nucleus scattering direct search status

Figure 6. Parameter space for elastic spin-independent dark matter-nucleon scattering. The first result from CRESST-III Phase 1 (solid red) is compared with the limit from CRESST-II Phase 2 (dashed red) [3]. For comparison, exclusion limits (90% C.L.) of other dark matter experiments are shown [11, 12, 13, 14, 15, 16, 17, 18, 19, 20]. The favoured parameter space reported by CDMS-Si [21] and CoGeNT [22] are drawn as shaded regions.

4. Conclusion and outlook

The first results on low-mass dark matter obtained with the Phase 1 of CRESST-III confirm that a low energy threshold represents a crucial requirement for direct dark matter searches aiming to achieve sensitivity to dark matter particles with masses in the 1 GeV/c^2 range and below.

With only 2.39 kg days of raw data taken with Det-A and with an analysis threshold conservatively set at 100 eV, the CRESST-III experiment improves the sensitivity of CRESST-II by one order of magnitude for a dark matter particle mass of 500 MeV/c^2 and further extends the reach of the experiment down to 350 MeV/c^2, reaffirming its leading sensitivity for light dark matter.

Despite the presence of background in the acceptance region, using the full exposure of the CRESST-III experiment and further extending the lower boundary of the search energy range down to the detector threshold, a significant progress is expected in the near future in the exploration of the low-mass regime.

References

DM-nucleus scattering direct search status

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References


no evidence for WIMP yet
DM-nucleus scattering direct search status

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References


Dark Sector and Light Dark Matter

$1 \text{ keV} \quad 1 \text{ MeV} \quad 1 \text{ GeV} \quad 1 \text{ TeV}$

**Dark sectors**

$(\text{DM} + \text{new mediators})$

**WIMPs**

several sharp “theory” targets

(freeze-out, asymmetric, freeze-in, SIMP, ELDER)

Dark sector:

interaction between DM and standard model particle mediated by a dark photon

(one example of mediators)

DM scattering

image credit R. Essig

Clear predictions from multiple models over wide DM mass region, including $\text{keV} \sim \text{GeV}$

$\rightarrow$ comparable observables in experiments
DM-electron scattering

**kinematically**

to overcome binding energy $\Delta E$

need $E_{DM} \sim \frac{1}{2} m_{DM} v_{DM}^2 > \Delta E$

$v_{DM} \lesssim 800 \text{ km/s} \implies m_{DM} \gtrsim 300 \text{ keV} \left( \frac{\Delta E}{1 \text{ eV}} \right)$

\[ O(100 \text{ keV}) \]
DM-electron scattering

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$v_{DM} \lesssim 800 \text{ km/s} \implies m_{DM} \gtrsim 300 \text{ keV} \left( \frac{\Delta E}{1 \text{ eV}} \right)$

O(100 keV)

bound e\(^{-}\) does not have definite momentum, typical momentum transfer is set by e\(^{-}\) not by DM.

$q_{typ} \sim \alpha m_e \sim 4 \text{ keV}$ (for outer shell electron)

transferred energy: $\Delta E_e \sim \vec{q} \cdot \vec{v}_{DM}$

$\Delta E_e \sim 4 \text{ eV}$

typical recoil energy

JHEP05(2016)046
## Target materials for electron recoils

<table>
<thead>
<tr>
<th>Target Type</th>
<th>Examples</th>
<th>$E_{th}$</th>
<th>$m_\chi$ threshold</th>
<th>Status</th>
<th>Timescale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noble liquids</td>
<td>Xe, Ar, He</td>
<td>$\sim 10$ eV</td>
<td>$\sim 5$ MeV</td>
<td>Done w data; improvements possible</td>
<td>existing</td>
</tr>
<tr>
<td>Semi-conductors</td>
<td>Ge, Si</td>
<td>$\sim 1$ eV</td>
<td>$\sim 200$ keV</td>
<td>($E_{th} \sim 40$ eV, $E_{th} &lt; 1$ eV) *SENSEI, DEPFET R&amp;D</td>
<td>$\sim 1$-2 years</td>
</tr>
<tr>
<td>Scintillators</td>
<td>GaAs, NaI, CsI, ...</td>
<td>$\sim 1$ eV</td>
<td>$\sim 200$ keV</td>
<td>R&amp;D required</td>
<td>$\leq 5$ years</td>
</tr>
<tr>
<td>Superfluid</td>
<td>He</td>
<td>$\sim 1$ eV</td>
<td>$\sim 1$ MeV</td>
<td>R&amp;D required unknown background</td>
<td>$\leq 5$ years</td>
</tr>
<tr>
<td>Super-conductor</td>
<td>Al</td>
<td>$\sim 1$ meV</td>
<td>$\sim 1$ keV</td>
<td>R&amp;D required unknown background</td>
<td>$\sim 10$ - $15$ years</td>
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*Talk of J. Tiffenberg*

arXiv:1608.08632
structure of a basic DEPFET cell:

structure of RNDR DEPFET “super-pixel”
DEPFET with RNDR

structure of RNDR DEPFET “super-pixel”

RNDR readout

read N times effective noise:  
\[ \sigma_{\text{eff}} = \sigma / (\sqrt{N}) \]

EPJ C, 77(12), 279 (2017)
DEPFET with RNDR

structure of RNDR DEPFET “super-pixel”

RNDR readout

read 1: noise $\sigma$

read N times effective noise $\sigma_{\text{eff}} = \sigma/(\sqrt{N})$
DEPFET with RNDR

structure of RNDR DEPFET “super-pixel”

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structure of RNDR DEPFET “super-pixel”

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read 1: noise $\sigma$

transfer gate

read 2: noise $\sigma$

read N times effective noise: $\sigma_{\text{eff}} = \sigma/\sqrt{N}$

EPJ C, 77(12), 279 (2017)
DEPFET with RNDR

structure of RNDR DEPFET “super-pixel”

RNDR readout

read 1: noise $\sigma$

transfer gate

read 2: noise $\sigma$

: repeat $N$ times independent measurements

clear charges

read $N$ times effective noise: $\sigma_{\text{eff}} = \sigma/(\sqrt{N})$

EPJ C, 77(12), 279 (2017)
DEPFET RNDR single pixel performance

confirmed the $1/\sqrt{N}$ decrease of $\sigma_{\text{eff}}$

minimal noise level limited by leakage current at 230 K (-40 °C)

![Graph showing the dependency of equivalent noise on number of readout cycles](image-url)
confirmed the $\frac{1}{\sqrt{N}}$ decrease of $\sigma_{\text{eff}}$

minimal noise level limited by leakage current at 230 K (-40 °C)

estimated temperature dependence (only DC from thermal excitation) to be testified in measurement
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minimal noise level limited by leakage current at 230 K (-40 °C)

estimated temperature dependence (only DC from thermal excitation) to be testified in measurement

deeply doped regions on the dead material. The amount of dead material at sensor detector and therefore the exposure. The exposure quoted in the dead material.

new architecture with “blind-gate”

possibility of reducing leakage current during readout
3.3 Planned improvements for future devices

In addition to the leakage current, a more serious perturbation of the RNDR process arises from the DEPFET’s permanent sensitivity. In case signal charge arrives during the RNDR cycle, the signal charge is altered and the resulting mean value of the measurements does not represent the original signal charge. This is mainly a problem for applications were the incoming radiation is not synchronized with the readout cycle and for the background events for applications where it is. Although running average techniques can be applied during the RNDR process to detect the occurrence of these so-called misfit events, it is better to reduce their overall influence or even to completely avoid it. In this respect, two different approaches have been pursued to optimize RNDR-based detectors for future applications:

- A substantial reduction of the initial noise figure $\sigma$ for a single reading decreases not only $\sigma_{opt}$ (see Eq. 5), but also $\sigma_{eff}$.
DEPFET-RNDR in DANAЕ
Schematics of the DEPFET-RNDR assembly

DEPFET assembly on ceramics

Pitch adaptors

DEPFET-RNDR 64 pixel x 64 pixel matrix

N

W

S

E

DEPFET source 64 ch in one row

Flex PCB ~ 70 mm in length

To DEPFET control gates at N, W, E

Drain, substrates, guard ring

DEPFET Back HV

VERITAS

Preamplifier

Sample & Hold Filter

Static settings RAM

Sequence RAM

OUT (multiplexed)

CLK

Switcher-S (N, W, E)

static settings RAM

Power for DEPFET control gates

Load

Static settings RAM

SPECTRUM 59xx

ADC

TRG

CLK

AI-Ch0+

DI_X1

DI_X2

Ethernet card

Sequencer

Static RAM settings for ASICs

Sequencer core RAM

SEQUENCE RAM

Static RAM

Sequencer core program

FPGA

CLK 50 MHz

Ethernet

USB

DAQ PC

Power supply lines

Signal / data communication

Runtime control / logic

PCIE interface

TRG

DI_X1 DI_X2 CLK AI-CN0+

Ethernet

LEMO

Preamp

Sample & Hold

Filter

To DEPFET control gates at N, W, E

DC power supply crate

R&S HMC 8043 30 channels

TTi HV

DANAE EPP

DANAE ROB
Schematics of the DEPFET-RNDR PCBs

DEPFET assembly on ceramics

DEPFET-RNDR 64 pixel x 64 pixel matrix

DEPFET source 64 ch in one row

Flex PCB ~ 70 mm in length

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Switcher-S (N, W, E)

Power for DEPFET control gates

static settings RAM

CLK

LOAD

To DEPFET control gates at N, W, E

Drain, substrates, guard ring

DEPFET Back HV

DEPFET source 64 ch in one row

Vacuum part

Cold part

DANAE ROB

DANAE EPP

Runtime control / logic

Power supply lines

Signal / data communication

16
Sensor assembly

Cold part

DEPFET assembly on ceramics

DEPFET Back HV

Pitch adaptors

DEPFET-RNDR 64 pixel x 64 pixel matrix

N

W

E

S

DEPFET source 64 ch in one row

To DEPFET control gates at N, W, E

Drain, substrates, guard ring

Flex PCB ~ 70 mm in length
DEPFET prototype detector

cold part

- ceramics
- flexible PCB

proto-type:
- $75 \text{ um} \times 75 \text{ um} \times 450 \text{ um}$ single pixel,
- $64 \times 64$ pixel matrix
- sensitive volume $0.024 \text{ g}$
Front-end ASICs on ROB
Front-end ASICs and functions

VERITAS processes **64 DEPFET pixels simultaneously**

source-follower readout, shaping amp

**Switcher-S** 64x2 channel analog multiplexer

<table>
<thead>
<tr>
<th>switcher id</th>
<th>W</th>
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DEPFET
Ceramic
Pitch adaptors

South
clear rows
source columns
substrate guard
Gate common
clear & transfer gate
Gate 1 & 2

MOS
Source follower readout, shaping amp

VERITAS
64 DEPFET pixels simultaneously
source-follower readout, shaping amp

Switcher-S 64x2 channel analog multiplexer
Front-end ASICs and functions

VERITAS processes 64 DEPFET pixels simultaneously
source-follower readout, shaping ampl

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RNDR matrix
operation sequence
Matrix operation sequence

Initial situation

active row of Switcher-S

full matrix constantly sensitive when bias voltage applied

figure credit J. Treis
Matrix operation sequence

Initial transfer I

Initial transfer II

Initial transfer III

Initial transfer IV
Matrix operation sequence

Signal readout A

Veritas
Matrix operation sequence

Baseline readout A

CDS readout A: signal - baseline

Veritas

MUX out of the VERITAS p1 p2 p3 p4
Matrix operation sequence

Gate B

Gate A

Signal readout B

Veritas

Transferagate
Matrix operation sequence

Signal transfer B I

Signal transfer B II

Signal transfer B III
Matrix operation sequence

Baseline readout B

CDS readout B: signal - baseline

Veritas

one RNDR cycle

repeat N times then go to the next row
Matrix operation sequence

Initial situation

next row:
all switchers
shift by one
DEPFET-RNDR control and interface

DC power supplies
Matrix operation sequence

one RNDR cycle of a row → \( N = 5 \)

simulated FPGA output for matrix control
Matrix operation sequence

one RNDR cycle of a row  \( \text{N} = 5 \)

Simulated FPGA output for matrix control

100 \( \mu \text{s} \)

MUX out of VERITAS one row

10 \( \mu \text{s} \)

Oscilloscope waveform

Next page
Sequence of one row
Data acquisition and synchronization

DAQ PC:

Sequencer core program

Sequencer scripts
Static RAM settings for ASICs

Ethernet card

PCIE interface

ADC

TRG DI_X1 DI_X2 CLK AI-Ch0+

Ethernet
USB
LEMO

CLK 50 MHz

FPGA

Sequencer

Trigger (TRG)
Frame key
Line key

Sequencer core RAM

DEPFET-RNDR 64 pixel x 64 pixel matrix

Pitch adaptors
N E S W

USB
LEMO

Preamp
Sample & Hold
Filter

Ethernet

To DEPFET control gates at N, W, E

DEPFET source
64 ch in one row

DEPFET Back HV

Drain, substrates, guard ring

Power for DEPFET control gates

ASIC CLK

TTi HV

....

runtime control / logic

Power supply lines

LOAD

Signal / data communication

PCIE interface

Data acquisition and synchronization

...
Setup at HLL

Feedthrough rotary for calib source holder
DANAE
EPP

Cryocooler

Power supply crate

DAQ PC

Pumping station

outer shielding/support

to Stirling-cycle cryocooler

inner shielding/cooling pad

cold part

detector window

ROB

Munich - 09.07.2019 at 18:46

Munich - 22.05.2019
Calibration configuration

- green LED
  - 520 nm
  - 2.38 eV

- Fe-55
  - ~ 6 keV
Electronics qualification with standard readout

RNDR matrix

Clear
Clear gate
Gate 1
Gate 2
Transfer gate

simpler sequence, voltage optimization for qualification of the new system

operational August 2019

standard readout: no repetition

Clear
Clear gate
Gate 1
Gate 2
Transfer gate

First Fe-55 source data 05.07.2019
Perspectives towards physics run

- DEPFET-RNDR prototype matrix:
  establish calibration method, optimization of operating parameters;
dark current temperature dependence;
- design and plan for the first physics run underground with prototype matrix;
- radioactive impurity measurement of the sensor;
larger volume for longer future, goal at 40 matrices for second physics run.
Perspectives towards physics run

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  - dark current temperature dependence;
- design and plan for the first physics run underground with prototype matrix;
- radioactive impurity measurement of the sensor;
- larger volume for longer future, goal at 40 matrices for second physics run.

plot based on QEdark calculation results

\[
\sigma_e = 10^{-41} \text{ cm}^2
\]

\[E_T = 2e^-, 6 \text{ background events, } 1.0 \text{ kg} \cdot \text{y}\]

\[E_T = 2e^-, 6 \text{ background events, } 3.0 \text{ kg} \cdot \text{y}\]

\[E_T = 2e^-, 6 \text{ background events, } 0.0009 \text{ kg} \cdot \text{y}\]

\[E_T = 2e^-, 6 \text{ background events, } 1.0 \text{ kg} \cdot \text{y}\]
Summary

- DEPFET-RNDR with sub $e^{-}$ ENC low noise is capable of detecting the energy deposit from sub-GeV DM-electron recoil, reported by single-pixel measurement;

- DEPFET-RNDR prototype matrix (64 x 64 pixels) for DANAE under test-of-principle measurement and optimization;

- first result of DEPFET-RNDR matrix performance within 2019.
DANAE (DANAË)

Direct dArk matter search using DEPFET with repetitive-Non-destructive-readout Application Experiment

OeAW funding for innovation in detector technology

Collaboration


Max-Planck-Gesellschaft Halbleiterlabor, Germany A,
Institut für Hochenergiephysik der Österreichischen Akademie der Wissenschaften, Vienna, Austria B,
Atominstitut, Technische Universität Wien, Vienna, Austria C
ONE OF THE QUADRANTS HAD UNUSUALLY HIGH NOISE DUE TO A LARGE NUMBER OF ELECTRONS.

The thickness of the light-tight copper housing that was cooled to an estimated 130 K to prevent thermal noise.

The sensor was read by a modified Monsoon electronics system, with a small amount of data. The SENSEI data thus also contain one or more electrons.

The number of events is listed in Table I. No events are seen for 5 electrons or less, but for 6 electrons, the number of events is significantly higher than expected.

The expected one-day exposure compared to SENSEI is shown in the graph.

Expected 1 day exposure compared to SENSEI

Exposure: 0.019 gram-days

Table I. E

<table>
<thead>
<tr>
<th>Charge [e⁻]</th>
<th>Entries</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>10⁶</td>
</tr>
<tr>
<td>4-5</td>
<td>10⁵</td>
</tr>
<tr>
<td>6</td>
<td>10⁴</td>
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</table>

DANAE prototype 24 mg one-day exposure zero background expected reach (Preliminary)

SENSEI prototype physics run

Preliminary

ArXiv:1804.00088v1 from SENSEI homepage

DM-electron cross section

m_x [MeV] from SENSEI homepage

Expected 1 day exposure compared to SENSEI

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DM-electron cross section

m_x [MeV] from SENSEI homepage
**Skipper CCD for SENSEI**

DAMIC CCD with **repetitive readout**

Readout noise:
- 1 sample: 3.55 e⁻ rms
- 4k samples: 0.068 e⁻ rms

@ 140 K

expected dark current (from DAMIC CCD):

< 10⁻³ e⁻/pix/day
SENSEI first result with “skipper” CCD

Active mass: 0.071 grams
427 minutes exposure (0.33 g-hr)
above sea level 220 m
single read noise: $\sim 4\ e^-$
effective noise: $\sim 0.14\ e^-$ (800 repetitions)
dark current: $\sim 1.14\ e^-/\text{pixel/day}$
assume all events DM induced
$\rightarrow$ conservative limit

<table>
<thead>
<tr>
<th>Noise</th>
<th>$\text{e}^-$</th>
</tr>
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<tbody>
<tr>
<td>Single read</td>
<td>4</td>
</tr>
<tr>
<td>Effective</td>
<td>0.14</td>
</tr>
<tr>
<td>Dark current</td>
<td>1.14</td>
</tr>
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</table>

- 1 g, 2 he - MINOS
- 10 g, 10 day - MINOS
- 100 g, 1 year

arXiv:1804.00088v1 from SENSEI homepage
Correlated double sampling:
1st measurement: signal + baseline
clear: removal of signal charges
2nd measurement: baseline

difference = signal
complete clear is mandatory!

matrix operation

vertical signal lines
1 active row, other pixels integrating

option to speed up (1)
readout parallelisation
2 x readout channels, 2 active rows
Lowering the noise: Skipper CCD

- **Main difference:** The Skipper CCD allows multiple sampling of the same pixel without corrupting the charge packet.
- The final pixel value is the average of the samples:
  \[
  \text{Pixel value} = \frac{1}{N} \sum_{i=1}^{N} (\text{pixel sample})_i
  \]

Regular CCD

- high frequency noise
- low frequency noise

Skipper CCD

- high frequency noise
- low frequency noise

SW : summing-well gate
OG : output gate
RG : reset gate
VR : V_ref

Capacitance of the system is set by the SN: $C = 0.05 \text{pF} \rightarrow 3 \mu \text{V/e}$