Developments on Skipper-CCD detectors for dark matter searches

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for the SENSEI Collaboration

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† Sub-Electron-Noise SkipperCCD Experimental Instrument
Fully-Depleted Charge Coupled Devices (CCDs)

- $C_{SN} < 0.05 \text{ pf} \rightarrow S_{V/e^-} > 3 \mu\text{V}/e^- \rightarrow$ low readout noise $\rightarrow \sim 50 \text{ eV}$ energy threshold.
- $675 \mu\text{m}, 6 \times 6 \text{ cm}^2$ detector have a mass of 5.2 g

Has motivated their application in **low energy threshold particle experiments**. Two examples are CONNIE (Coherent Neutrino Nucleous Interaction Experiment) and DAMIC (Dark Matter in CCDs).
CCDs readout noise

- CDS is excellent for removing high frequency noise but sensitive to low frequencies.
- 1/f impose a minimum noise.

\[ \sigma^2 = \sigma_W^2 + \sigma_{1/f}^2 + \sigma_{1/f}^2 \]

Integration time [\( \mu s \)]

\[ \sigma^2 [\mu V^2] \]
SENSEI: Sub-Electron-Noise SkipperCCD Experimental Instrument

SENSEI LDRD Collaboration (2015)

- **Fermilab**: Tiffenberg, Guardincerri, Sofo Haro
- **Stony Brook**: Rouven Essig
- **LBNL**: Steve Holland, Christopher Bebek
- **Tel Aviv University**: Tomer Volansky
- **University of Oregon**: Tien-Tien Yu
- **Stanford University**: Jeremy Mardon

Objective:

Develop a CCD-based detector with an energy threshold close to the silicon band gap (1.1 eV) using SkipperCCDs.

Skipper-CCD:

Idea proposed in 1990 by Janesick et al. (doi:10.1117/12.19452)
SENSEI: First working instrument using SkipperCCD tech

**Sensors**
- Skipper-CCD prototype designed at LBNL MSL
- 200 & 250 μm thick, 15 μm pixel size
- Parasitic run, optic coating and Si resistivity \( \sim 10kΩ \)
- 4 amplifiers per CCD, three different RO stage designs

**Instrument**
- System integration done at Fermilab
- Modified DES electronics for read out
- Firmware and image processing software
- Optimization of operation parameters
Skipper-CCD

Output stage with non-destructive charge readout.

The final pixel value is the average of the samples $\frac{1}{N} \sum_{i}^{N} (\text{pixel sample})_i$. 
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Skipper-CCD

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The final pixel value is the average of the samples \( \frac{1}{N} \sum_{i}^{N} \text{(pixel sample)}_{i} \).
Counting electrons: 0, 1, 2..

Standard CCD mode: charge in each pixel is measured once

New Skipper CCD: charge in each pixel is measured multiple times

Readout-noise: 3.5 e RMS

Readout-noise: 0.06 e RMS
55 Fe X-ray source: keep counting: ..1550, 1551, 1552..
Noise vs. #samples - $1/\sqrt{N}$
SENSEI Collaboration

Build a detector using Skipper-CCDs to search for light DM candidates

- **Fermilab**: Michael Crisler, Alex Drlica-Wagner, Juan Estrada, Guillermo Fernandez, Miguel Sofo Haro, Javier Tiffenberg
- **Oregon University**: Tien-Tien Yu
- **Stony Brook**: Rouven Essig
- **Tel Aviv University**: Liron Barack, Erez Ezion, Tomer Volansky
- + several additional students + more to come

Fully funded by Heising-Simons Foundation & Fermilab
SENSEI: lower the energy threshold to look for light DM candidates

Detect DM-e interactions by measuring the ionization produced by the electron recoils. See arXiv:1509.01598

Idea: use electrons in the bulk silicon from a CCD as target

This requires very low noise!
We used the parasitically-fabricated R&D sensors to learn how to optimize operations and produce early-science results.
ProtoSENSEI @MINOS

Technology demonstration: installation at shallow underground site
protoSENSEI @MINOS: results

Light Dark Photon

Heavy Dark Photon

World best limit below 5 MeV!!
What are the next steps for SENSEI?

Build an experiment with more mass
Reduce dark current

- 10 gram Skipper-CCD system in 2019 → MINOS.
- 100-gram Skipper-CCD system in 2020 → SNOLAB, 2000 mts.

- New detectors
- New RO electronics.
LTA: Low Threshold Acquisition

- Single board → four quadrants Skipper-CCD
- Clock voltages range and shape suitable for Skipper-CCDs
- Fully digital: ADC → FPGA → DCDS.
- Smart readout and DSP techniques for noise reduction.
- Easy scalable to hundreds of detectors.

Meeting of the Division of Particles & Fields of the APS, Boston, July 18, 2019
New Skipper-CCDs

- New silicon with higher resistivity and IR cover to reduce DC.
- Thicker detectors of $675 \, \mu m$, $6144 \times 886$ pixels of $15 \times 15 \, \mu m^2$
  - 10 grams $\rightarrow$ 5 skp-CCDs
  - 100 grams $\rightarrow$ 50 skp-CCDs
- Detector packaging
  - low radiation background
  - good thermal conductivity
- Output stage with high single-electron sensitivity.
New Skipper-CCDs, surface test

\[ 0.14 \text{ e}^{-}_{\text{rms}}/\text{pix} \ (300 \text{ samples and IW}=30 \mu s) \]
Current Step: single-device at MINOS

Currently taking data:
- optimization
- DC measurement
SENSEI path

Summary

- SENSEI is the first dedicated experiment searching for electron-DM interactions

- protoSENSEI:
  - surface → probed 0.5-4 MeV masses for the first time, and larger xsec than existing direct-detection constraints.
  - MINOS → produced best limit for light DM with masses bellow 5 MeV

- SENSEI experiment will use better sensors & collect almost 2 million times the exposure of this surface run in next ~2-3 years, probing large regions of uncharted territory populated by popular models

- Fully funded: 10g & 100g design done, construction started.
  - Grant from Heising-Simons Foundation
  - Full technical support from Fermilab
THANK YOU!
BACK UP SLIDES
Dark current measurements and expectation

DC (e-/pix/day)

- General purpose CCD setups. No IR cover. At sea level. Output transistor ON.
- SENSEI prototype surface run (low resistivity Si) and CONNIE experiment (high resistivity Si). ~IR cover. At sea level. Output transistor ON.
- SENSEI prototype run (low resistivity Si). ~IR cover. At MINOS (100m underground).
- DAMIC experiment run (high resistivity Si). ~IR cover. At SNOLAB (2km underground). Output transistor ON.
- SENSEI expectation with high resistivity Si. IR cover. At SNOLAB (2km underground). Output transistor OFF.
SENSEI threshold vs dark current

- Counting electrons $\Rightarrow$ noise has zero impact
- It can take about 1h to read the sensors
- Dark Current is the limiting factor

It’s better to readout continuously to minimize the impact of the DC

### Dark Current

<table>
<thead>
<tr>
<th>$[e^{-}\text{pix}^{-1}\text{day}^{-1}]$</th>
<th>$\geq 1e^{-}$ [pix]</th>
<th>$\geq 2e^{-}$ [pix]</th>
<th>$\geq 3e^{-}$ [pix]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-3}$</td>
<td>$1 \times 10^{8}$</td>
<td>$3 \times 10^{3}$</td>
<td>$7 \times 10^{-2}$</td>
</tr>
<tr>
<td>$10^{-5}$</td>
<td>$1 \times 10^{6}$</td>
<td>$3 \times 10^{-1}$</td>
<td>$7 \times 10^{-8}$</td>
</tr>
<tr>
<td>$10^{-7}$</td>
<td>$1 \times 10^{4}$</td>
<td>$3 \times 10^{-5}$</td>
<td>$7 \times 10^{-14}$</td>
</tr>
</tbody>
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Operation mode (continuous-RO or long-exposures) will depend on the measured DC and spurious charge of the Science sensors
SENSEI: reach of a 100g, zeroish-background experiment

Light Dark Photon

Heavy Dark Photon

Meeting of the Division of Particles & Fields of the APS, Boston, July 18, 2019
The gain is the same for all the samples
Charge in pixel distribution. Counting electrons: 0, 1, 2..
Charge in pixel distribution. Counting electrons: 0, 1, 2..

4000 samples

Entries 1635
χ² / ndf 19.6 / 25
Mean -0.002 ± 0.0016
Sigma 0.06 ± 0.001
Snolab vacuum vessel design

- Cold copper box for CCD modules
- Flex cables slot
- Heat shield
- Inner shield
- Copper bell
- Service access ports
Snolab shield design

50cm HDPE/Water neutron shield
15cm copper
5cm lead

50cm HDPE/Water neutron shield
15cm copper
5cm lead
Observed spectrum using 800 samples per pixel

Exposure: 0.019 gram-days

dark current: $\sim 1.1$ e$^{-}$/pix/day; no events with 5-100 electrons
First direct-detection constraints between $\sim 500$ keV to 4 MeV!

\[ F_{\text{DM}} = \left( \frac{\alpha m_e}{q} \right)^2 \]

Terrestrial effects: Emken, Essig, Kouvaris, Sholapurkar (to appear)
First direct-detection constraints between $\sim 500$ keV to 4 MeV!

Terrestrial effects: Timon Emken, RE, Kouvaris, Mukul Sholapurkar (to appear)
SENSEI commissioning run at surface: arXiv:1804.00088

First direct-detection constraints between $\sim 500$ keV to 4 MeV!

![Graph showing constraints between dark matter mass and cross-section]

Terrestrial effects: Timon Emken, RE, Kouvaris, Mukul Sholapurkar (to appear)
Single pixel distribution: X-rays from $^{55}\text{Fe}$

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