New mK-temperature Germanium detectors for Dark Matter direct search and for precision measurements of CEvNS

Evgeny Yakushev, JINR, Dubna
Two very interesting directions: Neutrino Physics and Dark Matter

The Universe

- ~5% Normal Matter
- ~25% Dark Matter
- ~70% Dark Energy

The Particle Universe

- Photons
- Neutrinos
- Protons
- Neutrons
- Electrons
- Dark Matter (local)
- Dark Matter
LSM underground laboratory (France), 4800 mwe
- Clean room + deradonized air
- Rn monitoring down to few mBq/m³
- Active muon veto (>98% coverage)
- External (50 cm) + internal polyethylene shielding
  - Thermal neutron monitoring with $^3$He detector
- Lead shielding (20 cm, incl. 2 cm Roman lead)
- Selection of radiopure material
- Cryostat can host up to 40 kg detector, at 18 mK
EDELWEISS (Heat and ionization Ge bolometers)

Using of *Heat and Ionization* HPGe detectors, running in $^3$He-$^4$He dilution cryostat (<20 mK)

Ratio $E_{\text{ionization}}/E_{\text{recoil}}$ is

$= 1$ for electronic recoil

$\approx 0.3$ for nuclear recoil

$\Rightarrow$ Event by event identification of the recoil

$\Rightarrow$ Discrimination g/n > 99.99%

Detectors with special concentric planar electrodes for active rejection of surface events (miss-collected charge)
Direct detection of Dark Matter, germanium target, LSM deep underground laboratory

For the past 25 years EDELWEISS is the leading experiment for direct Dark Matter search with Germanium detectors.

Unique, continuously developing technology of ultra-low temperature HPGe detectors-bolometers operated at low background environment.

Thanks to the excellent energy resolution, the experimental program is shifted in the energy region inaccessible by other technologies (Ar/Xe based).
An increasing gain of interest for the search of low-mass, very-heavy WIMPs, other possible candidates

- Non evidence yet for SUSY at the LHC;
- New theoretical approaches favoring lighter candidates;
- No WIMP signals in the “expected” region;
- Controversial results in the region around and below of 10 GeV/c^2.
Observation of Excess Electronic Recoil Events in XENON1T

![Energy vs Events](image)

- **Events/(t.y. keV)**
- **Energy [keV]**

- **Legend**
  - **$B_0$**
  - **SR1 data**

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Event rate [ton.year.keV⁻¹]

- WIMP signal: $m_\chi = 6$ GeV/c², $\sigma_{\chi n} = 4.4 \times 10^{-45}$ cm²
- Total CNS background
- Weak neutrino-electron

1 keV threshold: 100 evt/ton/year on Ge detector

Recoil energy [keV]

pp
7Be
pep
8B
hep
atmospheric
Threshold

Mass & Discrimination Threshold, Mass & Discrimination

WIMP Mass (GeV/c²)

WIMP-nucleon SI cross section (cm²)

CRESST-Nucleus
CDMSLite
DAMIC
LUX
PANDA-X
XENON 1t
EDELWEISS-SubGeV: Scientific context

EDELWEISS-SubGeV program

Hidden sector Dark Matter and others

Absorption
Electronic recoil

DM-electron scattering
Electronic recoil

DM-Nucleus scattering
Nuclear recoil

Standard WIMP

$^8$B neutrinos (~ 6 GeV)

Reactor neutrinos (~ 2.7 GeV)

Not competitive with noble gases experiments
EDELWEISS SubGeV two modes

Low Voltage Objectives

- 10 eV (RMS) Heat energy resolution
- 20 eV (RMS) Ionization energy resolution

Particle identification & surface event rejection down to 50 eV

Low-voltage objectives are part of a common effort with the Picocar collaboration, dedicated to studying CENS at reactors supported by the ERC-CENS Starting Grant (2019-2024)

High Voltage Objectives

- 10 eV (RMS) Heat energy resolution
- 100 V with signal amplification only

Single-e/h pair sensitivity with massive (~30g) bolometers

Single ELECTron Nuclear recoil DIScrimination SELENDIS

SELENDIS project has received funding from the European Union’s Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No 838537

\[ E_t = E_r + \frac{1}{3 \, eV} E_\Omega \Delta V \]

- 133Ba 356 keV line

Charge/Phonon sensors

prompt phonons

Charge/Phonon sensors

EDELWEISS R&D

FID803

L湖 boost = 1 + V/3
How to improve resolution (decrease noise)

- Intense R&D on NTD sensors
- Detailed thermal model: optimization of the best configuration
- Test of different glues
- Alternative sensors: NbSi superconductive transition edge sensors
- First amplification: JFET at 100K to HEMTs at 4K

- **JFET to HEMT**
  - Lower intrinsic noise, low heat load
  - Works at 4K: shorter cables reduces capacitance and improves resolution

- **Successful HEMT amplifier with sub-100 eV$_{\text{rms}}$ ion. resolution** [A. Phipps, arXiv:1611.09712, collaboration between SuperCDMS and EDELWEISS]

- Step#1: Upgrade EDELWEISS ionization readout with this new design
- Step#2: Electrode design to reduce detector capacitance to reach 50 eV$_{\text{RM}}$
Resolution improvements on a 32g detector

- R&D with 32 g combined with the objective of testing the above-ground sensitivity to sub-GeV WIMPs
- Optimized NTD heat sensor on a 32g crystal, no electrodes (i.e. 1 keV = 1 keV_{NR})
- Kept at 17 mK in low-vibration dilution fridge [ArXiv:1803.03463]
- Stable $\sigma = 18$ eV baseline resolution
- DM search in [0-2] keV region

![Graph showing energy resolution vs. time]

$\sigma = 18$ eV baseline

![Graph showing event rate vs. energy]

$\sigma = 34$ eV @ 6 keV
- Achieved resolution on a smaller detector exceeds by x5 the original LT goal with 800 g detectors
- Best above-ground limit down to 600 MeV/c²: SIMP
- First sub-GeV limit with Ge, down to 500 MeV/c²
- Opens the way for the 0.1 – 1 GeV/c² range
Run at LSM underground laboratory:
Continuous running at <21 mK since January 2019 to June 2020

11 different Ge detectors
Rest of cryostat used for joint physics run with CUPID-Mo 0ν2β search.

Compare detector physics in 32g, 200 g and 800g detectors. Compare performance of NTD and NbSi-TES heat sensors.

Obtaining near single-electron sensitivity on 33 and 200 g detectors: exploration of DM interactions with electrons and nuclei.


EDELWEISS has been able to obtain at LSM the lowest radioactive background levels below 10 keV in massive Ge detectors (~0.1 evt/kg/day/keV)
Current run @ LSM: obtaining near single-electron sensitivity on 33 and 200 g detectors: Calibration of nuclear recoils down to low thresholds.

NbSi209

[200g Ge] \( \sigma = 6 \text{ eV}_{ee} \) heat resolution at 66V

ER calibration at 0.16 & 1.3 keV checked by activation with strong AmBe source
- Efficiency determined by injecting pulses at random time in the recorded data streams.
- The injected pulses are actual $^{71}$Ge K-line events (from the activation that immediately followed the search), rescaled to the desired energy.
- Some sensitivity to 1 electron-hole pair signal.
An unprecedented **charge resolution of 0.53 electron-hole pairs** (RMS) has been achieved using the Neganov-Trofimov-Luke internal amplification. We set the first Ge-based constraints on sub-MeV/c² DM particles interacting with electrons, as well as on dark photons down to 1 eV/c². These are competitive with other searches and demonstrate the high relevance of cryogenic Ge detectors for the search of DM interactions producing eV-scale electron signals.

**In new class of light DM models the interaction with normal matter comes from the coupling of a Dark Sector photon with the normal photon.**

**How to detect: DM-electron scattering**

Theory predictions: complete coverage ($10^{-40}$ cm²) possible with 1 kg year exposure of a detector sensitive to the single electron in the absence of any background.
Expected future results
Bolometers - Not only DM

RICOCHET aims at building the ultra low-energy CEνNS neutrino observatory dedicated to physics beyond the Standard Model.

50 eV energy threshold with a $10^3$ background rejection down to the threshold.

The first key feature of the RICOCHET program, compared to other planned or ongoing CEνNS projects, is to aim for a kg-scale experiment with significant background rejection down to the $O(10)$ eV energy threshold.

The CRYOCUBE: a compact tabletop size setup

- 27 x 33 g detectors
- 8 x 8 x 8 cm$^3$ radio-pure infrared-tight copper box
RED20: 55 eV energy threshold, moderate lead shield (10 cm thick, 70% coverage) and no discrimination.

- **Strong source** (KNPP @ 15 m): $2.4 \times 10^{13}$ nu/cm²/s
- **Moderate source** (ILL @ 8 m): $1.2 \times 10^{12}$ nu/cm²/s
- **Weak source** (DC @ 400 m): $5 \times 10^{10}$ nu/cm²/s
\[ \frac{d\sigma(E_{\nu}, E_r)}{dE_r} = \frac{G_f^2}{4\pi} Q_w^2 m_N \left(1 - \frac{m_N E_r}{2E_{\nu}^2}\right) F^2(E_r) \]

\[ Q_w = N - Z(1 - 4\sin^2 \theta_w) \]

\[ PDG - electroweak (2016) \quad \mu [GeV] \]
**RICOCHET: Searching for nuclear reactor site - ILL**

- 58 MW nominal thermal power
- Large neutrino flux: $\sim 1 \times 10^{19}$ v/s
  - 5m from core: 40 evts/day/kg
  - 7m from core: 20 evts/day/kg
- 3 to 4 cycles per year: excellent ON/OFF modulation to subtract uncorrelated backgrounds
- Significant overburden ($\sim 15$ m.w.e)
- Ricochet could make use of STEREO casemate after its dismantling (2021 - 2022)
- Ricochet would benefit from the strong STEREO experience and background characterization
- Monte Carlo studies ongoing to estimate the expected backgrounds:
  - *reactogenic* and cosmogenic
- **LoI submitted to ILL directors end-Feb**

Just approved (640 kEuro for installation at ILL)
Optimised for extraction of intense neutron beams

High-(neutron)flux reactor of the ILL

- 58.3 MW\textsubscript{thermal}
- Single compact fuel element:
  - $\varnothing 40 \text{ cm} \times 80 \text{ cm}$
  - Highly enriched fuel: $^{235}\text{U}$ (93%)
  - 1 cycle $\sim 50$ days
  - 3-4 cycles/year
- Heavy-water moderated
- Flux in moderator: $10^{15}$ n/cm$^2$s
Site H7

Antineutrino source and site

- Baseline: ≥ 8m
- Overburden: 15 m.w.e.
- Shielding improved for STEREO
- H6-H7 beam tube removed, or closed by plug

Advantages

- Pure $^{235}$U spectrum, compact core
- Frequent on-off changes
- 15 m.w.e. overburden
- Profit from STEREO (site prep, reactor spectrum)
- Scientific environment and technical support

Disadvantages

- Need to be close to core for high flux $\rightarrow$ Signal/ReactorBG?
- Backgrounds from neighbour instruments
- Limited crane access
CEνNS discovery significance and precision as a function of exposure. Median significance and precision (and 95% confidence level bands) for the discovery of CEνNS using Ge (blue), Zn (yellow), and the combination of the two (red).
<table>
<thead>
<tr>
<th></th>
<th>Cosmogenic</th>
<th>Reactogenic</th>
<th>Total (MC)</th>
<th>Total (goal)</th>
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<tbody>
<tr>
<td><strong>Electronic recoils</strong></td>
<td>No Shielding</td>
<td>260 ± 5</td>
<td>4365 ± 301</td>
<td>4625 ± 301</td>
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<tr>
<td>[50 eV, 1 keV]</td>
<td>Passive Shielding</td>
<td>166 ± 2</td>
<td>34 ± 4</td>
<td>200 ± 5</td>
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<td>(evts/day/kg)</td>
<td>Passive Shielding + muon-veto</td>
<td>1.1 ± 0.1</td>
<td>35 ± 4</td>
<td>100</td>
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<td><strong>Neutron recoils</strong></td>
<td>No Shielding</td>
<td>1554 ± 12</td>
<td>53853 ± 544</td>
<td>55407 ± 545</td>
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<tr>
<td>[50 eV, 1 keV]</td>
<td>Passive Shielding</td>
<td>39 ± 1</td>
<td>5.4 ± 0.2</td>
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<td>(evts/day/kg)</td>
<td>Passive Shielding + muon-veto</td>
<td>17 ± 1</td>
<td>23 ± 1</td>
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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Uncertainty on Parameter</th>
<th>Approximate Uncertainty on CENNS Rate</th>
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<tr>
<td>$P_{th}$</td>
<td>1.4 %</td>
<td>1.4%</td>
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<tr>
<td>Distance</td>
<td>0.3%</td>
<td>0.6%</td>
</tr>
<tr>
<td>E/fission</td>
<td>~0.3 %</td>
<td>~0.3%</td>
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<tr>
<td>$\alpha_i$</td>
<td>$\leq 1% \ \ 235$U</td>
<td>$\leq 0.5%$</td>
</tr>
<tr>
<td></td>
<td>$\approx 5-10% \ \ 239$Pu, $241$Pu</td>
<td></td>
</tr>
<tr>
<td>$S_i$</td>
<td>Conversion: 2-3%</td>
<td>2-3%</td>
</tr>
<tr>
<td></td>
<td>Summation: 5-10%</td>
<td></td>
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<tr>
<td>$\sigma_k$</td>
<td>0.5% ($\theta_W$)</td>
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</tr>
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</table>
32 gram zinc bolometer

The zinc absorber was instrumented with an NTD thermal resistor and cooled to 15 mK.

Each detector is instrumented with two gold pads, one in direct contact with the zinc absorber, the other having a 50-100 nm ZnO layer in between the two metals.

Such a configuration will allow one to simultaneously measure the phonon and the phonon+quasi-particle population from a given particle energy deposition.
RED20: 55 eV energy threshold, moderate lead shield (10 cm thick, 70% coverage) and *no discrimination*.
Unit #6 of Novovoronezh NPP
new 3+ generation WWER-1200
Maximal thermal power is 3212 MW

First place proposed
-5.4 m (underground)
Strong basement,
No noise or vibrations

Maximal registered muon flux is 16.2 $\mu$ m$^{-2}$ sr$^{-1}$ sec$^{-1}$,
About 7 times less with respect to the max of the sea level,
This corresponds to $\sim$50 mwe.

There is expected anisotropy (better shielding from the reactor)

Measured neutron flux: $<10^{-5}$ m$^{-2}$ sec$^{-1}$,
More than 20 times less with respect to the max of the sea level.
**RICOCHET: ** *Timeline*

The Ricochet timeline is the following:

**-End-2019:** Nuclear site decision and first version of Ricochet’s Conceptual Design Report (CDR) to ask for funding of the setup at the chosen nuclear site to various agencies.

**-2021:** Ricochet’s Technical Design Report (TDR) completed, including the mechanical infrastructure, the cryostat and tubing, the cabling and the warm electronics. The cold cabling, below the 4 K stage, is already being designed in the context of the ongoing CryoCube and Q-array R&D for which the fundings are fully and partially secured for the former and the latter respectively.

**-2022:** Deployment of the Ricochet experiment at the chosen nuclear reactor site.

**-2024:** Deliver the first low-energy (sub-100 eV) high-precision (‰-level) CENNS measurement after one year of data taking leading to unprecedented sensitivities to various new physics scenarios.
Two main conclusions:

• In general, all modern methods of nuclear physics have to be applied to achieve the sensitivity levels that are interesting now for particle physics;

• Direct measurement of energy deposition and the excellent energy resolution provided by the bolometric technique are base for its further use for investigation of rear processes.