NUCLEUS Experiment:
Exploring Coherent Elastic Neutrino Scattering with Gram-Scale Cryogenic Detectors

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New Directions in the Search for Light Dark Matter Particles
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Coherent Elastic Neutrino Nucleus Scattering (CEνNS)

\[ \sigma_{CE\nu NS} \propto \left( Z (4 \sin \theta_W - 1) + N \right)^2 F(q^2) E^2_\nu \]

Key parameters:
- Energy threshold < 100 eV
- Low background
- Different target materials to test \( N^2 \)-dependence

Synergies with detector R&D for light DM search

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Physics Potential of CE$\nu$NS

- Precision test of Standard Model (SM): e.g. **Weinberg angle at low momentum transfer**
- **New physics BSM & fundamental neutrino properties and interactions:** e.g. new $q-\nu$ couplings, neutrino magnetic dipole-moment, etc.
- New channel for **sterile neutrino searches**, **Supernovae** detection, **nuclear physics**
- Possible application in nuclear reactor monitoring
- **Neutrino floor:** irreducible background for DM experiments from CE$\nu$NS
NUCLEUS Experiment

Reactor anti-neutrinos

- $E_\nu < 10$ MeV
- High $\nu$-flux
- Experimental site at shallow depth $< 10\text{m.w.e.}$

Gram-scale cryogenic calorimeters based on CRESST technology:

- Demonstrated energy threshold in 10eV-regime
- Operation above ground

Establishing new experimental site, VNS @ Chooz Reactor (France) for NUCLEUS


Detector Concept:

so far 5 institutes with ~30 members + strong interest from INFN groups
The NUCLEUS Detector Concept

Gram-scale cryogenic calorimeter

- Low systematics: energy scale well known (no significant quenching involved)
- Down-scaling of detector mass:
  - $E_{\text{th}} \sim M^{2/3} \rightarrow$ predicts $E_{\text{th}} \leq 10 \, \text{eV}$
  - Achieved threshold so far: $E_{\text{th}} = (19.7 \pm 0.8) \, \text{eV}$

0.5g $\text{Al}_2\text{O}_3$ prototype

Thermometer: Transition-edge-sensor based on CRESST technology

Single $\text{Al}_2\text{O}_3$ or $\text{CaWO}_4$ cubic crystal
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  - \( E_{\text{th}} \sim M^{2/3} \rightarrow \text{predicts } E_{\text{th}} \leq 10 \text{ eV} \)
  - Operationable above ground:
    - Low rate O(0.1Hz)
    - Fast pulses → critical for timing with veto detectors

- Uncertainty of pulse on-set depends on pulse rise-time: \( \sigma_\tau \sim \tau_r \)
- Define a veto window of \( \pm 5\sigma_\tau \)
The NUCLEUS Detector Concept


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  - Operationable above ground

  - **Fiducialization** of detector & new holder scheme for active background reduction:
    - Inner veto: holding force + $4\pi$ surface veto
    - Outer veto: reduction of external $\gamma$- and $n$-background
    - MC simulations show a **suppression factor of $O(10^3)$** can be reached

[Diagram showing detector setup with labels: Outer veto, Inner veto, Target crystal]
The NUCLEUS Detector Concept


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  - Operationable above ground
- Fiducialization of detector & new holder scheme for active background reduction:
  - Full demonstrator tested → analysis ongoing

NUCLEUS-1g

- target crystal: 0.5g Al$_2$O$_3$
- inner cryogenic veto + holder: Si wafer
- outer veto: 200g Si crystal
The NUCLEUS Detector Concept


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- Down-scaling of detector mass:
  - $E_{\text{th}} \sim M^{2/3}$ $\rightarrow$ predicts $E_{\text{th}} \leq 10$ eV
  - Operationable above ground
  - Fiducialization of detector & new holder scheme for active background reduction
- **Multi-target approach**: CEvNS rate differs by a factor of $\sim 10$-100 $\rightarrow$ constrain background

![Graph showing counts vs. energy with different materials](image)

- $E_R$ [eV]
- Counts / [keV kg d]
- Materials: Li$_2$WO$_4$, CaWO$_4$, Ge, Al$_2$O$_3$
The Very Near Site (VNS) at Chooz


- **New experimental site** in a 24 m$^2$ room in an administrative building
- In-between the two 4.25 GW$_{th}$ reactor cores
- Expected $\nu$-flux: $10^{12}$ (s cm$^2$)$^{-1}$
- Muon rate attenuation measurements yield an overburden of 3 m.w.e. at the VNS
The Very Near Site (VNS) at Chooz

The Very Near Site (VNS) at Chooz

NUCLEUS-10g
- 3x3 array with CaWO$_4$ (6g)
  + 3x3 array with Al$_2$O$_3$ (4g)

NUCLEUS-1kg
- Upgrade towards 1kg target mass
Target crystals: 3x3 array with CaWO$_4$ (6g) + 3x3 array with Al$_2$O$_3$ (4g)

- First observation of CEνNS of lowest energy reactor neutrinos
- Signal observation after 2 weeks possible
- 10% measurement of CEνNS cross-section
- Worst case scenario: in case of signal-like background a 4$\sigma$-observation can be reached after one year → unique to multi-target approach

Exp. sensitivity (flat background)
Conclusion & Outlook

- **Gram-scale cryogenic calorimeters** are a very promising technology to measure CEνNS of reactor neutrinos:
  - Unprecedentedly low energy threshold $E_{th} < 20$ eV
  - Operational above ground
  - Fiducialisation of detector for background reduction

- Plan to install **NUCLEUS-10g at VNS** by 2021:
  - Observation of CEνNS of low energy neutrinos within 2 weeks
  - 10% precision after 1y → great potential for new physics

- **NUCLEUS-1kg** aims at a percent level measurement of CEνNS cross-section

- First publication of NUCLEUS at VNS:
Bonus Slides
Statistical Precision of NUCLEUS

- NUCLEUS-10g dominated by statistics
- **NUCLEUS-1kg** envisions **precision** measurement of few percent for CEνNS

![Graph showing relative precision vs. time](image)

*Improvement on systematics necessary: e.g. ν-flux, energy scale @ O(10 eV), ...*
Low Energy Background

... measured with the NUCLEUS prototype at surface w/o shielding

Fig. 2 Total energy spectrum of the 5.3h measurement in presence of the $^{55}\text{Fe}$ X-ray source with peaks at 5.90 and 6.49keV. The inset shows the events in the region-of-interest for DM search from the energy threshold of 19.7–600eV (binning 5 eV). No data quality cuts are applied.
Dark Matter Search with NUCLEUS Prototype

- 0.5 $\text{Al}_2\text{O}_3$ NUCLEUS prototype
- Operated above ground w/o significant shielding
- First limits in mass region $140 \text{ – } 500 \text{ MeV}/c^2$

New parameter space excluded for SIMPs

Testing the SM with NUCLEUS-10g

Measuring the Weinberg angle at low momentum transfer

\[
\left( \frac{d\sigma}{dE} \right)_{\nu_{\alpha} A} = \frac{G_F^2 M}{\pi} F^2(2ME) \left[ 1 - \frac{ME}{2k^2} \right] \times \\
\left\{ [Z(g_V^p + 2\varepsilon_{\alpha\alpha} + \varepsilon_{\alpha\alpha}^d) + N(g_V^n + \varepsilon_{\alpha\alpha}^u + 2\varepsilon_{\alpha\alpha}^d)]^2 \right\}
\]

With \( g_V^p = \left( \frac{1}{2} - 2\sin^2 \theta_W \right) \) and \( g_V^n = -\frac{1}{2} \)
Searching for BSM with NUCLEUS-10g

Non-standard neutrino interactions

\[
\left( \frac{d\sigma}{dE} \right)_{\nu_{\alpha}A} = \frac{G_F^2 M F^2(2ME)}{\pi} \left[ 1 - \frac{ME}{2k^2} \right] \times \]

\[
\left\{ \left[ Z (g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}) + N (g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV}) \right]^2 \right\}
\]
Neutrino Magnetic Dipole Moment

Modified recoil spectra in NU-CLEUS

\[ \mu_\nu = 2.9 \times 10^{-11} \mu_B \]

\[ \mu_\nu = 0 \]

rate \([1/(\text{keV kg d})]\)

\[ 10^3 \]

\[ 10^2 \]

\[ 10^1 \]

\[ E_R [\text{eV}] \]

\[ 10^{-1} \]

Ge

Si
CEνNS vs IBD

Exploring CEνNS with NUCLEUS

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Nuclear Reactor as Neutrino Sources

- **Reactor (anti-)neutrinos**
  - high $\nu$-flux $10^{12}-10^{13}$ s$^{-1}$cm$^{-2}$
  - $E_\nu < 10$ MeV → full coherence
    → test SM @ low energies
  - correlation with reactor power
NUCLEUS Detector Array

(a) Target: (5x5x5)mm³ calorimeter read out with TES

(g-h) passive components: 2mm thick Si slaps
- support structures
- (h) equipped with Al (Au) wiring for electrical (thermal) connections of (a-f)

(b-f) active components: Si wafers read out by TES
- $4\pi$ veto against surface events
- (b) & (c) hold target with Si pyramids
- (b) 200mm thick → acts as a spring & compensates for thermal contraction
- Events induced by e.g. thermal-stress relaxation vetoed as they induce signals in (b) & (c)
Energy Threshold of NUCLEUS Detectors


**Model:**
- $E_{th} \sim 4$ eV ($\text{Al}_2\text{O}_3$)
- $E_{th} \sim 7$ eV ($\text{CaWO}_4$)

**Measurement:**
- $E_{th} = (19.7 \pm 0.9)$ eV ($\text{Al}_2\text{O}_3$)
- non-optimized noise
Fiducial-Volume Cryogenic Detector


MC simulation (β-background Po-210) - inner veto

MC simulation (γ-background) - outer veto

Rate / keV·kg⁻¹·d⁻¹

Energy / keV

0 5 10 15 20 25 30 35 40

10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 10⁰ 10¹ 10²

0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2

10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 10⁰ 10¹ 10² 10³ 10⁴

0 1 2 3 4 5 6 7 8 9 10

Energy / keV

no veto
passive outer veto
active outer veto

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Quenching Factor

Exploring CEvNS with NUCLEUS

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LDM workshop 06/05/19
Muon-induced Dead-Time at the VNS

- Pulse on-set well measured for CRESST detectors with uncertainty $\sigma_t = 4.8\mu s$
- Uncertainty on pulse on-set proportional to rise-time $\tau_r$
- Define veto window of $\pm 5\sigma_t$

**Pulse on-set**

- MC simulation of muon-rate at VNS (3 m.w.e.)

**MC simulation of muon-rate at VNS (3 m.w.e.)**

- Dead-time from simulated muon-rate

**MC simulation of muon-rate at VNS (3 m.w.e.)**

- 493 Hz/m² · m²
- MC

**MC simulation of muon-rate at VNS (3 m.w.e.)**

- Dead-time from simulated muon-rate

**MC simulation of muon-rate at VNS (3 m.w.e.)**

- 10 ms
- 5 ms
- CRESST-II detector
- NUCLEUS prototype
- NUCLEUS goal - 100 μs