CEνNS at the low-energy frontier
with

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NOW 2018, Ostuni
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Key ingredients:
- Coherent neutrino-nucleus scattering
- Nuclear power reactor
- Ultra-low threshold detectors
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• Coherent neutrino-nucleus scattering
• Nuclear power reactor
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New Physics
• Nature of neutrinos
• Fundamental neutrino interactions
• Precision tests of electro-weak theory
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Reactors physics
Nuclear physics
Dark Matter, Solar Neutrinos
Miniaturized neutrino detectors
Key ingredients:
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New Physics
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- Reactor physics
- Nuclear physics
- Dark Matter, Solar Neutrinos
- Miniaturized neutrino detectors

ERC Starting Grant 2018: NU-CLEUS
Exploring coherent neutrino-nucleus scattering with gram-scale cryogenic calorimeters
Coherent Neutrino-Nucleus Scattering

ν

recoiling nucleus
Coherent Neutrino-Nucleus Scattering

- Elastic coherent scattering

Superposition of individual scattering amplitudes:

$$F(q) = \sum_{j=1}^{A} f_j(q) \exp(i\varphi_j)$$

$$\frac{d\sigma}{d\Omega} = |F(q)|^2$$
Coherent Neutrino-Nucleus Scattering

- Elastic coherent scattering

Superposition of individual scattering amplitudes:

\[ F(q) = \sum_{j=1}^{A} f_j(q) \exp(i\alpha_j) \]

\[ \frac{d\sigma}{d\Omega} \approx N^2 |f_j(q)|^2 \]

coherence! \( qR \ll 1 \)

\( E_\nu < 20\,\text{MeV} \)

enhancement for heavy nuclei
Coherent Neutrino-Nucleus Scattering

Neutrino cross sections

- **Coherent scattering**
- **Inverse beta decay**

No energy threshold

Strongly enhanced cross-sections

$\nu \rightarrow e^{-} + \nu_e$
Coherent Neutrino-Nucleus Scattering

Neutrino cross sections

\[ E_\nu = 2 \text{MeV} \]

recoiling nucleus \( E_R \approx 20 \text{eV} \)

Neutrino cross sections

- Coherent scattering
- Inverse beta decay

No energy threshold

\[ \sigma_{\text{CaWO}_4} \]

Strongly enhanced cross-section

NU-CLEUS, Johannes Rothe
Experiments - Overview

COHERENT Experiment at the Spallation Neutron Source at Oak Ridge

First observation of CEVNS in Aug 2017!

Other projects being planned or starting up:
- CONNIE (int.)
- CONUS (MPIK)
- MINER (US)
- ν-GEN (RU)
- RICOCHET (US+FR)
- TEXONO (int.)
- RED-100 (RU)
- ...

NU-CLEUS Experiment at a nuclear power reactor
Why NU-CLEUS?

Neutrino physics at the **low energy** and **precision** frontier!

**The neutrino source**
- Antineutrinos from a nuclear reactor
- Low energy
- High intensity

**The detector**
- Gram-scale cryogenic calorimeters
- Ultra-low threshold
- Low systematics

Picture: M. Mancuso, MPP
Why NU-CLEUS?

Neutrino physics at the low energy and precision frontier!

**The neutrino source**
Antineutrinos from a nuclear reactor

- Low energy
- High intensity

**The detector**
Gram-scale cryogenic calorimeters

- Ultra-low threshold
- Low systematics

Two-phased approach:

- **Phase 1** NU-CLEUS 10g (CaWO$_4$ + Al$_2$O$_3$ targets)
- **Phase 2** NU-CLEUS 1kg (Ge + Si targets)
NU-CLEUS Potential

Neutrino signal rate

- Counts / [kg keV day]
- Recoil energy [eV]

- CaWO$_4$

- Expected background range

- NU-CLEUS prototype $E_R \approx 20$eV

- Existing neutrino detectors

NU-CLEUS, Johannes Rothe
NU-CLEUS Potential

Neutrino signal rate

Counts / [kg keV day]

Recoil energy [eV]

NU-CLEUS prototype $E_R \approx 20\text{eV}$

Expected background range

CaWO$_4$

Existing neutrino detectors

Signal boost

NU-CLEUS, Johannes Rothe
Neutrino signal rate

Counts / [kg keV day]

Neutrino signal rate

Recoil energy [eV]

10
100
1000

CaWO₄

expected background range

NU-CLEUS prototype \( E_R \approx 20 \text{eV} \)

Existing neutrino detectors

5-sigma observation in two weeks with 10g

5mm

4GW

NU-CLEUS Potential

NU-CLEUS, Johannes Rothe

16
Neutrino signal rate

Counts / [kg keV day]

10^4
10^3
10^2
10^1

Recoil energy [eV]

10
100
1000

CaWO_4

expected background range

NU-CLEUS prototype E_R \approx 20eV

Existing neutrino detectors

Potential:
- Low energies
- High S/B
- High rate

5-sigma observation in two weeks with 10g
Neutrino signal rate

Counts / [kg keV day]

Neutrino signal rate

Multi target:
• Smoking gun signal
• Background discrimination

CaWO$_4$

Al$_2$O$_3$

expected background range

Recoil energy [eV]

NU-CLEUS Potential

NU-CLEUS, Johannes Rothe
THE NU-CLEUS DETECTOR
The NU-CLEUS Detector Concept

Gram-Scale Cryogenic Calorimeters

Single crystal
Si, Ge, Al$_2$O$_3$, CaWO$_4$

Thermometer
Transition-edge-sensor

Operation at mK temperatures
The NU-CLEUS Detector Concept

Gram-Scale Cryogenic Calorimeters

Single crystal
Si, Ge, Al₂O₃, CaWO₄

Thermometer
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Operation at mK temperatures

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The NU-CLEUS Detector Concept

Gram-Scale Cryogenic Calorimeters

Single crystal
Si, Ge, Al₂O₃,
CaWO₄

Operation at mK temperatures

- CRYogenics

+ thermal signal without quenching
\[ 100 \text{ eV}_{ee} = 100 \text{ eV}_{nr} = 100 \text{ eV} \]
The NU-CLEUS Detector Concept

CRESST-III cryogenic calorimeter

- Single crystal CaWO$_4$
- Energy threshold <100eV
- Leading technology for low-mass dark matter searches

Scaling down:

\[ E_{th} = (\text{const.}) \times M^{2/3} \]


Gram-scale cryogenic calorimeter

- Al$_2$O$_3$, CaWO$_4$, Si, Ge...
- Threshold expectation (fully optimized): <10eV

Picture: M. Mancuso, MPP

see talk by L. Pattavina
The NU-CLEUS Detector Concept

A first prototype detector

Optimized thermometer

Innovations:
- Low threshold
- Above-ground operation
- Fiducialisation

Technology for neutrino detector demonstrated

- World-best energy threshold for nuclear recoils, 
  $E_{th} = (19.7\pm0.8)\text{ eV}$
- Low systematics – precise knowledge of energy scale
The NU-CLEUS Detector Concept

A first prototype detector

- Rate sufficiently low for operation in high-background environments
- Fast pulses: \textit{anti-coincidence with muon-veto} of kHz count rate (for above ground setup)
The NU-CLEUS Detector Concept

Inner veto against surface backgrounds

Outer veto against external neutrons/gammas

Encapsulation by cryogenic veto detectors:
- Crucial background reduction
- Dedicated MC studies: 2-3 orders of magnitude improvement

Fiducial-volume cryogenic detector
Veto Simulations

- External / muon-induced gammas negligible compared to intrinsic radiopurity
- Dedicated MC study needed for neutrons

NEWS: Recent Measurements

NU-CLEUS 1g demonstrator

• Sapphire and CaWO$_4$ crystals
• Flexible Si wafers as inner veto detectors

Si outer veto prototype

Seed money project
NU-CLEUS 10g and 1kg

NU-CLEUS 10g

NU-CLEUS 1kg

A scalable cryogenic detector

- Exploit semiconductor technology
- SQUID multiplexing

6 inch wafers

200g array in 1 production step

NU-CLEUS, Johannes Rothe
NU-CLEUS 10g and 1kg

NU-CLEUS 10g

NU-CLEUS 1kg

A scalable cryogenic detector

- Exploit semiconductor technology
- SQUID multiplexing

- Multi-year R&D program
- New approach for rare-event search and small precision $\nu$ experiments

6 inch wafers

200g array in 1 production step

Inner part

Outer part

10cm
Background studies at CHOOZ

The Nuclear Reactor
The CHOOZ Power Plant in France

CHOOZ reactor cores
4.25GW\text{th} each

Th. Lasserre (CEA)
M. Vivier (CEA)
V. Wagner (CEA)
G. Munch (EDF)
J. Molina (EDF)
R. Strauss (MPP)
A. Langenkämper (TUM)

Established relation to reactor company (EDF)

Since March 2018:

- Full access to inner zone of power plant
- Support from engineers on-site for infrastructure and safety
- Permission for background measurements on-site
- Convention (CEA-EDF) for NU-CLEUS in preparation
The Very-Near-Site at CHOOZ

Background measurements ongoing:

Cosmic muons: attenuation by 1.5
Fast neutrons: attenuation by factor $\sim 8$

First results presented at NEUTRINO2018
Publication in preparation
Coherent Neutrino-Nucleus Scattering

Potential for New Physics
Neutrino Non-Standard Interactions

Standard parametrization of modified CEνNS cross-section:

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

With \[ g_V^p = \left( \frac{1}{2} - 2\sin^2 \theta_W \right) \]
and \[ g_V^n = -\frac{1}{2} \]

Additional coupling to u-quark

Additional coupling to d-quark
Neutrino Non-Standard Interactions

Standard parametrization of modified CEνNS cross-section:


\[
\frac{d\sigma}{dE} = \frac{G_F^2 M}{\pi} F^2(2ME) \left[1 - \frac{ME}{2k^2}\right] \times \\
\left\{\left[Z \left(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}\right) + N \left(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV}\right)\right]^2\right. \\
\left.\text{With } g_V^p = \left(\frac{1}{2} - 2\sin^2 \theta_W\right) \right. \\
\text{and } g_V^n = -\frac{1}{2}
\]

COHERENT Experiment 2017

CHARM Experiment 1986

Improve upon existing constraints after few months.
Weak mixing angle

Running of weak mixing angle

\[
\left( \frac{d\sigma}{dE} \right)_{\nu_{\alpha\beta}} = \frac{G_F^2 M}{4 \pi} F^2(2ME) \left[ 1 - \frac{ME}{2k^2} \right] \times \\
\left\{ [Z(g^p_V + 2\varepsilon^u_{\alpha\alpha} + \varepsilon^{dV}_{\alpha\alpha}) + N(g^n_V + \varepsilon^u_{\alpha\alpha} + 2\varepsilon^{dV}_{\alpha\alpha})]^2 \right\}
\]

With \( g^p_V = (\frac{1}{2} - 2\sin^2 \theta_W) \) \( g^n_V = -\frac{1}{2} \)

First determination of the weak mixing angle at \( q = 1\text{MeV/c} \)

CE\nuNS measurement can provide most stringent neutrino constraint

Neutrino magnetic dipole moment ($\nu$MDM)

$\nu$MDM can be written as (minimally extended SM): 

$$\mu_\nu \approx 3.2 \times 10^{-19} (m_\nu/1\text{eV}) \mu_B$$

$\nu$MDM in SM extensions:
M. Fukugita et al., PRL 58 (1987) 1807

$\rightarrow 10^{-12}-10^{-10} \mu_B$ (Majorana)

NU-CLEUS can improve presently best limit on $\nu$MDM to $10^{-12} \mu_B$
$\rightarrow$ Study nature of neutrinos
$\rightarrow$ Indications for new physics

Additive component to CNNS cross-section:

$$\frac{d\sigma_{EM}}{dE_R} \sim \mu_\nu^2 \left(1 - \frac{E_R/E_\nu}{E_\nu} + \frac{E_R}{4E_\nu^2}\right)$$

Conclusions

Coherent neutrino-nucleus scattering: Portal to new physics

Gram-scale cryogenic calorimeters: Miniaturization of neutrino detectors

NU-CLEUS at a nuclear reactor: Explore low-energy neutrino frontier
Conclusions

Coherent neutrino-nucleus scattering: 
**Portal to new physics**

Gram-scale cryogenic calorimeters: 
**Miniaturization of neutrino detectors**

**NU-CLEUS** at a nuclear reactor: 
**Explore low-energy neutrino frontier**

Thank you!
Backup Slides
NU-CLEUS: Dark Matter Results

First limit for dark matter particle masses below 500MeV/c\(^2\) via NR


New parameter space excluded for SIMPs

Cross-Disciplinary: Dark Matter Search

Current experimental limits on Dark Matter

Coherent scattering of solar neutrinos as ultimate background for Dark Matter searches (?)

Precise knowledge of coherent neutrino scattering cross-section and Form factors necessary!


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Nuclear physics: Neutron rms radius


Coherence valid for neutrino energies < 20 MeV (e.g. for CsI)
→ Measurement at low energy breaks degeneracy (cross-section vs. decoherence)

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Solar neutrinos with a table-top experiment


NU-cleus 1kg could get sensitive to pp neutrinos!
Modeling NU-CLEUS Detectors

- Predict performance of calorimeters
- Threshold expectation: **4-10eV regime**

\[ E_{th} = (\text{const.}) \times M^{2/3} \]

arXiv: 1704.04320
NU-CLEUS Detector Prototype

100eV pulse

Trigger Efficiency

Baseline Resolution

0.5g NU-CLEUS detector in new Si holder and different TES

New results from May 2018

$\sigma = (2.88 \pm 0.05)\text{eV}$

$\rightarrow E_{th} \approx 14.4\text{eV}$
Modeling NU-CLEUS Detectors

\[ E_{th} = (\text{const.}) \times M^{2/3} \]

Modeling NU-CLEUS Detectors

Noise level of setup factor 2-3 worse compared to CRESST benchmark setup

$E_{th} = (\text{const.}) \times M^{2/3}$

Sensitivity Study on Sterile Neutrinos

3+1 neutrino model: \[ P_{e \to s} = 1 - \sin^2(2\theta_{14}) \sin^2 \left( 1.27 \frac{\Delta m_{14}^2 d}{E_v} \right) \]

for \( \frac{\Delta m_{14}^2}{E_v} \) in units of \( \text{[eV}^2\text{MeV}] \)

Oscillation maximum at reactor: \( d [\text{m}] \approx 4 / \Delta m_{14}^2 [\text{eV}^2] \)

→ Extend searches to lower \( \Delta m_{14}^2 \)
Sterile Neutrino Search at Reactors

Neutrino flux for global best fit to eV sterile neutrino [JHEP 11 (2017) 099]

For ultimate precision (<5%):
- New evaluation of neutrino fluxes at reactors (e.g. NeNuFar @ CEA)
- add near(er) detector for flux normalization
Measurements at the Very-Near-Site

Muon measurements on-site at CHOOZ

Average attenuation by a factor of 1.4 → Input for MC simulations
The NE\textsc{V}FAR project: New Evaluation of $\nu$ Fluxes At Reactors

Project motivated by anomalies and discrepancies in latest reactor $\nu$ experiments:

\begin{itemize}
  \item Reactor antineutrino anomaly: deficit in the total measured fluxes with respect to predictions
  \item Reactor shape anomaly: distortion in the measured energy spectra
  \item Evolution of measured reactor fluxes with reactor core isotopic composition do not agree with model predictions
\end{itemize}

Refined reactor $\nu$ spectrum calculations along with revised uncertainty budgets. Will include:

\begin{itemize}
  \item details of reactor physics yet unaccounted for in the calculations
  \item refined treatment of $\beta$ branch spectra modeling
  \item extension of the predictions to low energy regime ($E_\nu \leq 1.8$ MeV) for CE\textsc{v}NS
  \item comparison to existing experimental data to address anomalies
\end{itemize}

Cross-disciplinary project involving people working in various fields at CEA:

\begin{itemize}
  \item Matthieu Vivier (PI)/Alain Letourneau (particle & nuclear experimental physics)
  \item Davide Mancusi (simulation for reactor physics)
  \item Xavier Moulgeot (nuclear theoretical physics and nuclear database evaluation)
\end{itemize}

Funded by CEA for a 2-yr post-doc (Anthony Onillon) + a 3-yr PhD (Lorenzo Perisse)

Project started in April 2018

Courtesy: M. Vivier (CEA)
NU-CLEUS: Setup

**Cryogenic infrastructure**
requested in ERC proposal as major equipment (350k€)

**Shielding and muon veto** will be provided by CEA

**Data acquisition** will be provided by HEPHY
Muon Veto and Dead Time

- Rise time governs the onset determination
- Measure rise-times:
  - CaWO$_4$ (this): $\tau_{\text{rise}} = 0.1$ ms
  - Al$_2$O$_3$ (NU-CLEUS): $\tau_{\text{rise}} = 0.1$ ms
  - CaWO$_4$ (24g): $\tau_{\text{rise}} = 1.3$ ms
  - Ge (NTD based): $\tau_{\text{rise}} \approx 10$ ms

**Measurement of pulse onset with a pulsed accelerator beam**

- $\sigma = (4.8 \pm 0.4) \mu$s
- NU-CLEUS: 5-sigma timing of 24$\mu$s

**Dead-time expectation at the Very-Near-Site at CHOOZ**

- Trigger rate of muon veto at the Very-Near-Site derived from dedicated simulation (V. Wagner, CEA)
- Onset-Rise time relation from accelerator experiment

→ **NU-CLEUS detector fast enough for operation in compact shielding** (e.g. ~1% deadtime for (1m)$^3$ veto)
Fighting Backgrounds

Background observed with the NU-CLEUS prototype detector in un-shielded setup.

Fighting Backgrounds

Background level

Shallow site

above ground
no shielding

counts / [kg keV day]
Fighting Backgrounds

- Active muon veto around compact shielding
  - Fast pulse response of NU-CLEUS detectors
  - Dedicated simulation: 1% of dead-time in (1m)$^3$ cubic muon veto

Counts / [kg keV day] vs. Background level

- Shallow site
- Muon veto

Above ground no shielding
Fighting Backgrounds

- Shallow site
- Muon veto
- Passive shielding

Background level

Counts / [kg keV day]

- Above ground: no shielding
- Shallow lab: shielding
Fighting Backgrounds

- Background level
- Shallow site
  - Muon veto
  - Passive shielding
  - Active shielding
- Fiducial volume cryogenic detector
  - Above ground no shielding
  - Shallow lab shielding
  - Fiducial volume cryogenic detector

Counts / [kg keV day]
Fighting Backgrounds

- Shallow site
- Muon veto
- Passive shielding
- Active shielding
- Multi target

Background level

Counts / [kg keV day]

Ultimate background identification by material dependence
Fighting Backgrounds

Neutrino signal

Background level

- above ground no shielding
- shallow lab shielding
- Fiducial volume cryogenic detector

Counts / [kg keV day]

- Shallow site
- Muon veto
- Passive shielding
- Active shielding
- Multi target
Multi-Target Aspect

Coherent neutrino-nucleus scattering rate at 40m to a 4GW reactor
NU-CLEUS Detector: Inner Part

Segmented detector array of cubic $\text{Al}_3\text{O}_3$ and $\text{CaWO}_4$ crystals

Prototype under construction

A fiducial-volume cryogenic detector

Fits into standard commercial cryostat!
First 1g Demonstrator

seed money
Projects R. Strauss
2017 + 2018
20k€

NU-CLEUS, Johannes Rothe
Designed to be **LARGE**

Second stage of NU-CLEUS:

**Detector unit for NU-CLEUS 1kg**

- 6 inch wafer
- 200g array in 1 production step

**A scalable cryogenic detector!**

- Exploiting semiconductor techniques!
- Using Si and Ge wafers
- Multiplexed SQUID readout.

**1kg target, 5 units**
Microwave SQUID Multiplexing

CRESST-type single readout

NIST: 128 channel multiplexer

- Simultaneous readout of 128 channels (bandwidth 300kHz)
- Available bandwidth sufficient for ~1000 channels

+ Contact established with group of L. Gastaldo in Heidelberg (ECHO experiment)

Reactor Physics: 5 MeV bump

Observation in reactor neutrino experiments:

Signature in NU-CLEUS 1kg recoil spectrum

- Independent, complementary probe of the bump
- Clear signature in recoil spectrum
Application of NU-CLEUS Technology

Mobile cryogenic detector

Use neutrinos to monitor nuclear reactors

Surveillance of power plants world-wide

Nuclear non-proliferation

e.g. Phys. Rev. Lett. 113, 042503 (2014)
Fuel content modifies antineutrino spectrum.

Following the scenario of

At 40m distance:
Significance for diversion of fuel elements after 8 days (90% conf.)