Coherent elastic neutrino-nucleus scattering and the NUCLEUS experiment

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Coherent elastic neutrino-nucleus scattering - physics potential

NUCLEUS experiment - status report

Coherent elastic neutrino-nucleus scattering

CEνNS prediction

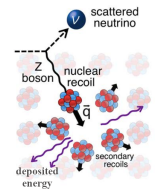
- Predicted[a] by D. Freedman in 1974 (doi:10.1103/PhysRevD.9.1389): a sharp coherent forward peak for the elastic scattering process $\nu + A \to \nu + A$

CEνNS observation

- Observed in 2017 by the COHERENT Collaboration
  - Observed at "6.7σ confidence level, using a low-background, 14.6-kilogram CsI[Na] scintillator exposed to the neutrino emissions from the Spallation Neutron Source" (doi:10.1126/science.aao0990)
  - Subsequent measurement of CEνNS on Ar, with less precision ("over 3σ significance") (doi:10.1103/PhysRevLett.126.012002)
- No other experiment observed CEνNS yet

Characteristics

- Experimental signature: tiny energy deposited by nuclear recoil in the target material
- Coherency: $qR \lesssim 1$
  - Fulfilled for typical nucleus radius R and transferred momentum $\vec{q}$ at $E_\nu < 50$ MeV



Recoil energy kinematic limit

$$T^{\max} = \frac{E_\nu}{1 + M_N/(2E_\nu)}$$

- Typical values
  - $E_\nu \sim 30$ MeV, CsI[Na]: 6.5 keV (COHERENT, stopped-pion neutrinos)
  - $E_\nu \sim 1.3$ MeV: $CaWO_4$: 60 eV, Al_2O_3: 410 eV (NUCLEUS, reactor (anti)neutrinos)

[a] See also Kopeliovich and Frankfurt JETP Lett. 19, 145 (1974)

CEνNS in Standard Model

- CEνNS in the Standard Mode (SM): weak neutral current process - clean prediction of the cross section

$$\frac{d\sigma}{dT} = \frac{G_F^2 M_N}{2\pi}\left\{(G_V+G_A)^2 + (G_V-G_A)^2(1-\frac{T}{E_\nu})^2 - (G_V^2-G_A^2)\frac{M_N T}{E_\nu^2}\right\}$$

  G_F is the Fermi constant, M_N is the nucleus mass, $T = E_\nu - E'_\nu = q^2/(2M_N)$ is the nuclear recoil energy, E_ν (E'_ν) is the energy of incoming (outgoing) neutrino. G_V and G_A are the vector and axial vector weak charges

- For $T << E_\nu$, neglecting axial-vector contributions, radiative corrections, form-factors effects besides the density distributions

$$\frac{d\sigma}{dT} = \frac{G_F^2 M_N}{4\pi}\left(1-\frac{M_N T}{E_\nu^2}\right) Q_w^2 [F_w(q^2)]^2 \tag{1}$$

  where Q_w is the weak nuclear hypercharge $Q_w = Z(1-4\sin^2\theta_W) - N$, and the $F_w(q^2)$ is the weak form factor, with $q = \sqrt{2M_N T}$ the momentum transfer.

$$\frac{d\sigma}{dT} \propto N^2$$

- CEνNS: dominant interaction for neutrinos of energy $E_\nu \leq 100$ MeV; cross section of the order of 10^{-38} cm^2

Measurement of CEνNS

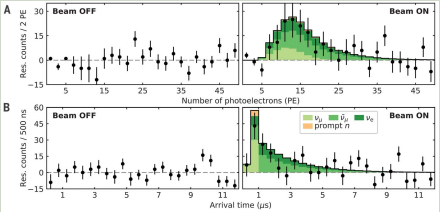
Ingredients for measurement of the CEνNS cross-section

- Measured counts
- Calibration, quenching factors (if necessary)
- Neutrino flux
- Background evaluation
- Predicted cross-section
- Values for other parameters in the cross section
- Uncertainties

Improving chances for measurement

- Periods with reactor on / reactor off
- Detectors requiring no quenching factors
- Coherence regime

COHERENT discovery

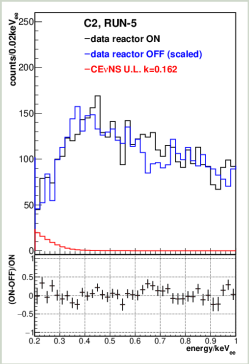


COHERENT, D. Akimov et al., Science 357 (2017) 1123

Measurement of CEνNS - other experiments

CONUS final results – null result

4 PPC HPGe detectors, Brokdorf reactor (Germany, operated until 12/2021)
CEνNS < 0.34 signal events/(kg d)

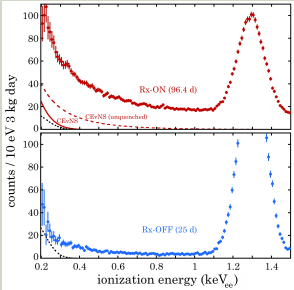


CONUS: N. Ackerman et al., arXiV:2401.07684

DRESDEN – controversial claim

PPC Ge detector, Dresden-II boiling water reactor (US).

Controversial quenching factors (twice as used by other experiments, disagree strongly with CONUS QF), peculiar analysis.



DRESDEN: J. Colaresi et al., PRL 129(2022) 21, 211802

"Constrained by the caveats that present uncertainties in quenching factor, background model and antineutrino spectrum introduce, this dataset provides a very strong preference for an interpretation that includes the Standard Model CEνNS signal, present during periods of reactor operation only."

CEνNS in SM – weak mixing angle

Weak mixing angle

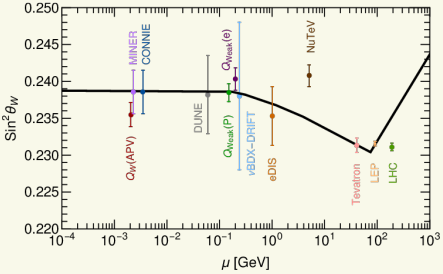
- $\sin^2\theta_W$ well measured at high energy scales
- lack a precise determination at low energy scale

$$\sigma_{\mathrm{CE\nu NS}} \sim Q_w^2$$

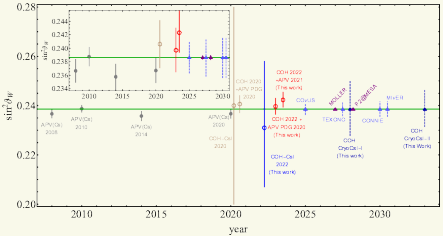
$$Q_w = Z(1 - 4\sin^2\theta_W) - N$$

- $\sin^2\theta_W$ can be extracted from the measured CEνNS counts
- Change of the weak mixing angle implies a different normalization of the CEνNS spectrum

- CEνNS results can be combined with results from Atomic Parity Violation (APV)



M. Abdullah et al., Snowmass 2021 whitepaper, arXiV: 2203.07361



M. Atzori Corona et al., Eur. Phys. J. 83(2023) 7, 683

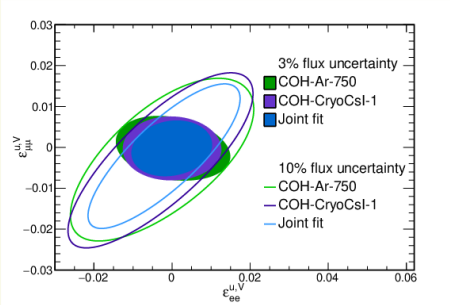
CEνNS beyond SM – non-standard interactions of neutrinos

Non-standard interactions

- parameterize possible new physics effects through the addition to SM Lagrangian of effective higher-dimensional operators
- neutrino physics: inclusion of four-fermion operators leading to the modification of SM Wilson coefficients
- for CEνNS: change Neutral-Current processes involving quarks and neutrinos

Example

$$\mathcal{L}_{NSI}^{NC} \supset -2\sqrt{2}G_F \sum_{\alpha,\beta} \sum_{P,q} \epsilon_{\alpha\beta}^{q,P} (\bar{\nu_\alpha} \gamma^\mu P_L \nu_\beta)(\bar{q}\gamma_\mu P q)$$



Fit of COHERENT CEνNS measurements on different nuclei.
M. Abdullah et al., Snowmass 2021 whitepaper, arXiV: 2203.07361

CEνNS beyond SM – neutrino electromagnetic properties

Motivation

- neutrino are massive (implied by the ν oscillations)
- consequence: neutrino may have non-trivial electromagnetic properties
- the electromagnetic properties reflects in an enhancement of the CEνNS cross section with respect to SM cross section

Neutrino magnetic dipole moment

- non-zero values add incoherently a term (mm) in the cross section (helicity flipping)

$$\frac{d\sigma^{tot}}{dT} = \frac{d\sigma^{SM}}{dT} + \frac{d\sigma^{mm}}{dT}$$

$$\frac{d\sigma^{mm}}{dT} \sim Z^2 |\frac{\mu_\nu}{\mu_B}|$$

Neutrino charge radius

- it preserves the helicity
- taken as a shift in $\sin^2\theta_W$ $(i = e, \mu, \tau)$

$$\sin^2\theta_W \to \sin^2\theta_W + \frac{\sqrt{2}\pi\alpha}{3G_F} < r^2_{\nu_i} >$$

Neutrino electric charge

- modify the $\nu - p$ vector coupling

$$g_V^p(\bar{\nu_e}) \to g_V^p(\bar{\nu_e}) + \frac{2\sqrt{2}\pi\alpha}{G_F q^2} q_{\bar{\nu_e}}$$

M. Abdullah et al., Snowmass 2021 whitepaper, arXiV: 2203.07361

CEνNS beyond SM – Sterile neutrinos

Sterile neutrino

- New gauge singlet fermions are a minimal extension of the SM
- Gauge and Lorentz invariance allow one to write $\mathcal{L} \supset yNHL$
  y: Yukawa coupling; H and L: Higgs and lepton doublets; N: new gauge singlet fermion ("sterile neutrino" or "neutral heavy lepton")
- Searches for sterile neutrinos
  - modified oscillations
  - direct production: sterile neutrino may mix with active neutrinos, so they can be produced in neutrino scattering

CEνNS and sterile neutrino

- CEνNS experiments are sensitive to total active neutrino flux
  - Signature at fixed distance baseline
    - depletion of the flux relative to that predicted by the SM
    - precise knowledge of ν flux from source
  - At different distance baselines
    - compare the energy spectrum of nuclear recoil events
    - independent of the systematic uncertainties associated with the source flux normalization
    - require detectors with sufficient energy resolution
- Many phenomenology papers studying sterile neutrinos with CEνNS, proposals for configurations
  - for COHERENT at the SNS, CCM at the Lujan facility, future CEvNS program at the ESS

CEνNS: interplay SM knowledge - physics beyond SM

Intricate aspect: nuclear-structure input $\longleftrightarrow$ physics beyond the SM

- CEvNS cross sections provide constraints on the combination of nuclear responses and beyond SM (bSM) effects
- $F_w(q^2)$ depends on the nuclear density distribution of protons and neutrons, encoding the entire nuclear dynamics
- current nuclear-structure calculations constrain the neutron distribution to a given level
- to distinguish between nuclear structure and potential bSM contributions, a combined analysis of multiple targets and momentum transfers is required

Coherent elastic neutrino-nucleus scattering - physics potential

NUCLEUS experiment - status report

NUCLEUS Collaboration

Purpose of NUCLEUS collaboration

- Design, build up and operate an experiment to explore coherent elastic neutrino-nucleus scattering (CEνNS), to be installed at EdF Chooz nuclear power plant

Institutes

Collaboration size: ∼60 members

Experimental site

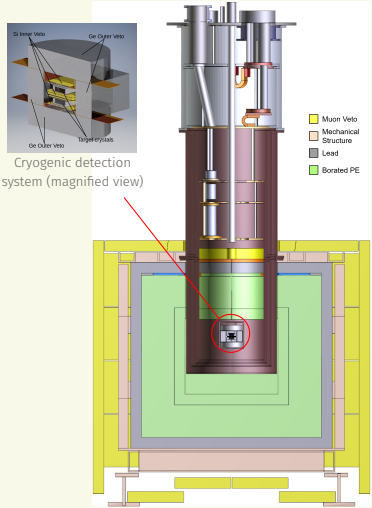
France, EdF Chooz B nuclear power plant

Additional funding

Manpower and financial contributions from Austria, France, Germany, Italy and EU-ERC

NUCLEUS experimental apparatus - overview

Cryostat



Cryogenic detection system (magnified view)

Cryogenic detection system - cryogenic calorimeters at $10\,\mathrm{mK}$

- multi-target approach: two 3x3 arrays of $CaWO_4$ and Al_2O_3 crystals
- silicon inner veto (veto α/β surface contamination)
- HPGe cryogenic outer veto (veto of external γ/n background)

Cryostat

- Bluefors cryostat with pulse tube dilution refrigerator at $10\,\mathrm{mK}$

Muon veto

JINST 17 T05020 (2022)

- 5-cm thick plastic scintillators, SiPM and WLS-fibre read out

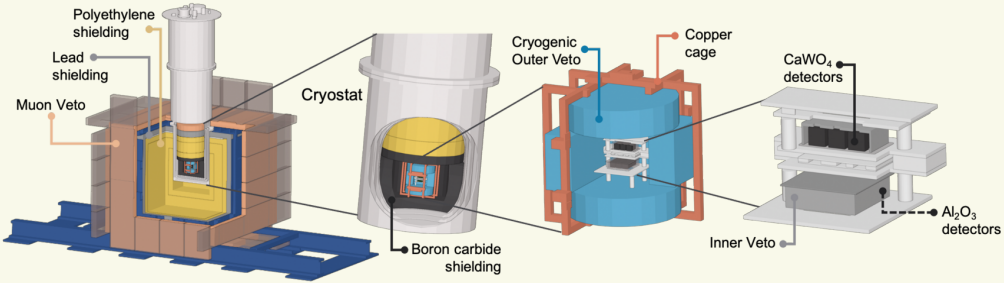
Passive shield

- external layer: 5 cm low radioactivity Pb (reduce ambient γ's)
- inner layer: 20 cm borated PE (reduce neutrons)

Inner cold shield and Cryogenic muon veto - "close the gaps"

- Pb / PE / B_4C / Cu in the cryostat, thermalized at $\sim$800–900 mK
- plastic scintillators, SiPM, WLS for cryogenic muon veto arXiv:2310.08457 EPJC

NUCLEUS detection system – open view

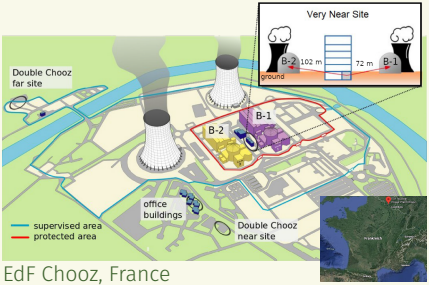


Chooz experimental site

Very Near Site (VNS)

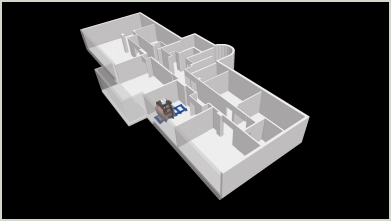
- 24 m^2 basement room in an administrative building in the protected area, 3 m.w.e.

doi:10.1140/epjc/s10052-019-7454-4

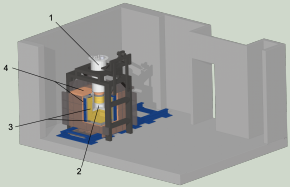


EdF Chooz, France

VNS location in the basement floor



NUCLEUS in the VNS room



Time scale of the NUCLEUS project

2019 ⟶ Sep 2022

Design & realization

Oct 2022 ⟶ Summer 2024

Blank assembly & commissioning

- full experiment assembly at UGL
- commissioning of the detectors
- physics and background model

UGL, TU Munich

Autumn 2024*

Chooz on-site installation

- relocation from UGL to Chooz
- installation at VNS
- quick commissioning

Chooz

Phase 1: measure CEνNS at Chooz nuclear reactor

Technical run, followed by physics run after relocation to Chooz (2025 – 2027)*

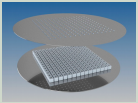
NUCLEUS EdF – CEA convention

Signed for 6 years (2021 – 2027), with possibility of extension for the lifetime of the experiment

Phase 2: high precision CEνNS measurement

Upgrade to NUCLEUS-1kg (2025 - 2030)

Dates pending Phase 1 schedule

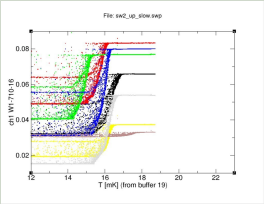


*Dates pending successful commissioning at UGL!

NUCLEUS detectors – commissioning in the CryoLab cryostat (TUM Physics building, 1st floor)

Array production and testing

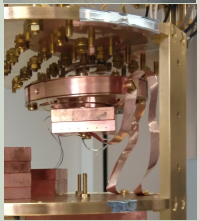
- Sapphire production for NUCLEUS-10g completed, tested for transitions
- $CaWO_4$ arrays: produced, tested for TC



- more detector configurations under development (double TES, etc)

Performance runs - Run 29

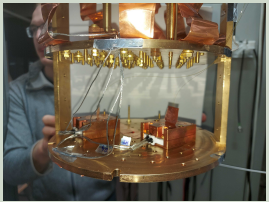
- $CaWO_4$ cube, 6 eV energy resolution with running Pulse Tube, calibration peak at 100 eV



Phys. Rev. Letters, May 2023

Operating cube(s) with inner veto, LED integration

- tests with one cube, two cubes
- 2022 "Christmas run": 2x $CaWO_4$ cubes + Vibration decoupling + 55Fe + LED fiber



NUCLEUS Blank assembly at UGL

Purpose of blank assembly

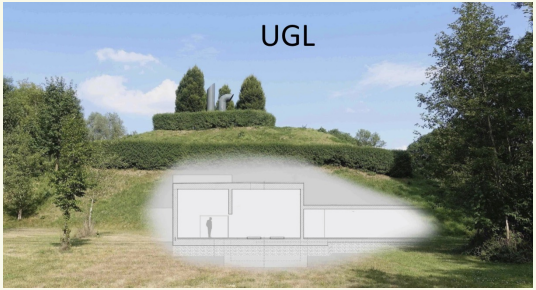
- Chooz is not the nearest and easiest place to work
- Access to Chooz NPP is difficult, both for persons and materials
- Space in VNS is tight
- The procedure to mount the experiment is complicated
- Testing and integrating all the components is slow (cool-down!) and complicated

$\Longrightarrow$ perform a blank assembly at TU Munich Underground Laboratory (UGL)

$\Longrightarrow$ commission each component and the whole experiment

$\Longrightarrow$ study the background at UGL

- although it can not be extrapolated to VNS

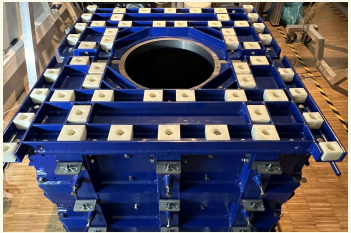


NUCLEUS Blank assembly at UGL - evolution 2023

Cryostat

Muon veto

Passive shielding

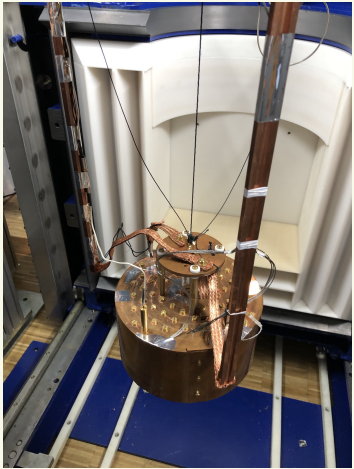


Merging cryostat and Muon veto and passive shielding

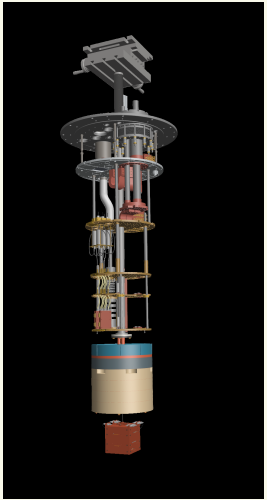
NUCLEUS Blank assembly at UGL - evolution 2023 - inside cryostat

Cryogenic inner shielding

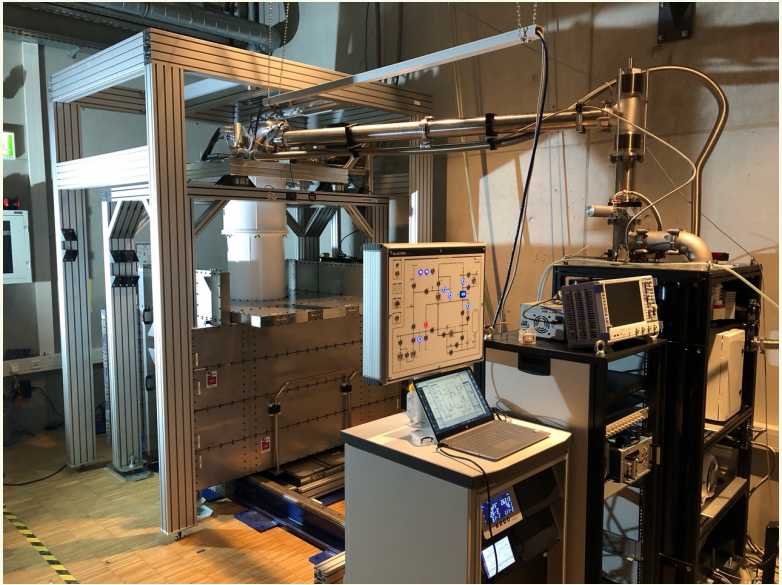
Detector and Cryogenic Outer Veto box



Sketch - cryostat internal



NUCLEUS blank assembly at UGL - current status



NUCLEUS commissioning at UGL

Mounting/dismounting of components

- documented, to be reproducible
- optimization

User manuals

- operation manuals written for each component
- adapted when necessary

Data management (storage, processing), eLog, ...

- data management scheme developed
- use manual scripts for the time being
- more eLog in place, filled
- shift organization

Synchronization of components

- in progress – difficult to be done with ad-hoc solutions for electronics and DAQ software

Thermalization optimization

- adding more material in the cryostat made the thermalization difficult
- improve technical contact between different layers
- reduce the vibration of the cryostat due to the pulse tube
- re-design cold fingers and holders
- we expected a need for optimization, and we are optimist that we can solve the current problems

Noise and grounding

- iterative and complex work to identify the noise sources, to reduce or eliminate the noise
- grounding scheme improved
- multiple on-site analyses, improvements, debugging
- still more effort needed

Chooz experimental site status

Very Near Site (VNS) status

- room floor reinforcement ready
- water chiller: mounted
- electrical installation: ready and tested (Dec 18, 2023: M. Friedl, V. Ghete)
- network infrastructure: ready
- additional compressor room

VNS ready to be used for the experiment!

Chooz NUCLEUS offices

- two new rooms outside protected area available from 2023
  - optic fiber from VNS to NUCLEUS offices
  - one room: to be arranged as (mini) on-site control room
  - meeting room & office

VNS room - 2020

VNS room - end of 2023

RES common contributions to CRYOCLUSTER experiments

VDAQ - Versatile DAQ system for CRYOCLUSTER experiments

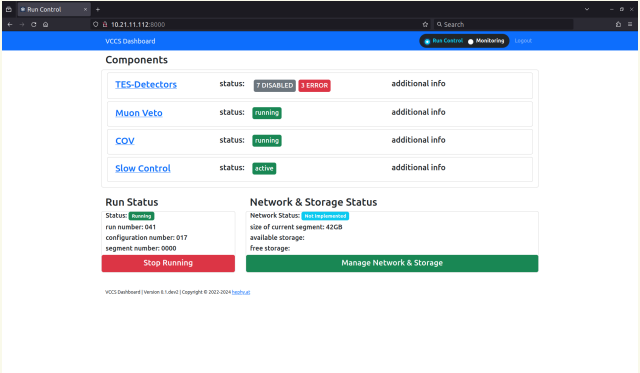
- see Mariano slides

VCCS - Versatile control and monitoring for cryogenic systems

- InfluxDB time series database
- Zabbix IT infrastructure monitoring tool
- Mosquitto lightweight message broker of MQTT web protocol

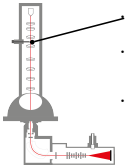
CRYOCLUSTER computing

- data-taking computational aspects
- data transfer and data organization
- computing for data analysis
- software deploying

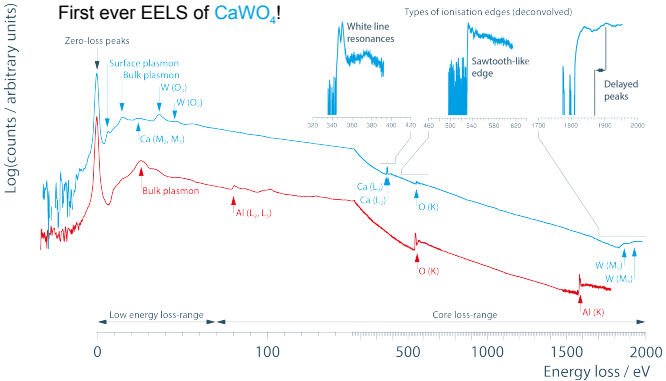


RES: ELOISE – Sub-keV electron energy loss in $CaWO_4$ and Al_2O_3 – results

Electron Energy Loss Spectroscopy (EELS) by M. Stöger-Pollach, TU Wien, USTEM



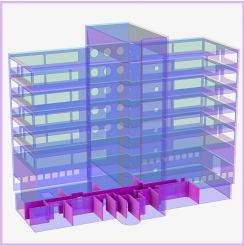
- $CaWO_4$, Al_2O_3 samples provided by NUCLEUS
- Only *single* e- interactions
  - *thin* target (~105 nm)
- Well established method: EELS
  - monochromatic e- (E_0=200 keV)
  - collection angle θ = 28 mrad
  - energy loss: E_0-E'



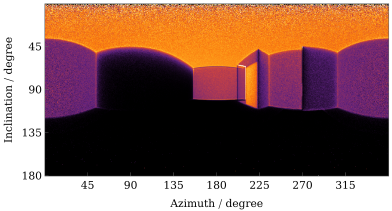
Funded by FWF Der Wissenschaftsfonds. under grant P34778-N, white paper [HK. SciPost Phys. Proc. 12 (2023) 064]

RES: VNS building attenuation of atmospheric neutrons and muons – method

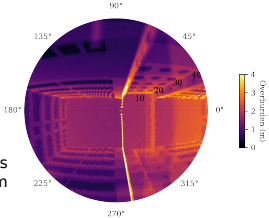
- Neutrons and muons cause major background in shallow lab effects of overburden on **angular** and **energy distribution** need to be understood
- Particles are generated (**Geant4**) on half-sphere around the building and propagated until they reach a wall of the setup room
- Spectra are recorded and studied
- File with recorded particles (position, energy, type, …) serves as input for **second stage**, where the building is removed, and only the NUCLEUS setup is simulated



Implemented geometry



Neutron flux in the setup room, as seen from the target crystals' position

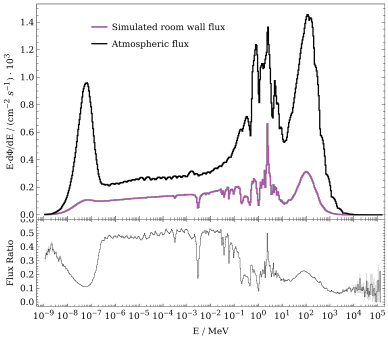


Concrete overburden, as seen from the setup room

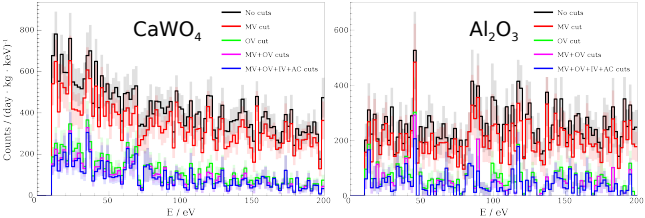
VNS attenuation of atm. neutrons & muons

- Majority of crystal events in energy region of interest (10-100eV) come from neutrons with > 10MeV
- VNS attenuates neutron flux above 10MeV by a factor of **5.63**
- Bonner sphere measurements yield an attenuation factor of $6.63^{+3.15}_{-1.65}$

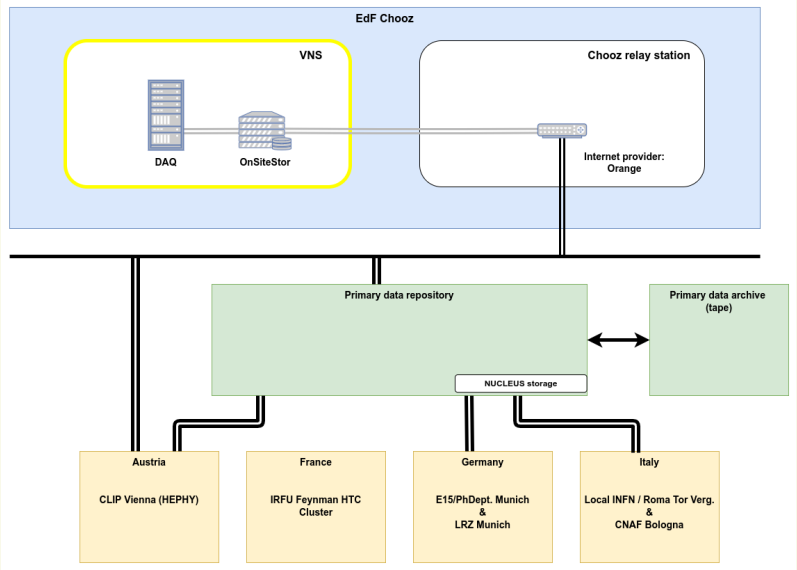
↪ Simulation using implemented VNS geometry is compatible with measurement results



- **Stage 2** simulation yields count rate in $CaWO_4$ targets of **11.6(7) cpd/kg** in ROI
- Expected **CEνNS** rate: **30 cpd/kg**
- Similar study done for muons: VNS attenuates ~22% of muons above 100MeV (stage 2 to be done)



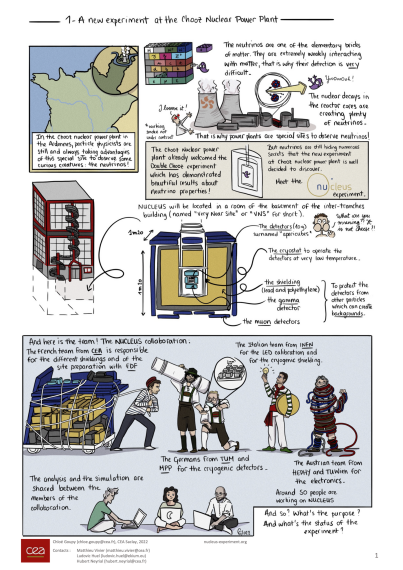
RES: NUCLEUS computing systems



NUCLEUS synergy with Dark Matter research at HEPHY

- Commonalities
  - NUCLEUS uses the same technology as CRESST (cryogenic detectors) - ”CRESST spin-off”
  - the signal analysis for CRESST, COSINUS and NUCLEUS is similar, using the same software
  - the simulation is similar to CRESST and COSINUS (but with different programs)
  - the DAQ system and its software, the electronics is the same as for COSINUS and the same as for the planned upgrade of CRESST
  - CEνNS is an irreducible background to Dark Matter searches
- Differences
  - Different physics, new research program
- Summary
  - We got a top neutrino experiment, with minimal financial and technical effort, complementing the Dark Matter research program

Summary



https://nucleus-experiment.org/

Thank you for your attention!