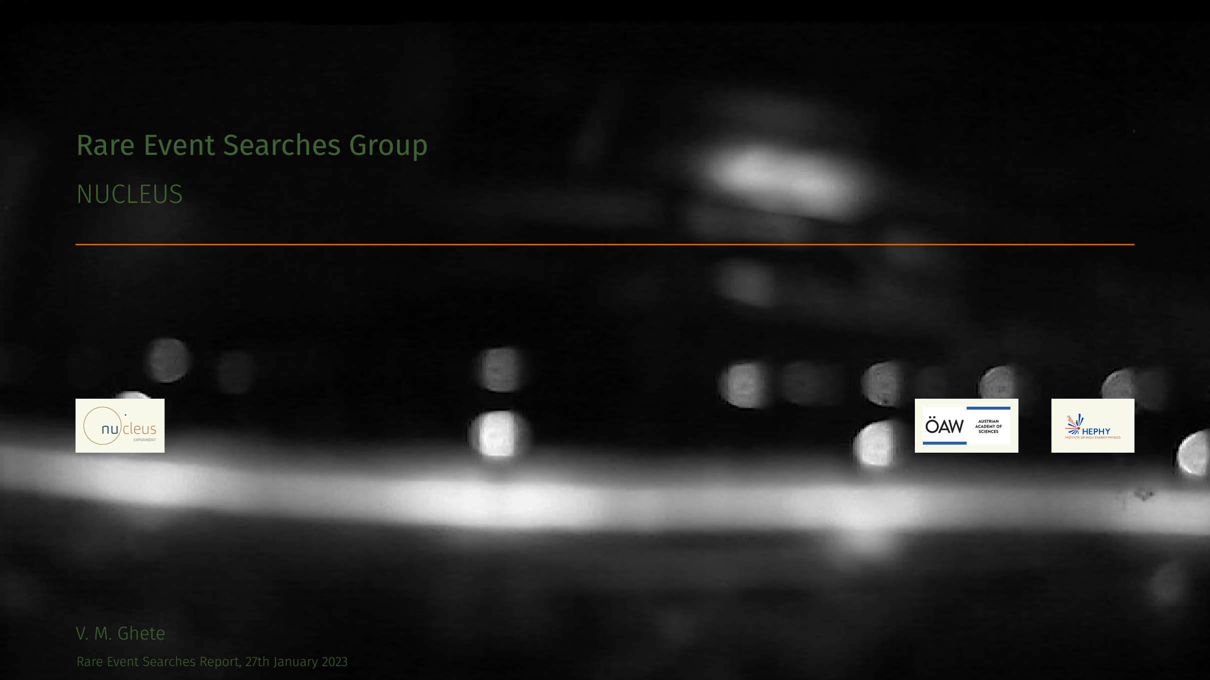


Rare Event Searches Group

NUCLEUS

V. M. Ghete

Rare Event Searches Report, 27th January 2023

Introduction

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: $\sim$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

RES NUCLEUS manpower

	Group	Experiments	Affiliation	Comments/Funds
Staff scientists				
Jochen Schieck	RES	CRESST, COSINUS, NUCLEUS	HEPHY/TU Wien	
Vasile Mihai Ghete	RES	CRESST, NUCLEUS	HEPHY	
Florian Reindl	RES	CRESST, COSINUS, NUCLEUS	HEPHY/TU Wien	
Markus Friedl	Electronics	COSINUS, NUCLEUS	HEPHY	
PostDocs				
Holger Kluck	RES	CRESST, NUCLEUS	HEPHY	FWF P 34778, PI: H. Kluck (2021–2025)
PhD students				
Jens Burkhart	RES	CRESST, NUCLEUS	HEPHY	FWF P 34778 (2022-2025)
Master/Project students				
Leo Maran	RES	NUCLEUS	TU Wien	
Technicians				
Christoph Schwertner	Electronics/RES	CRESST, COSINUS, NUCLEUS	HEPHY/TU Wien	
TU Wien group: part of HEPHY/TU Wien NUCLEUS core group				
Hartmut Abele	Prof.	NUCLEUS	TU Wien	
Erwin Jericha	Prof.	NUCLEUS	TU Wien	
Andreas Doblmayer	PhD	NUCLEUS	TU Wien	
Sebastian Dorer	PhD	NUCLEUS	TU Wien	

The NUCLEUS experiment

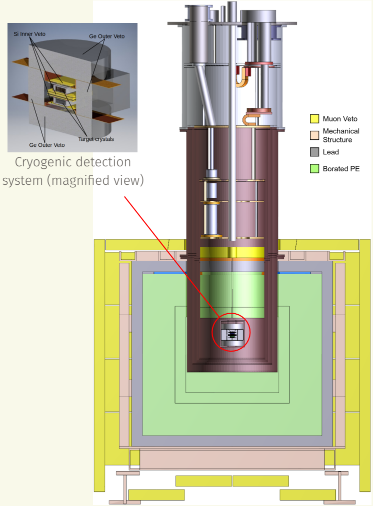
RES common contributions to CRYOCLUSTER experiments

RES contributions to NUCLEUS experiment

Recent NUCLEUS physics results

NUCLEUS experimental apparatus - overview

Cryostat



Cryogenic detection system (magnified view)

Cryogenic detection system - cryogenic calorimeters at 10 mK

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

Cryostat

- Bluefors cryostat with pulse tube dilution refrigerator at 10 mK

Muon veto

JINST 17 T05020 (2022)

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

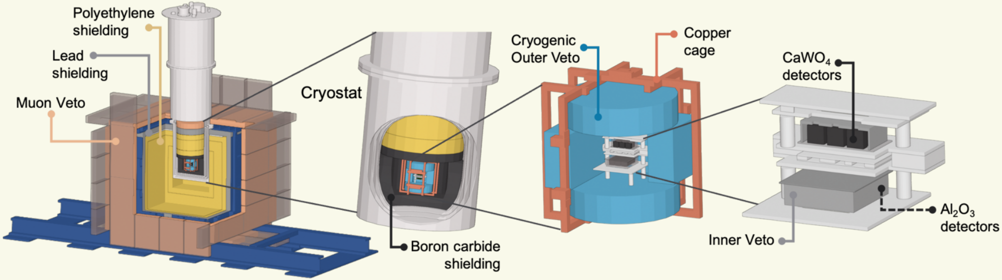
Passive shield

- 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 ~800–900 mK
- plastic scintillators, SiPM and WLS for cryogenic muon veto

NUCLEUS detection system – open view

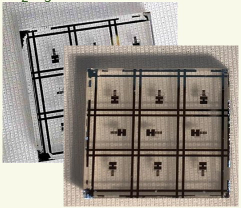


NUCLEUS detection system – fiducial volume

NUCLEUS target detectors

Multi-target approach: two 3×3 arrays

- $CaWO_4$ crystals ($6\,g$)
  - for background and CEνNS measurement
- Al_2O_3 crystals ($4\,g$)
  - essentially for background measurement



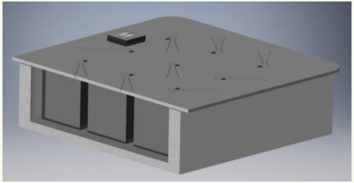
Al_2O_3

$CaWO_4$

Photos show crystal arrays with TES, before cutting

Silicon inner veto

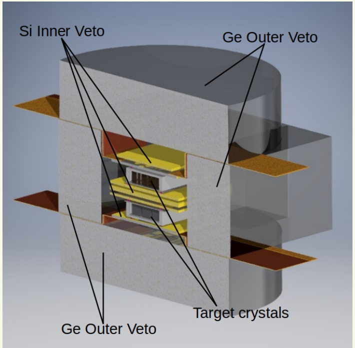
- TES-instrumented holder of crystals
- Veto α/β surface contamination
- Aim for 4π coverage



Silicon inner veto beaker

Germanium outer veto

- HPGe crystals, $2.5\,cm$ thick
- Veto of external γ/n background
- Aim for 4π coverage

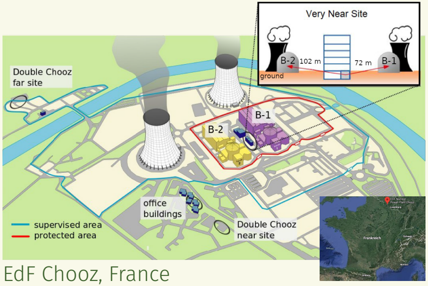


Chooz experimental site

Very Near Site (VNS)

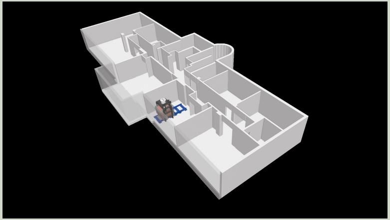
- 24 m^2 basement room in an administrative building in the protected area, 3 m.w.e.

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

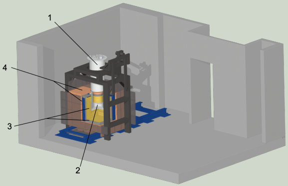


EdF Chooz, France

VNS location in the basement floor



NUCLEUS in the VNS room



Time scale of the NUCLEUS project

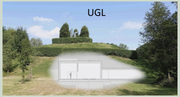
2019 ⟶ Sep 2022

Design & realization

Oct 2022 ⟶ Jan 2024

Blank assembly & commissioning

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



UGL, TU Munich

Spring 2024

Chooz on-site installation

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

Chooz

Phase 1: measure CEνNS at Chooz nuclear reactor

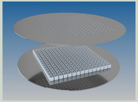
Physics run after relocation to Chooz
(Mid 2024 – 2027(?))

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

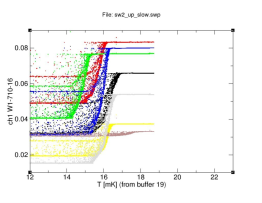
Upgrade to NUCLEUS-1kg (2025 - 2030(?))



NUCLEUS detectors – status

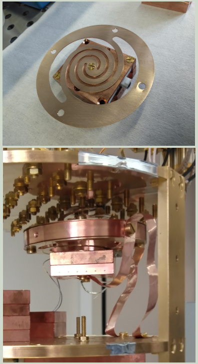
Array production and testing

- Sapphire production for NUCLEUS-10g completed, tested for transitions
- CaWO$_4$ arrays: produced, under testing for TC



Performance runs - Run 29

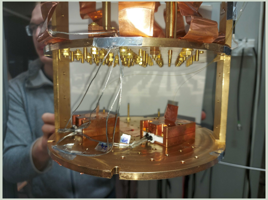
- CaWO$_4$ cube, 6 eV energy resolution with running Pulse Tube



arxiv.org/2211.03631 (Nov 2022)

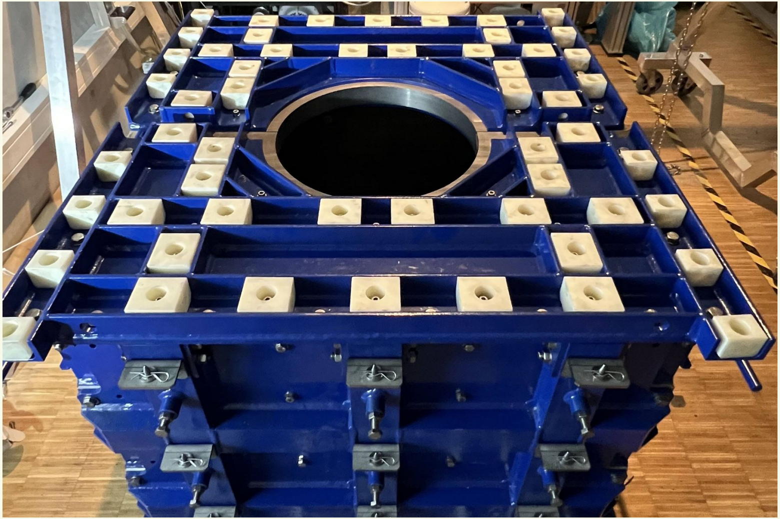
Operating cube(s) with inner veto, LED integration

- tests with one cube, two cubes
- 2022 "Christmas run": 2x CaWO$_4$ cubes + Vibration decoupling + 55Fe + LED fiber



NUCLEUS Muon Veto assembly at UGL

NUCLEUS Passive Shielding assembly at UGL (Mechanical structure & Lead)



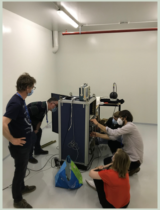
Chooz experimental site status

Very Near Site (VNS) status

- room floor reinforcement ready
- electrical installation, water chiller: due Feb 2023
- network infrastructure: T1 2023

VNS room - 2020

VNS room - measurements April 2022



VNS room – end of 2022

The NUCLEUS experiment

RES common contributions to CRYOCLUSTER experiments

RES contributions to NUCLEUS experiment

Recent NUCLEUS physics results

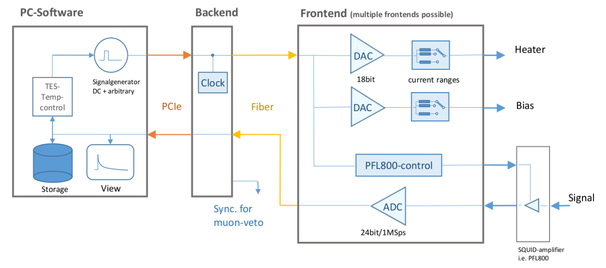
RES: VDAQ - Versatile DAQ system for CRYOCLUSTER experiments

VDAQ

- modular
- scalable
- highly customisable
- fast

VDAQ status - progress despite delivery problems

- PCB design (4 flavors) completed
- Mechanical mock-ups built for every type
- Tender for prototype and series production completed, contract signed
- Prototypes available in Feb 2023
- First production series expected mid of 2023

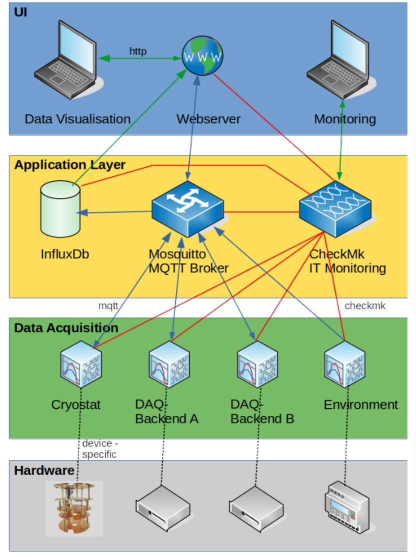


RES: VCCS - Versatile control and monitoring for cryogenic systems

Based on

- InfluxDB time series database
- CheckMK monitoring tool for network, hosts and processes
- Mosquitto lightweight message broker of MQTT web protocol

Status – in progress



RES: Computing and software for CRYOCLUSTER experiments

Computing

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

Software packages: analysis of raw data

- CAT ”Cryogenic Analysis Tools”, C++
- CAIT ”Cryogenic Artificial Intelligence Tools - A Python package for the raw data analysis with machine learning.”

Software packages: high-level analysis of data - mainly CRESST

- ROMEO ”Complete statistical analysis tool for CRESST-style detectors; unbinned likelihood approach”, Julia
- Limitless ”a likelihood band fit + limit setting program”

The NUCLEUS experiment

RES common contributions to CRYOCLUSTER experiments

RES contributions to NUCLEUS experiment

Recent NUCLEUS physics results

RES: NUCLEUS management

Management positions

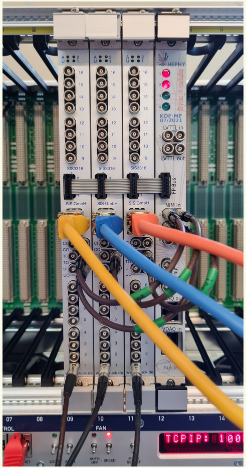
- HEPHY PI: V.M. Ghete
- M. Friedl Electronics coordinator
- V.M. Ghete Computing coordinator

RES: NUCLEUS electronics

Contributions

- design, produce, maintain and finance the whole DAQ system, based on VDAQ
- provide the control and monitoring software, based on VCCS
- provide and coordinate the site computing systems

Muon Veto DAQ



SiPM control module

RES: NUCLEUS simulation

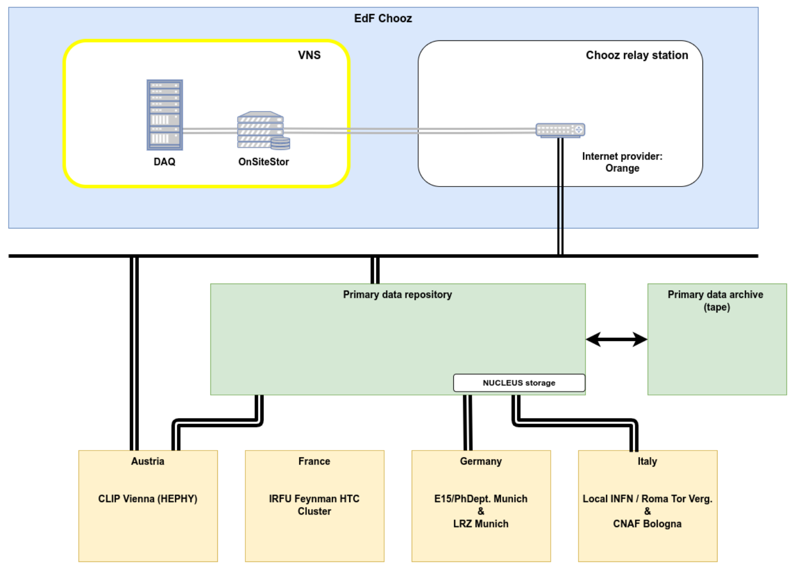
NUCLEUS simulation

- RES was involved in NUCLEUS simulation from the first idea of NUCLEUS as experiment
- extensive studies of experiment design and optimization, background estimation, etc

FWF project: ELOISE - Reliable background simulation at sub-keV energies (H. Kluck)

- implement CEvNS in Geant4 – long-term goal: validate it with NUCLEUS!
  - need validated background model at sub-keV
- validate Geant4 em processes below 250eV
  - if needed, extend/improve Geant4 down to ∼30 eV (onset of solid state effects)
  - compare to NUCLEUS blank assembly measurements at UGL
- measure experimental reference data with electron energy-loss spectroscopy of Al_2O_3 and $CaWO_4$ – ongoing, in cooperation with TU Wien

RES: NUCLEUS computing systems



The NUCLEUS experiment

RES common contributions to CRYOCLUSTER experiments

RES contributions to NUCLEUS experiment

Recent NUCLEUS physics results

In-situ calibration using a nuclear recoil peak at 100 eV scale induced by neutron capture

CRAB–NUCLEUS calibration: collaboration between CRAB and NUCLEUS Collaborations

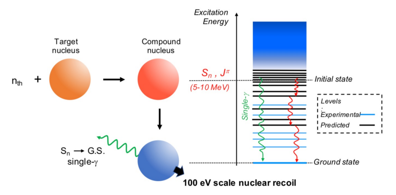
"Observation of a nuclear recoil peak at the 100 eV scale induced by neutron capture"

arxiv.org/2211.03631 (Nov 2022)

Motivation: calibration of nuclear recoil signature at 10 – 100 eV scale

- Cryogenic detectors can measure very low nuclear recoils - need calibration in this range
- Use capture of thermal neutrons in crystals, followed by single-γ de-excitation
- use a commercial ^{252}Cf neutron source
- for CaWO$_4$: expect a peak at 112.5 eV
  - single-γ de-excitation of ^{183}W after capturing a neutron on ^{182}W
  - $E_\gamma = 6.2$ GeV: γ escapes the gram-scale crystal, so pure nuclear recoil signal

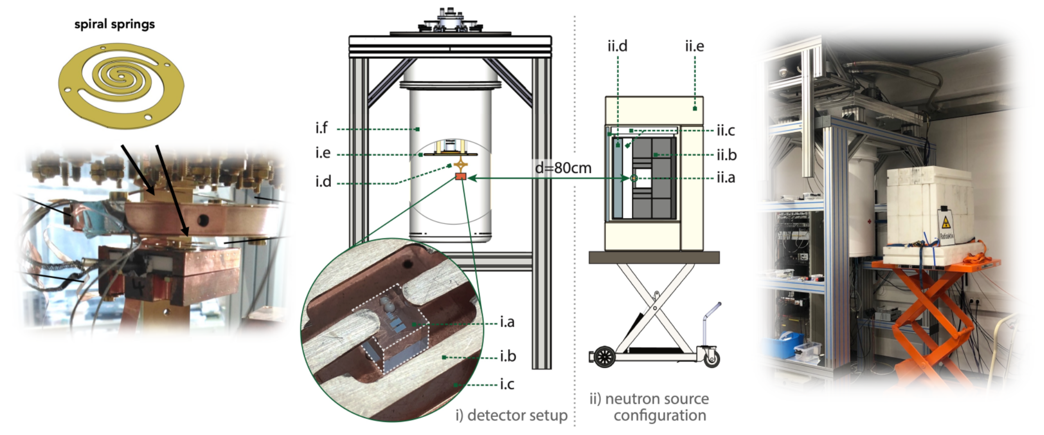
Principles of calibration



Tools

- Simulation tools: Geant4 package, FIFRELIN code (precise fission modelling)
- Analysis tools: CAT, DIANA

CRAB–NUCLEUS calibration - Run 29 setup *(contd.)*

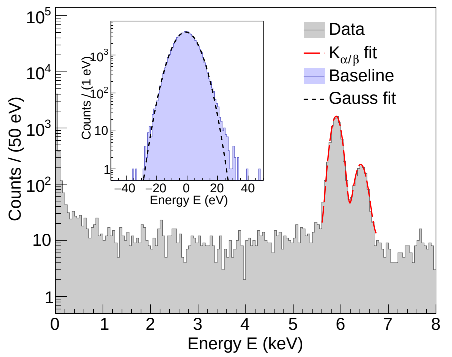


CRAB–NUCLEUS calibration - Results *(contd.)*

Standard electronic recoil calibration with ^{55}Fe source

- $K_\alpha = 5.985\,\mathrm{keV}$ (weighted average)
- $K_\beta = 6.490\,\mathrm{keV}$
- K_α and K_β clearly separated
- simple linear extrapolation of the energy calibration towards lower pulse heights

Energy spectra for measurements with ^{252}Cf source



CRAB–NUCLEUS calibration - Results *(contd.)*

Peak finding analysis

Maximum likelihood method with Poisson statistics

- two independent fits

$$f^{bck} = ae^{-bx} + ce^{-dx}$$

$$f^{bck+sig} = f^{bck} + \frac{a_2}{\sqrt{2\pi\sigma}} \cdot e^{-\frac{1}{2}(\frac{x-\mu}{\sigma})^2}$$

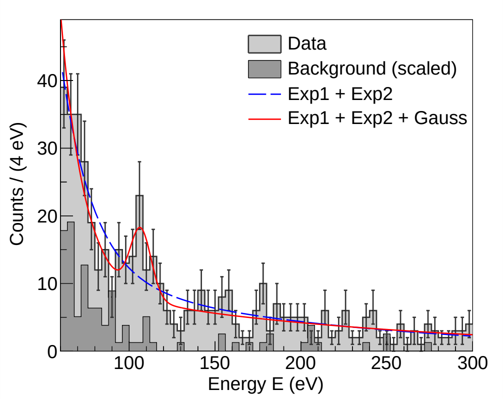
- statistical test

$$t = -2\ln\left(\frac{\mathcal{L}_{\text{bck}}}{\mathcal{L}_{\text{bck+sig}}}\right)$$

Results

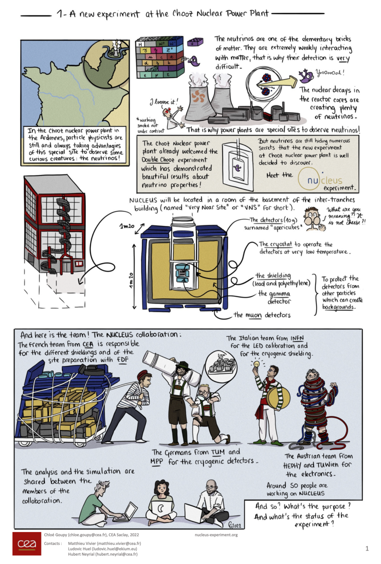
- Significance: 3.1 σ [non-existence of a Gaussian peak is rejected with 3.1 σ (2-sided].
- Gaussian peak: $\mu_{\text{peak}} = 106.7^{+1.9}_{-2.0}$ eV, $\sigma_{\text{peak}} = 6.0^{+1.6}_{-1.4}$ eV and an integral of $37.3^{+9.7}_{-9.0}$ counts.

Energy spectra for background (w/o source) measurements and measurements with ^{252}Cf source [0, 300 eV]



Submitted to Physical Review Letters: both referees recommend the publication!

Summary



1- A new experiment at the Chooz Nuclear Power Plant

In the Chooz nuclear power plant in the Ardennes, particle physicists are still and always taking advantagies of this special site to observe some curious creatures: the neutrinos!

The neutrinos are one of the elementary bricks of matter. They are extremely weakly interacting with matter, that is why their detection is very difficult.

The nuclear decays in the reactor cores are creating plenty of neutrinos.

That is why power plants are special sites to observe neutrinos!

The Chooz Nuclear power plant already welcomed the Double Chooz experiment which has demonstrated beautiful results about neutrino properties!

But neutrinos are still hiding numerous secrets that the new experiment at Chooz nuclear power plant is well decided to discover.

Meet the nucleus experiment.

NUCLEUS will be located in a room of the basement of the inter-tranches building (named "Very Near Site" or "VNS" for short).

The detectors (10g) surnamed "apericubes"

The cryostat to operate the detectors at very low temperature.

the shielding (lead and polyethylene)

the gamma detector

the muon detectors

To protect the detectors from other particles which can create backgrounds.

And here is the team! The NUCLEUS collaboration:

The French team from CEA is responsible for the different shieldings and of the site preparation with EDF

The Germans from TUM and MPP for the cryogenic detectors.

The Italian team from INFN for the LED calibration and for the cryogenic shielding.

The Austrian team from HEPHY and TUWien for the electronics.

The analysis and the simulation are shared between the members of the collaboration.

Around 50 people are working on NUCLEUS

And so? What's the purpose? And what's the status of the experiment?

Chloé Goupy (chloe.goupy@cea.fr), CEA Saclay, 2022

nucleus-experiment.org

Contacts :
Matthieu Vivier (matthieu.vivier@cea.fr)
Ludovic Huel (ludovic.huel@ekium.eu)
Hubert Neyrial (hubert.neyrial@cea.fr)

1

https://nucleus-experiment.org/

Thank you for your attention!