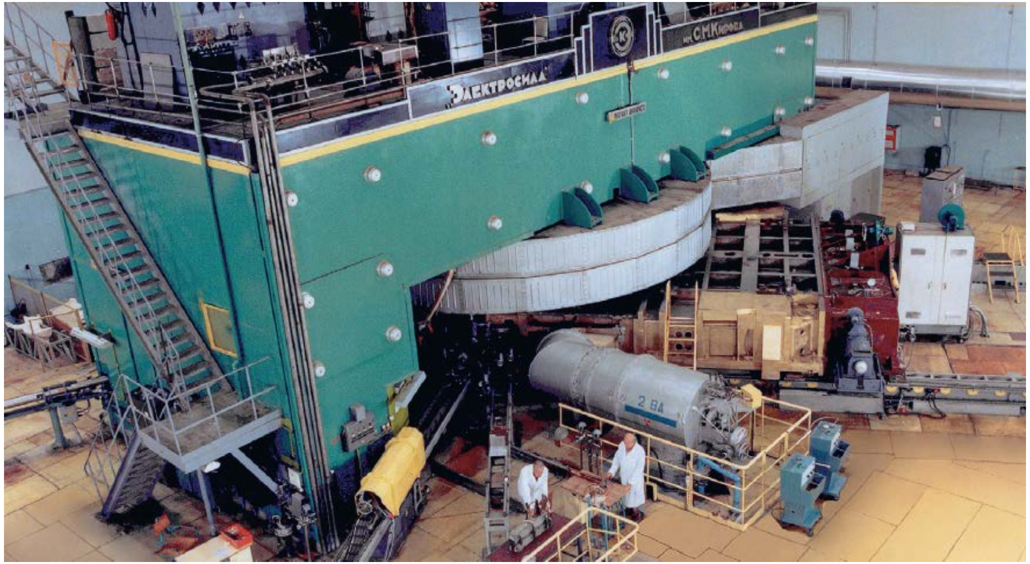
Review of nuclear physics at Dzelepov Laboratory of nuclear problems

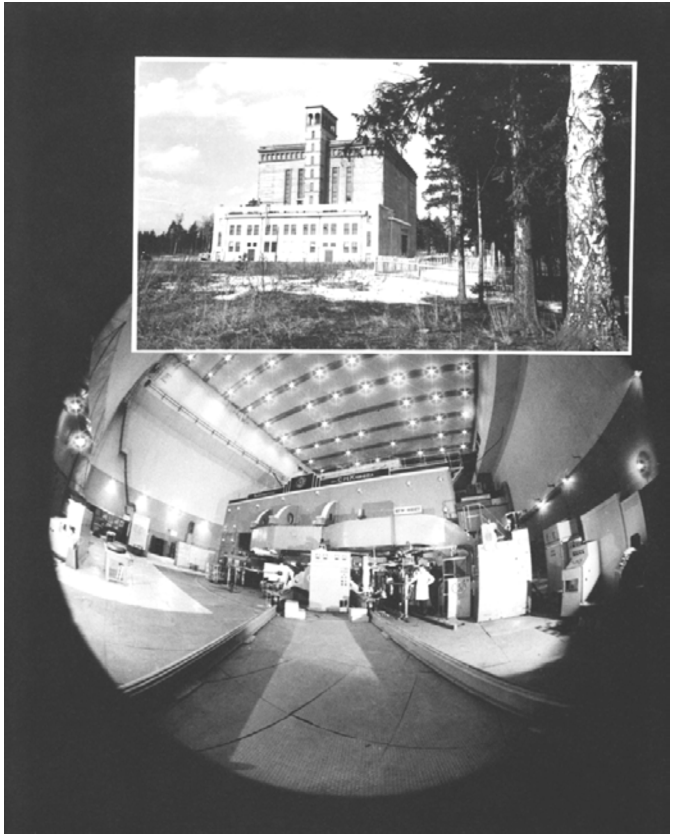
Evgeny Yakushev

58th meeting of the PAC for Nuclear Physics
Dubna, 2024

In August 1946, soon after the discovery of the principle of phase stability of particle motion in particle accelerators (V. Veksler, 1944, E.McMillan, 1945), the USSR government decided to build a large synchrocyclotron.

- First test start: night December, 13-14th 1949;
- After modernization in 1980th proton energy up to 680 MeV;
- Different targets were irradiated by protons;
- Isotopes created in the targets were used to nuclear physics studies, in particular by different spectrometry methods;





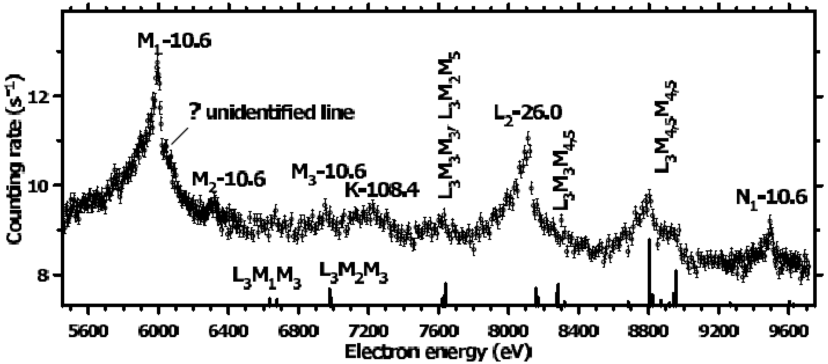


Figure 1. The low energy electron spectrum from the ^{225}Ac α-decay measured in the region from 5.5 to 9.7 keV.

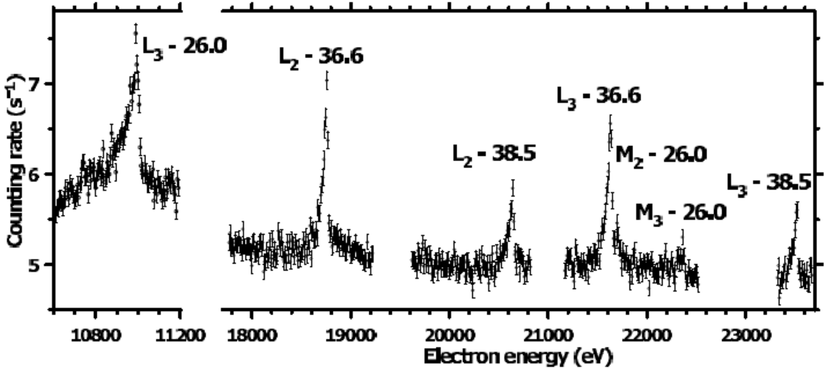
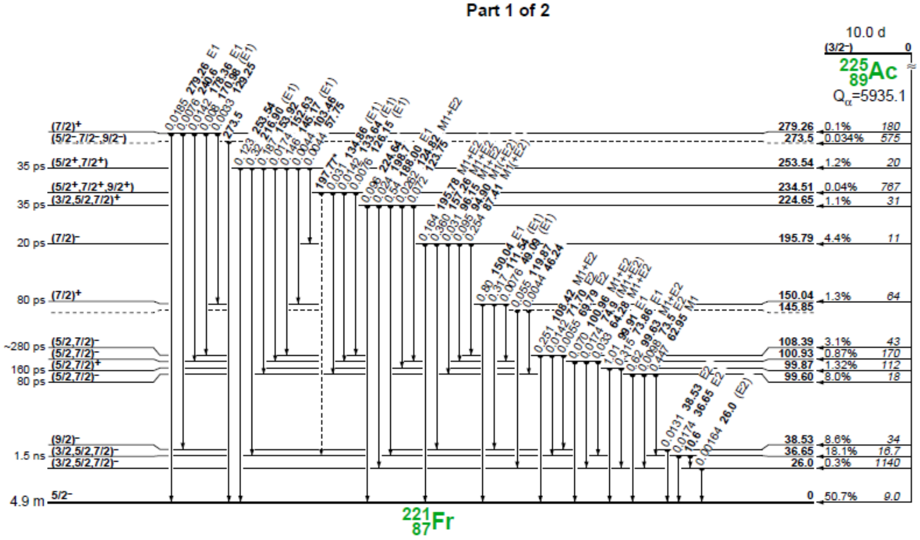


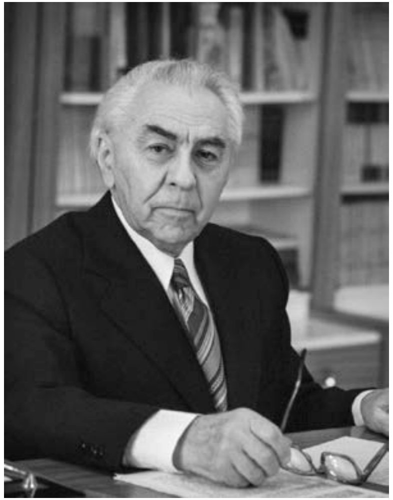
Figure 2. The experimental spectra of the L_3-, $M_{2,3}$-26.0, $L_{2,3}$-36.6, $L_{2,3}$-38.5 conversion lines of ^{221}Fr measured in the present work.



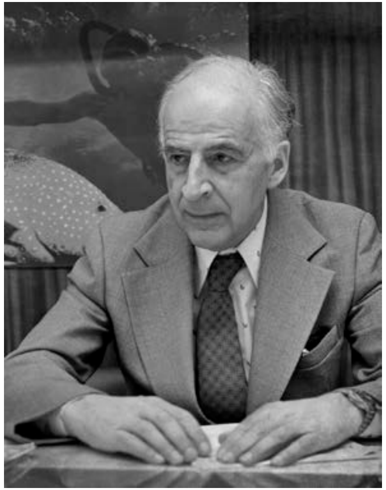
In 1980th the Laboratory started to use accumulated experience and methods to study neutrinos

Main scientific directions of the Laboratory now:

- ➢ Neutrino physics and astrophysics
- ➢ High energy physics
- ➢ New detectors, radiochemistry, applied research, biology, medical research



DZHELEPOV LABORATORY of NUCLEAR PROBLEM



- high-precision nuclear spectroscopy using semiconductor, scintillator and other types of detectors;
- experience in the production of radionuclides and radiopharmaceutical synthesis;
- experience in hyperfine interaction nuclear spectroscopy;
- etc.

Nuclear physics approaches are remained the basis of DLNP scientific program.

Research directions are:

- ❑ classical spectrometry of (with) radioactive isotopes
- ❑ search for evidences of new physics beyond the Standard Model

  - ➢ investigation of double beta-decay with different calorimetric and treko-calorimetric methods;
  - ➢ investigation of neutrino properties from different sources;
  - ➢ search for Dark Matter, etc;
  - ➢ significant part of the laboratory scientific program is devoted to investigation of processes inside of nuclear reactor core with neutrinos.

Our nuclear physics research work is impossible without

I.

- ➢ development of new methods for detection of charged and neutral particles

- ➢ development of modern radiochemistry for astrophysics and nuclear medicine.

Our nuclear physics research work is impossible without

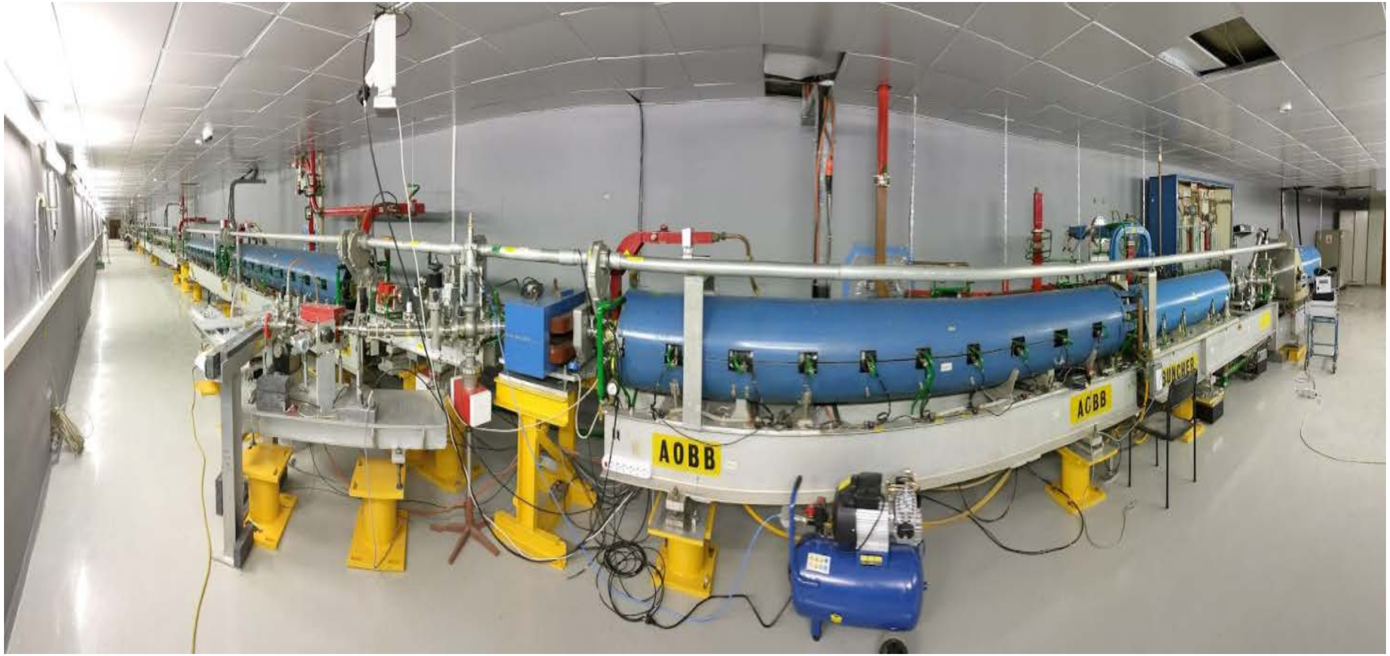
II. Basic facilities

- LINAC-200/800 electron accelerator (test runs ok, required some paper work to run);
- A spectrometry cluster;
- The radiochemistry laboratory: ICP-MS spectrometry, Mössbauer spectrometry, improved methods of perturbed angular correlations to study of radiopharmaceuticals and their precursors as well for development of cleanest materials for neutrino related studies;
- Positron spectrometry;
- New basic facility that is in process of creation: MSC230 proton cyclotron which will be the core for new proton therapy clinical research center.

JINR infrastructure experiment: BAIKAL-GVD

LINAC -200

The linear accelerator LINAC-200 at JINR is a new facility, constructed to provide electron test beams to carry out particle detectors R&D, to perform studies of advanced methods of electron beam diagnostics, and for applied research.



Two test beam channels tested and will be ready for users in 2024

5-25 MeV

40-200MeV

Parameter	Beam extraction point № 1 (EP1)	Beam extraction point № 2 (EP2)
Electron energy, MeV	5–25	40–200
Pulse duration, μs	0.2–3.5	
Max. pulse current, mA	60	40
Pulse repetition rate, Hz	1–50	1–25

RESEARCH PROGRAM AT THE LINAC-200

- Study the characteristics and calibration of elementary particle detectors;
- Applied research (radiation materials science, radiation genetics);
- Investigation of the characteristics of detectors for the straw tracker of the SPD facility;
- Study of the characteristics (efficiency, spatial resolution, maximum load) of gas detectors of the bulk Micromegas type for the SPD and AMBER experiments;
- Calibration of detectors for the COMET experiment on low-intensity electron beams with energies up to 100 MeV;
- Calibration of dosimetric instruments;
- Study of silicon pixel detectors for the vertex tracker of the MPD and SPD experiments;
- Calibration of electromagnetic calorimeter modules for the SPD experiment;
- Study of photonuclear reactions.

Cross sections for photoneutron reactions $^{107}Ag(\gamma,n)^{106g}Ag$ (a) and $^{107}Ag(\gamma,2n)^{105}Ag$ (b).

Chinese Physics C

PAPER

Interaction of photons with silver and indium nuclei at energies up to 20 MeV*

J. H. Khushvaktov[1,2], M. A. Demichev[1], D. L. Demin[1], S. A. Evseev[1], M. I. Gostkin[1], V. V. Kobets[1], F. A. Rasulova[1,2], S. V. Rozov[1], E. T. Ruziev[2], A. A. Solnyshkin[1], T. N. Tran[1,3], E. A. Yakushev[1] and B. S. Yuldashev[1,2] – Hide full author list

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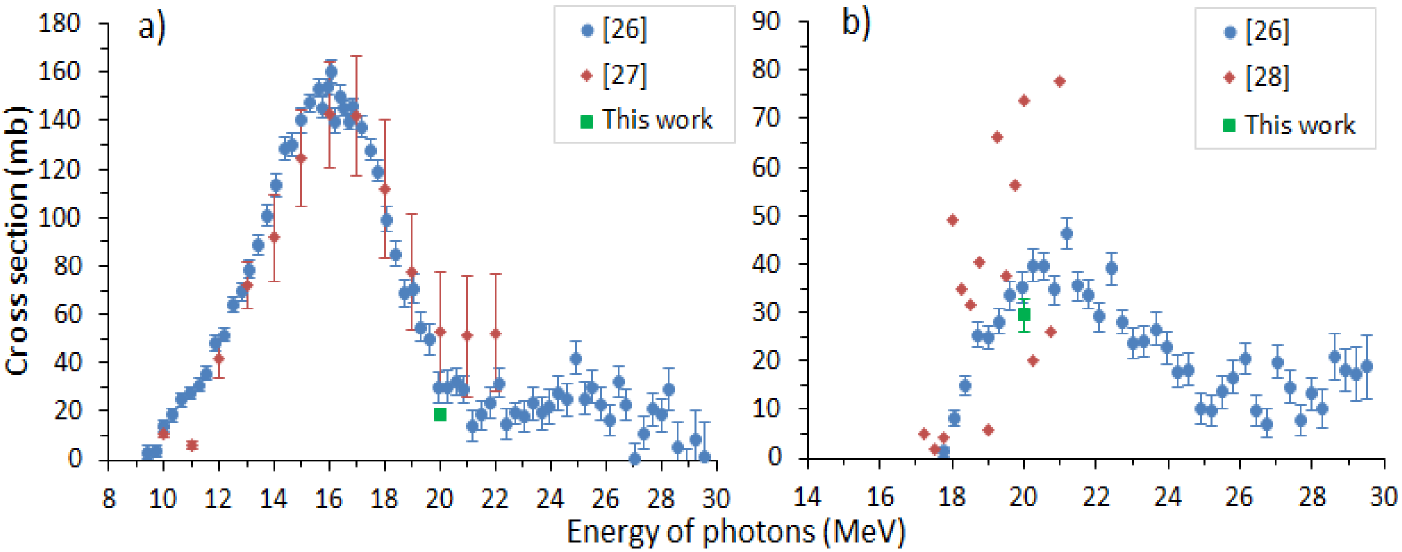


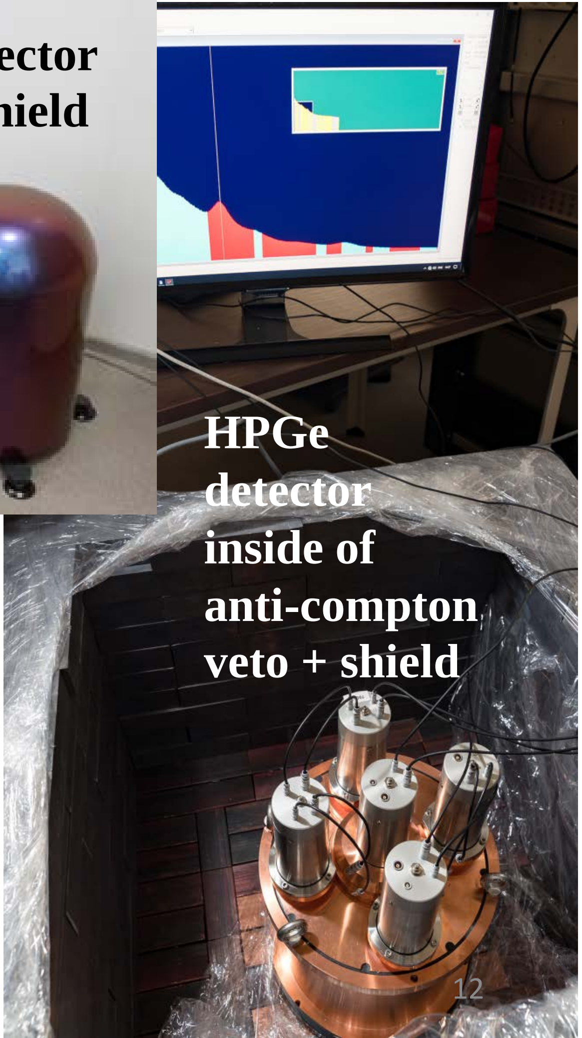
New basic facility: a spectrometry cluster

The laboratory has a lot of different types of detectors (HPGe, scintillators, etc) and a lot of requests from inside of the laboratory and often from outside to perform different spectrometry measurements.

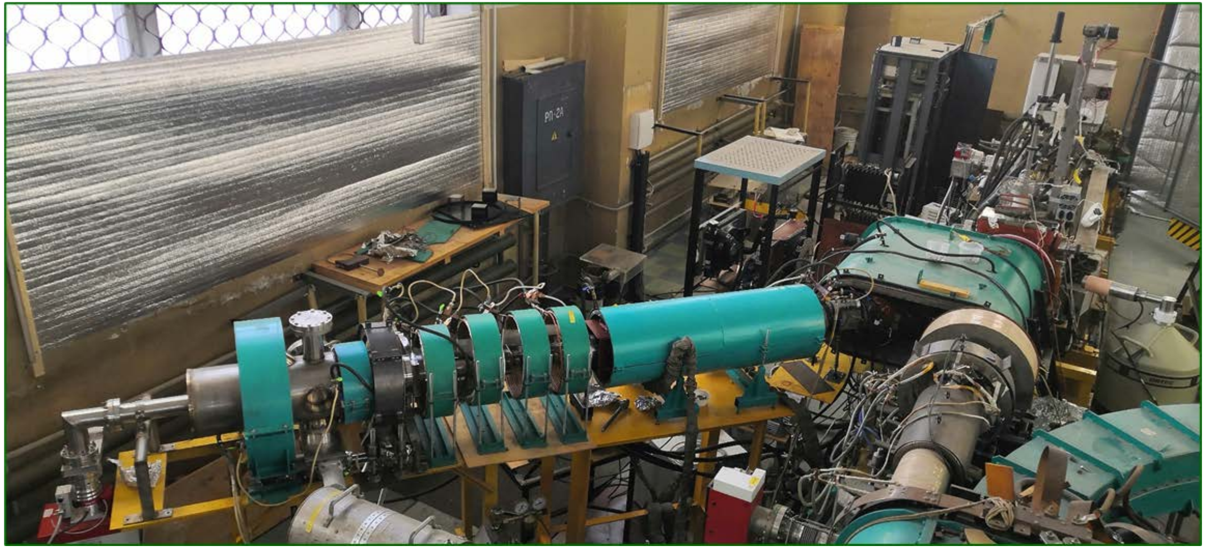
The cluster will have ~10 different size/shape HPGe detectors, NaI, CsI, organic scintillators, etc: all can be proposed for use in joint measurements (user committee, availability, schedule).

We have staff and experience to organize such work – this will be also highly useful for our student (DLNP) to do a real measurements and MC with real detectors.

This work will be headed by J.Khushvaktov (Uzbekistan), we also invited one person from Egypt with having in mind this project, some other personal from Uzbekistan, Russia also available.



Applied research with slow monochromatic positron beams (PAS)



- **Study of the formation of defects in materials**
- **Study of materials for detectors (Moscow)**

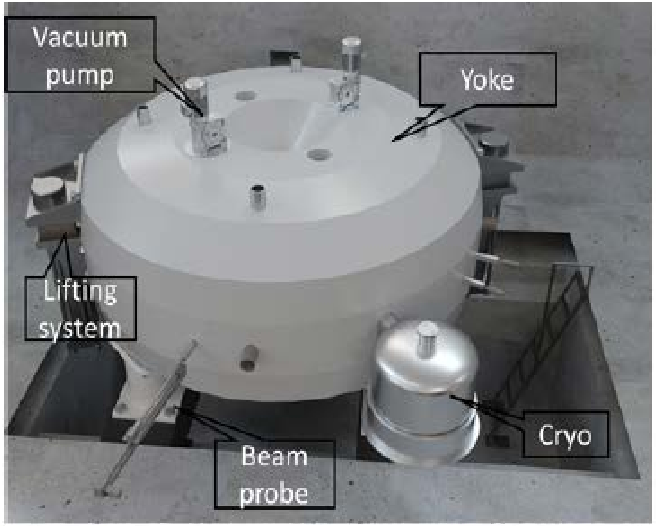
MSC-230 cyclotron

MSC230 is intended for basic research in radiobiology, biomedicine, and for beam therapy (proton ~10 mkA, 50msec, > 5Gr/l/s).

TDR is completed.

Superconducting coils are prototyping and scheduled for summer 2024.

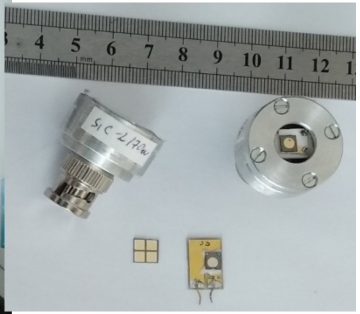
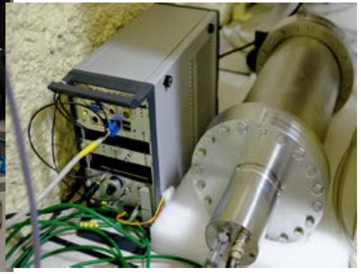
Other technical systems are in process of procurement and manufacturing.



Novel detectors

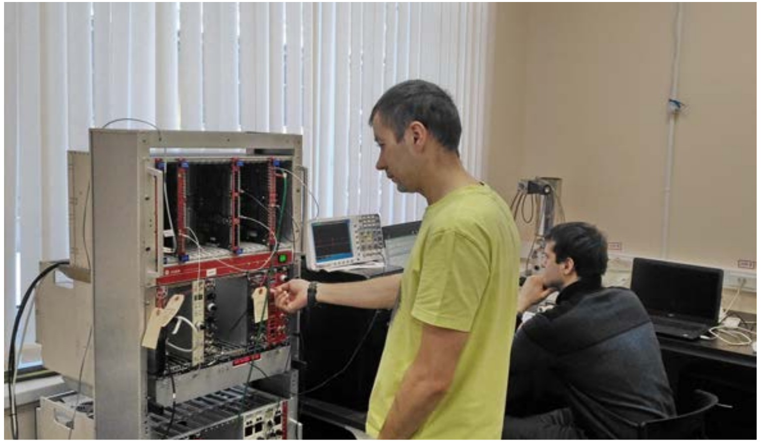
DLNP is widely known as the laboratory leading in development of new methods for detection of charged and neutral particles:

semiconductor detectors, liquid and plastic organic scintillators, composite scintillation detection systems, neutron and radon detectors, etc.

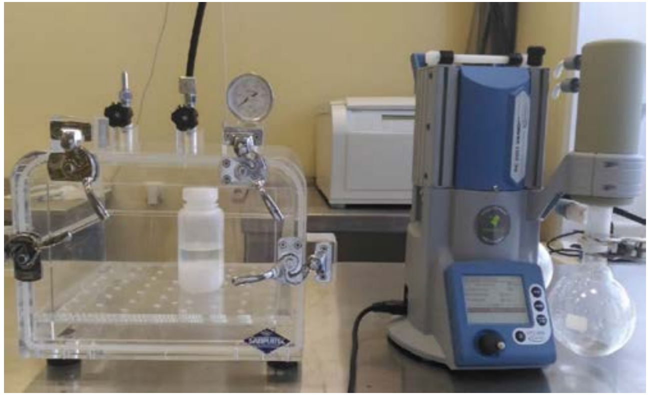
Infrastructure in the Laboratory

Facilities for works/test/repair semiconductor detectors

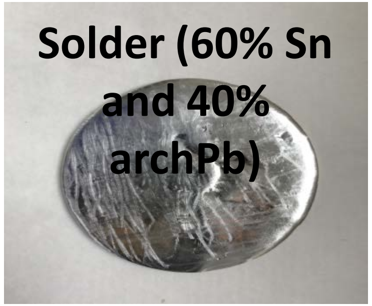


Radiochemistry and spectroscopy for astrophysics and nuclear medicine

Methods and techniques for the production and analysis of low-background materials



Radiopure ^{82}Se

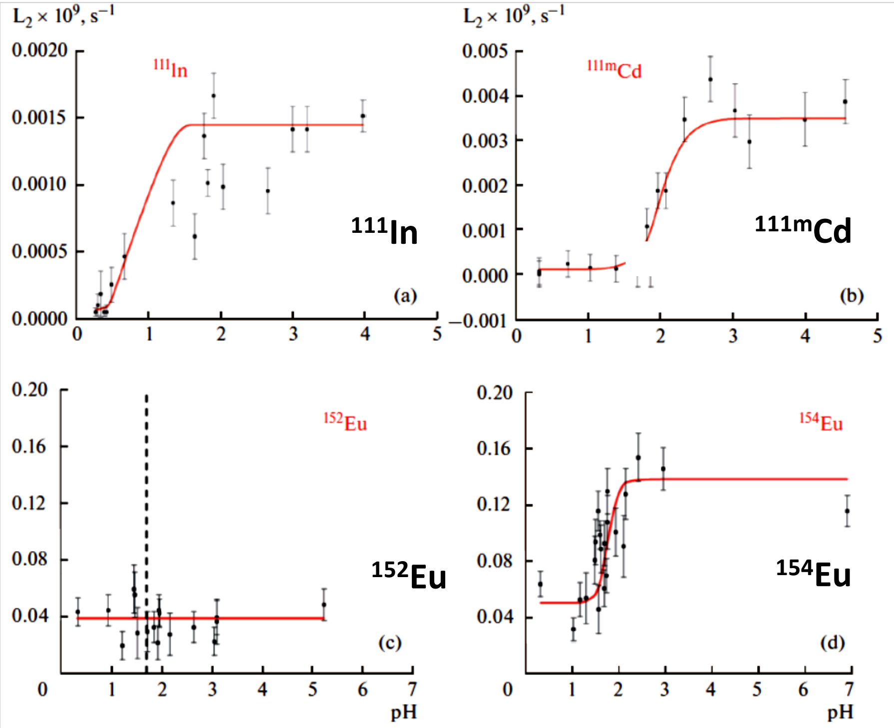


Methods and techniques for the production and analysis of low-background materials

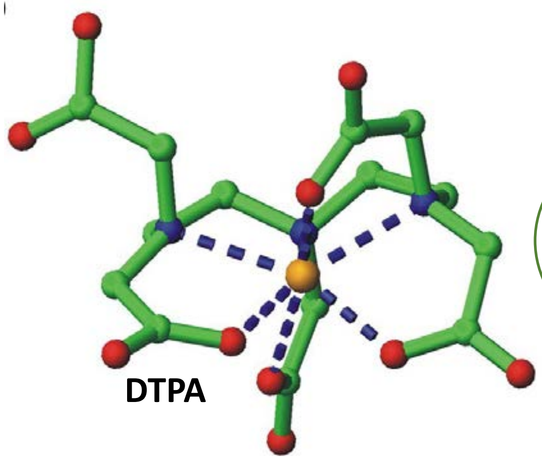
Development of samples production methods (^{82}Se; ^{96}Zr; shielding materials – Pb, Cu, Zn; solder; etc.) with impurities content μBq/kg

Development of samples analysis methods at an ultra-low sensitivity level using inductively coupled plasma mass spectrometry (ICP-MS) and other analytical and nuclear spectroscopic methods

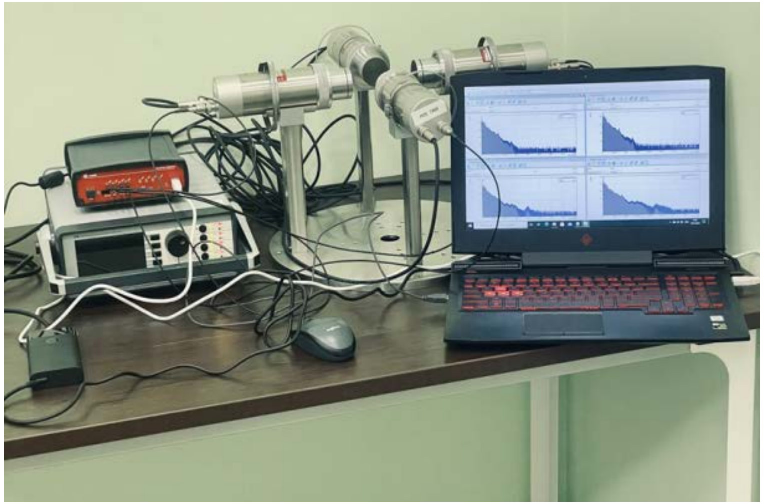
Hyperfine interactions methods using radioactive tracers



L_2 – PAC parameter

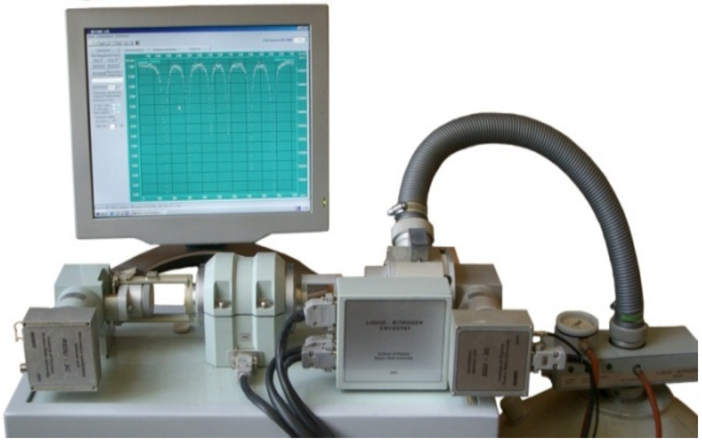


^{111}In, ^{111m}Cd, ^{152}Eu, ^{154}Eu with ***DOTA, DTPA***



Hyperfine interactions methods using radioactive tracers

^{111}In, ^{152}Eu, ^{154}Eu, ^{119}Sb, ^{119m}Sn, ^{57}Co, ^{161}Tb, etc.



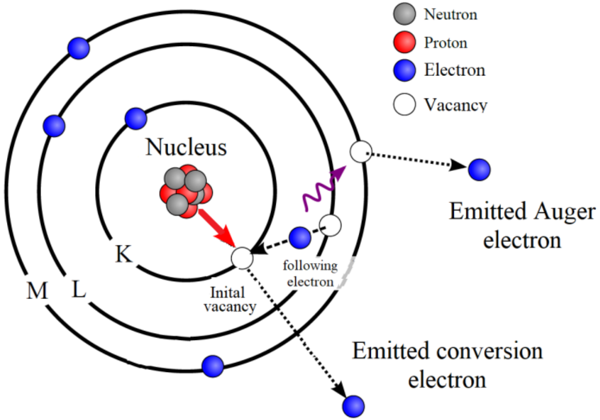
Perturbed angular correlations (PAC)

Radiopharmaceuticals and their precursors in aqueous systems and other matrices

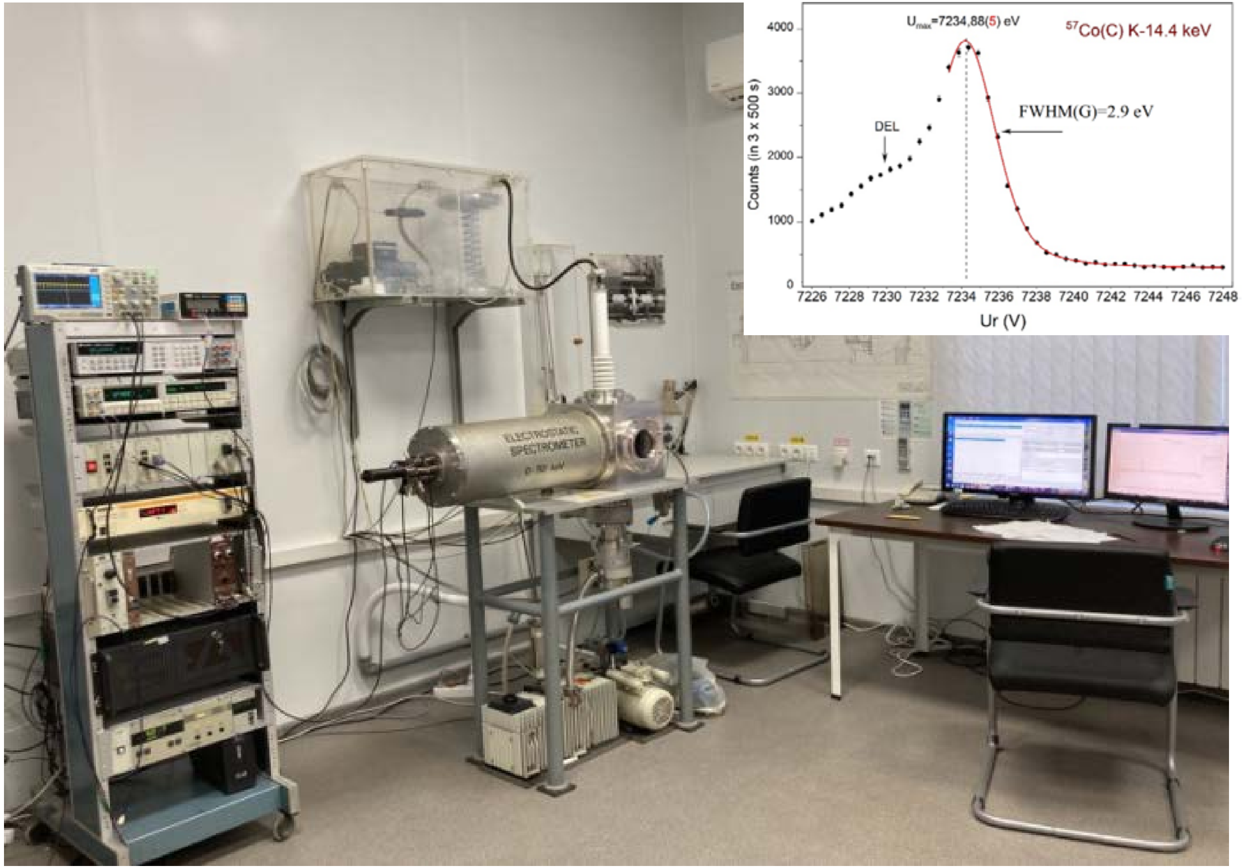
Mössbauer spectroscopy (emission mode)

Electron spectroscopy in the range of extremely low energies (0-50 keV)

Obtaining of experimental data for evaluation of Auger-electrons application in nuclear medicine



The Internal Conversion and Auger electron emission processes from radioactive decay of nucleus



Scientific directions :

- Double beta decay, clarification of the neutrino nature Majorana or Dirac (LEGEND, SuperNEMO, Cupid-Mo);
- Nuclear matrix elements for 2β-decays (Monument);
- **Fundamental neutrino properties** (magnetic moment, mixture with a sterile state, coherent scattering on nuclear);
- Monitoring of nuclear reactors with neutrino detectors;
- **Direct and indirect search for Dark Matter**;
- Investigation of galactic and extragalactic neutrino sources;
- **Spectrometry of nuclei** far from stability;
- Study of atomic processes accompanying radioactive decay;
- Development and implementation of methods for separation of macro-quantities of a substance from impurities, synthesis of materials from ultrapure precursors, design generators for production of nuclear medical radionuclides [PET diagnostics, radiopharmaceuticals, etc];
- Investigation of hyperfine interactions using the method of perturbed angular correlations on probe nuclei in solid and liquid samples.

Places: JINR, Underground laboratories, Nuclear reactors, Lake Baikal

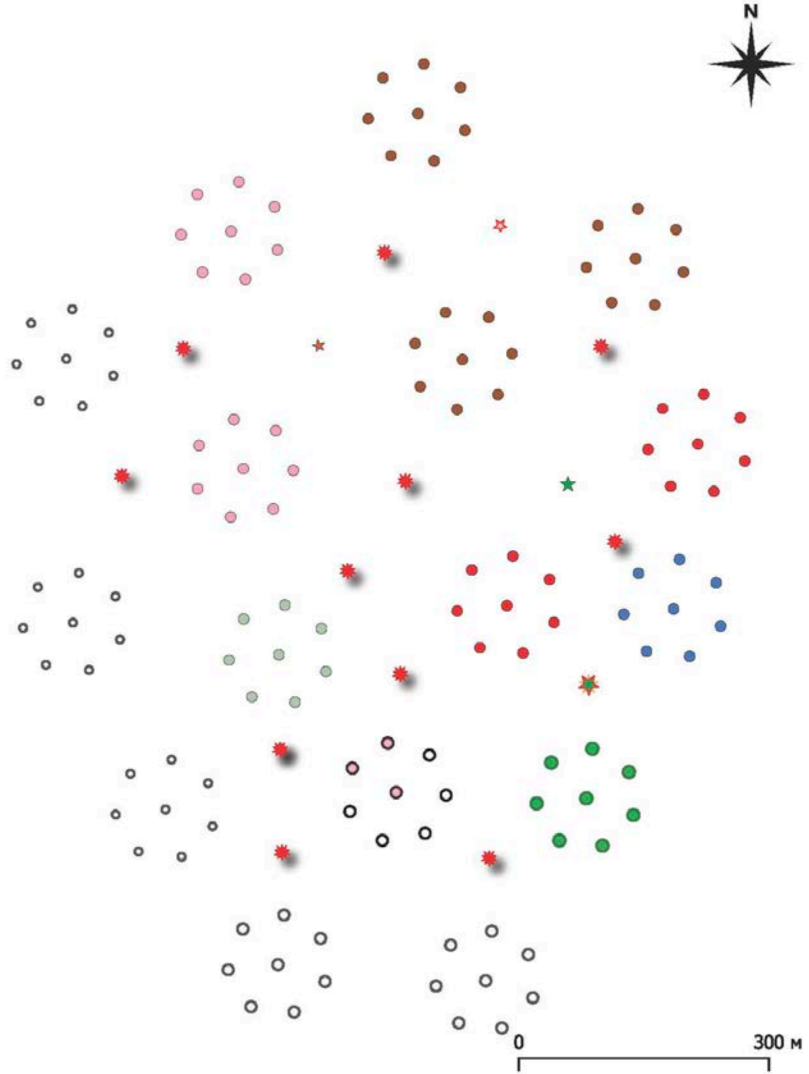
Nuclear spectrometry methods to study various processes that are interesting at the present stage of the development of science, including and with focus to rare processes.

North hemisphere biggest neutrino detector BAIKAL-GVD

Physics:
- Investigate Galactic and extragalactic neutrino "point sources";
- Diffuse neutrino flux – energy spectrum, local and global anisotropy, flavor content;
- Indirect search for Dark Matter;
- Exotic particles – monopoles, Q-balls, nuclearites, …

Main principle : determination of direction and energy of charged particles (appearing as result of neutrino interaction) with the help of Cherenkov radiation.

Baikal project: From 1980 tests and R&D, started in 1993.
Now – building BAIKAL-GVD (Gigaton Volume Detector) has huge progress and will be continued. The detector is build in frame of NP program (thanks to expertise and facilities)



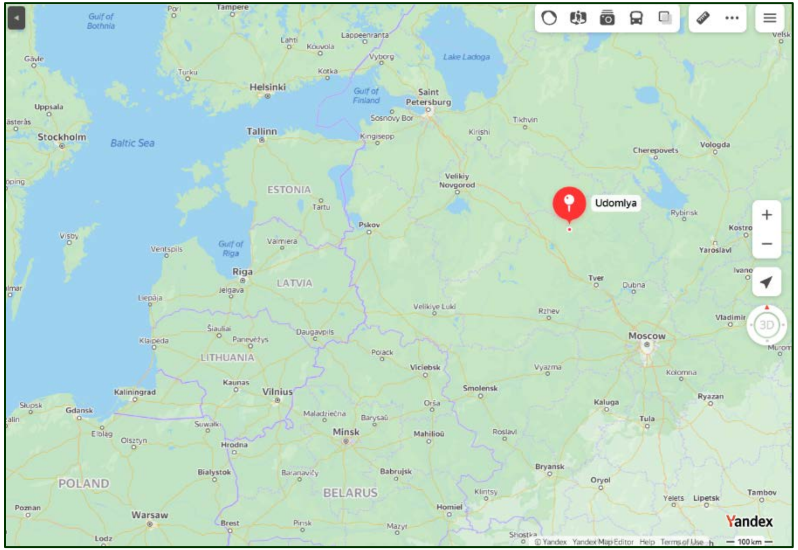
Deployment schedule

Year	Number of clusters	Number of OMs
2016	1	288
2017	2	576
2018	3	864
2019	5	1440
2020	7	2016
2021	8	2304
2022	10	2916
2023	12	3564
2024	14	4212
2025	16	4860

Reactor neutrino projects

Kalinin NPP:
➢ DANSS, DANSS-2: reactor monitoring, sterile neutrino

➢ νGeN: CEνNS + neutrino electromagnetic properties

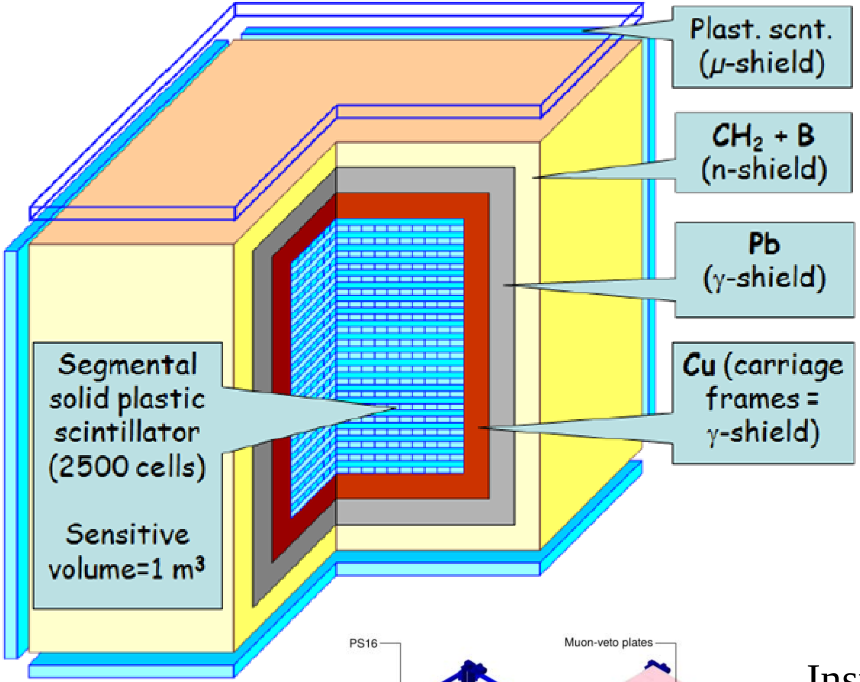


ILL:
➢ RICOCHET: new physics with CEνNS

Yangjiang and Taishan NPP
➢ JUNO: neutrino mass hierarchy, oscillation parameters

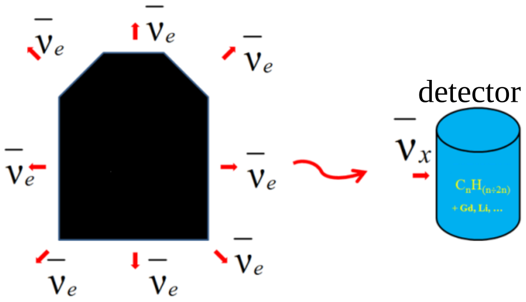
DANSS

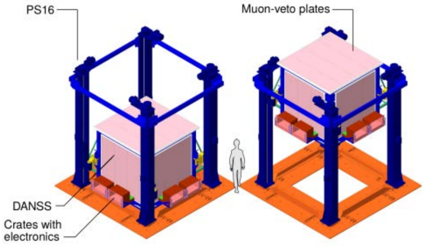
Investigations of reactor antineutrinos at the KNPP with an inverse beta decay detector



Compact (1 m^3) highly segmented (2500 plastic scintillator plates) neutrino spectrometer DANSS aims at searching for oscillations in sterile neutrinos, as well as monitoring with neutrinos the reactor power and the composition of nuclear fuel.

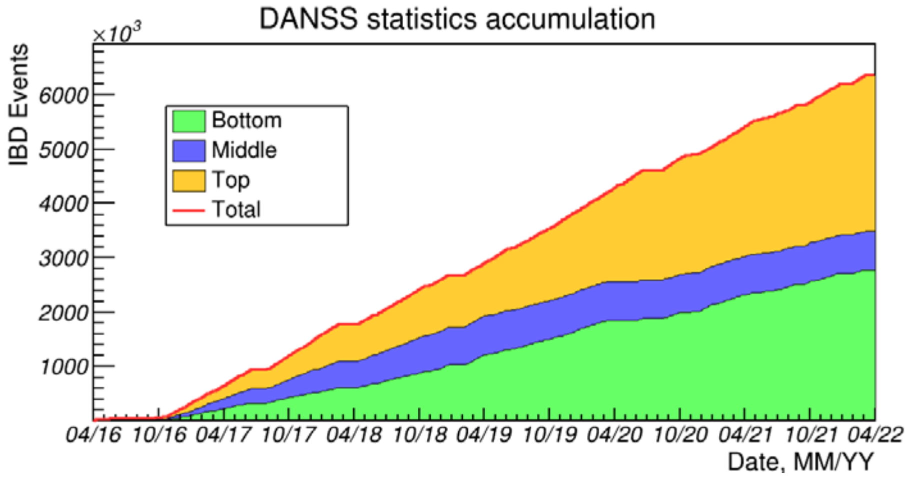
$$\bar{\nu}_e + p \rightarrow n + e^+$$



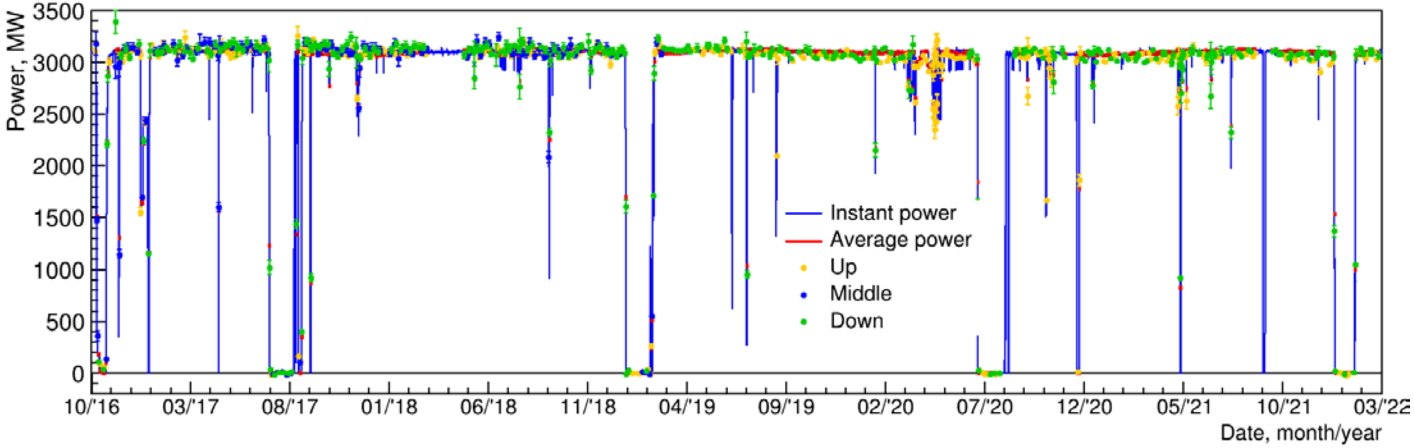


Installed on a movable platform under 3.1 GW WWER-1000 reactor

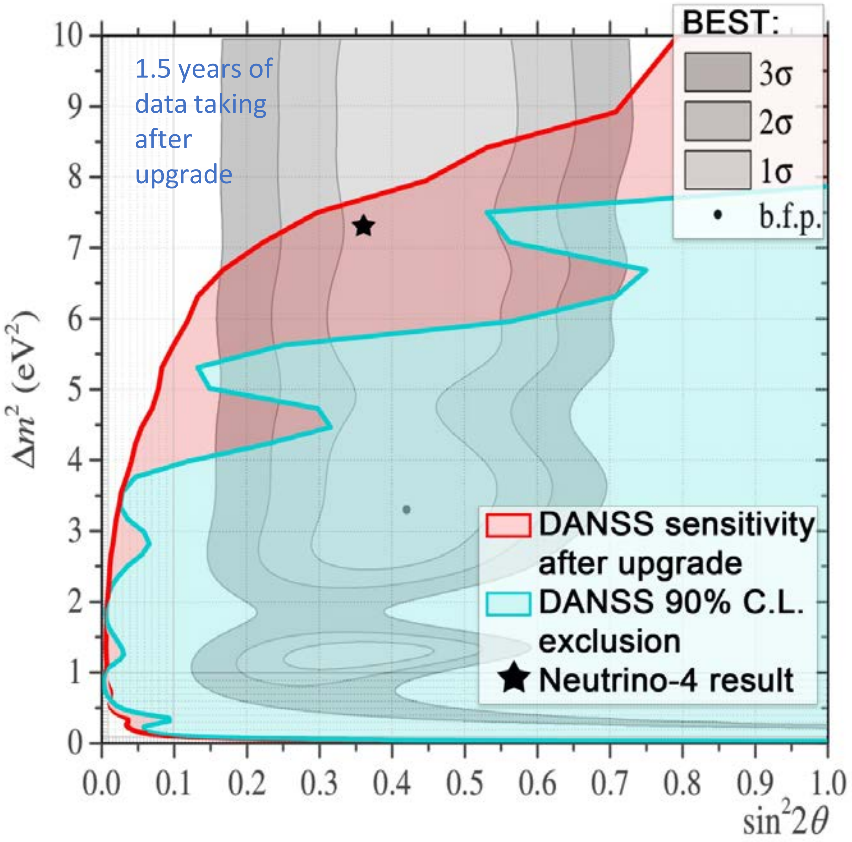
Detector distance from reactor core 10.9-12.9 m (center to center) is changed 2-3 times a week



Neutrino reactor power monitoring with 1.5% accuracy in 2 days

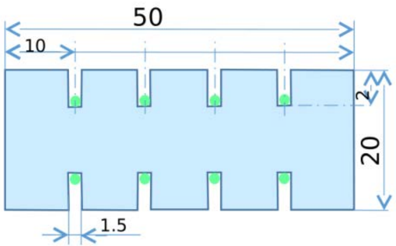


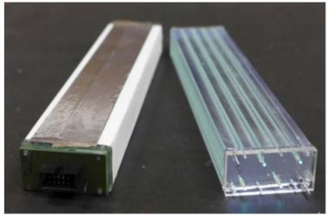
DANSS upgrade



Main goal:
to reach resolution **13%/√E**
current very resolution is 34%/√E.

New scintillator strips





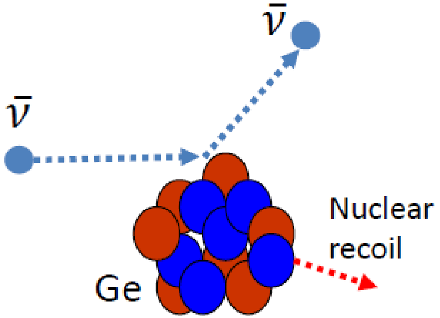
New geometry:
Strips: 2x5x120 cm,
2-side 4SiPM readout **Structure:** 60 layers x 24 strips: – **1.7 times larger fiducial volume**
Setup uses the same shielding and moving platform.
Gd is in foils between layers.

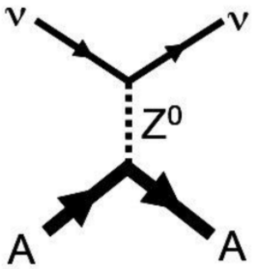
Coherent elastic neutrino nucleus scattering (CEνNS)

For low energy the cross section is 2-3 orders above of other channels

- Astrophysics and cosmology (early Universe, SN)
- The background for DM search

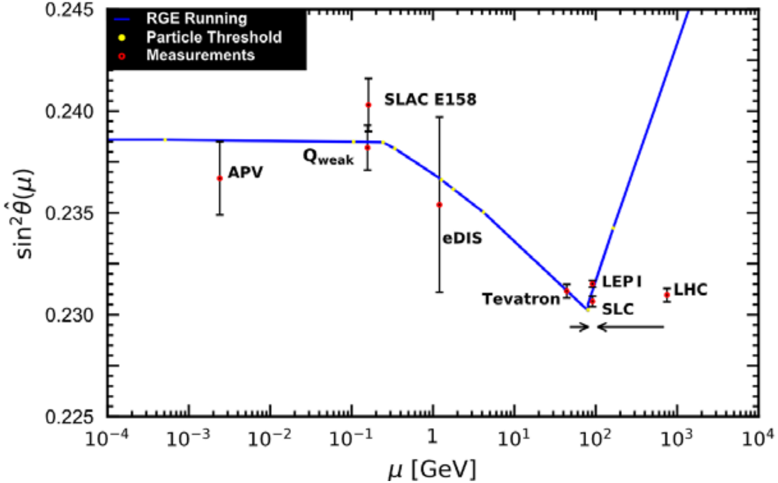
- Parameters of the Standard model
- Search for New physics

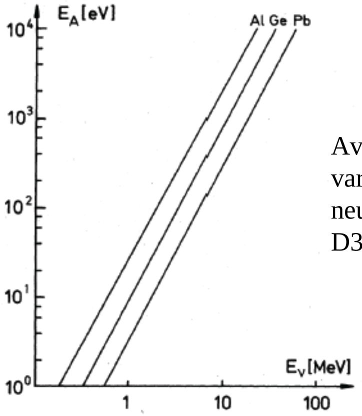




$$\frac{d\sigma(E_\nu, E_r)}{dE_r} = \frac{G_f^2}{4\pi} Q_w^2 m_N \left(1 - \frac{m_N E_r}{2E_\nu^2}\right) F^2(E_r)$$

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



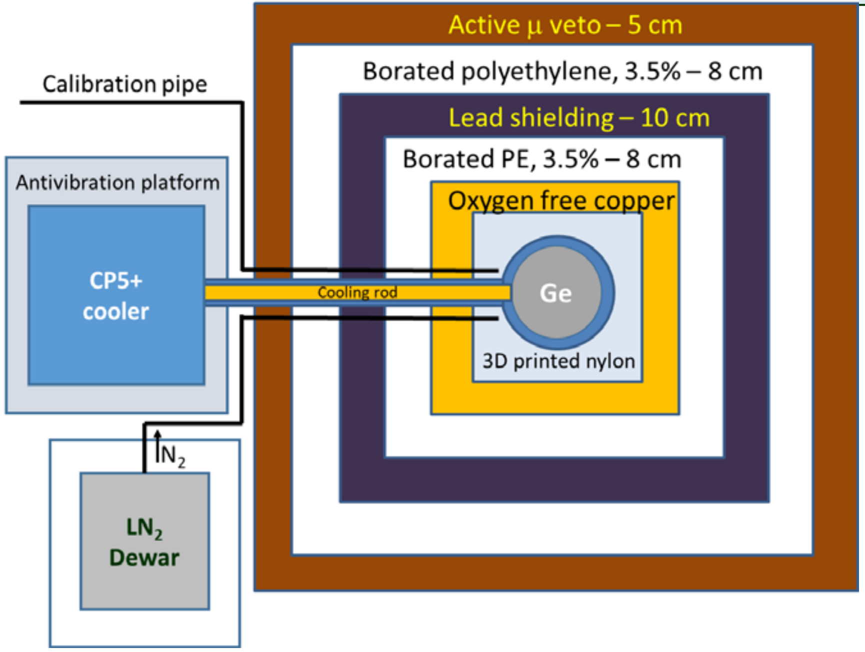


Average recoil energy, E_A, for various nuclei as a function of neutrino energy, from Phys. Rev. D30, 1984, p2295

The influence of New Physics is expected to produce spectral distortions in the energy region of recoil nuclei induced by coherent neutrino scattering (CEνNS) below 100 eV.

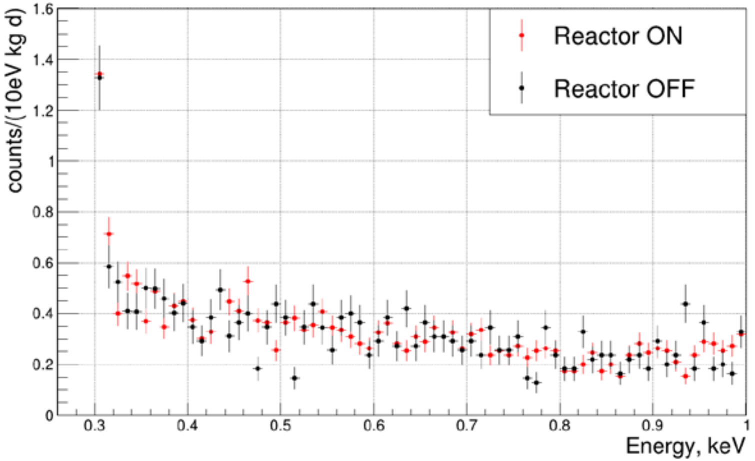
νGeN experiment: search for CEvNS and other rare processes

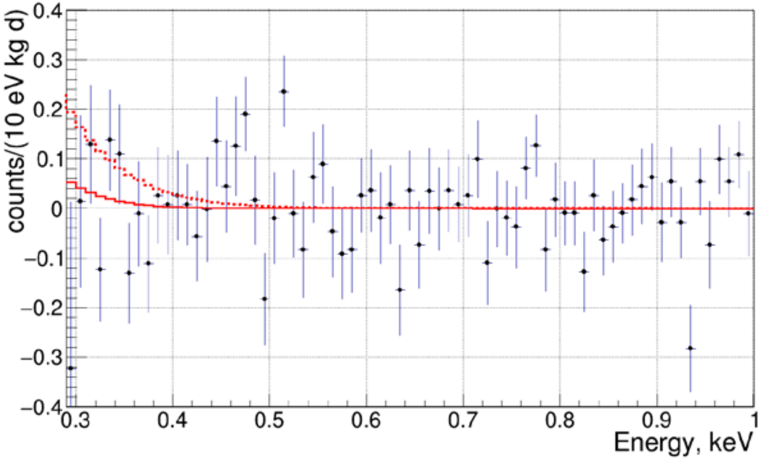
To detect signals from neutrino scattering we use a specially produced by CANBERRA (Mirion, Lingosheim) low-threshold, low-background HPGe detectors. At the moment, only one detector with a mass of 1.4 kg and e-cooling is used for the detection at KNPP.



The passive and active shielding has been organized in order to suppress background from surrounding. Additional systems to suppress radon background and microvibrations were developed. Special acquisition system has been developed to detect weak signals.

νGeN experiment: search for CEνNS and other rare processes





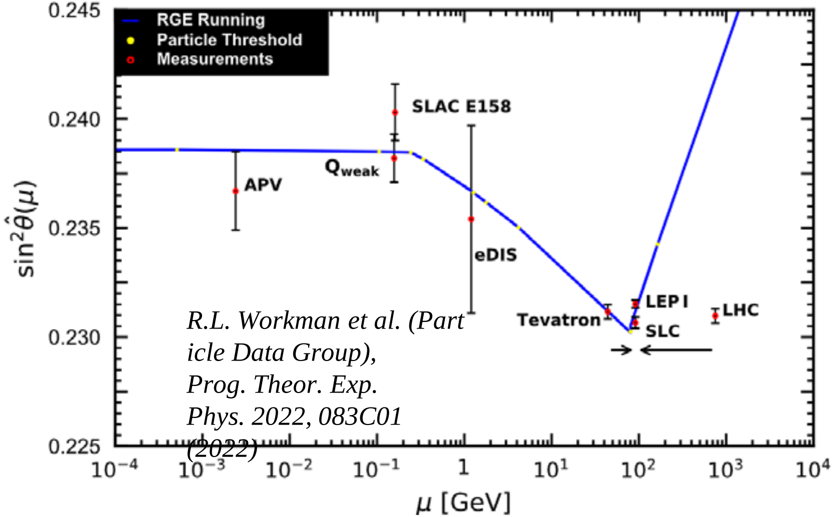
Analysis of the first data shows no significant difference in background level during reactor ON and OFF regimes. No excess at low energy connected with the CEνNS has been observed. The upper limit on the quenching parameter **k < 0.26** with 90% CL has been obtained (dashed line). Red solid line for quenching parameter k = 0.179.

- Measurements with the νGeN spectrometer at Kalinin Nuclear Power Plant are ongoing.
- First results have showed that achieved background level allows to search for CEνNS at KNPP. No significant difference between regimes with reactor ON and OFF has been observed so far.
- More than 1200 kgd of data has been accumulated so far. Since 09/2022 the data taking are performed at reduced distance to the reactor core.
- The optimization of data taking is performed as well. New results with more statistics are expected soon.

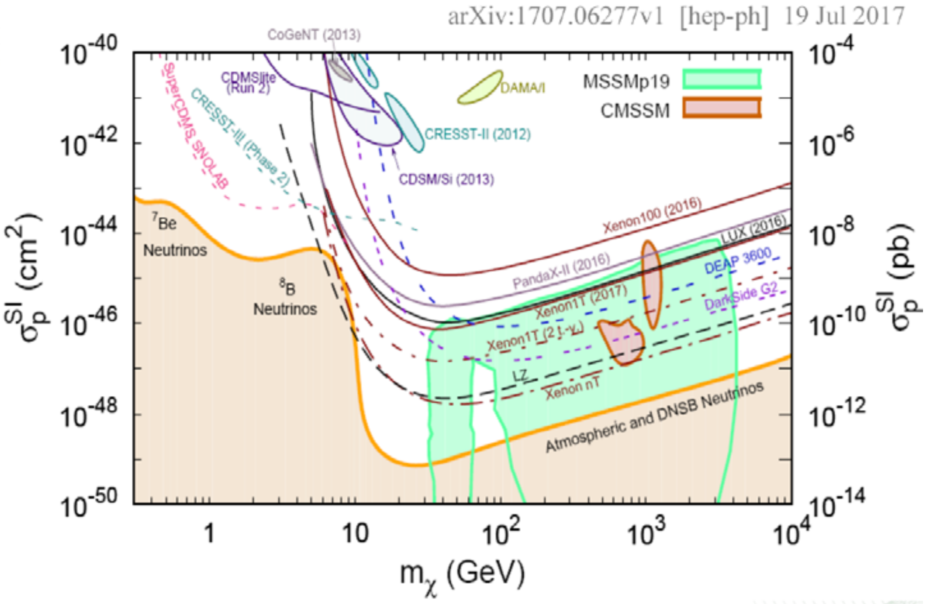
Why we want precision measurements?

$$\frac{d\sigma(E_\nu, E_r)}{dE_r} = \frac{G_f^2}{4\pi} Q_w^2 m_N \left(1 - \frac{m_N E_r}{2E_\nu^2}\right) F^2(E_r)$$

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



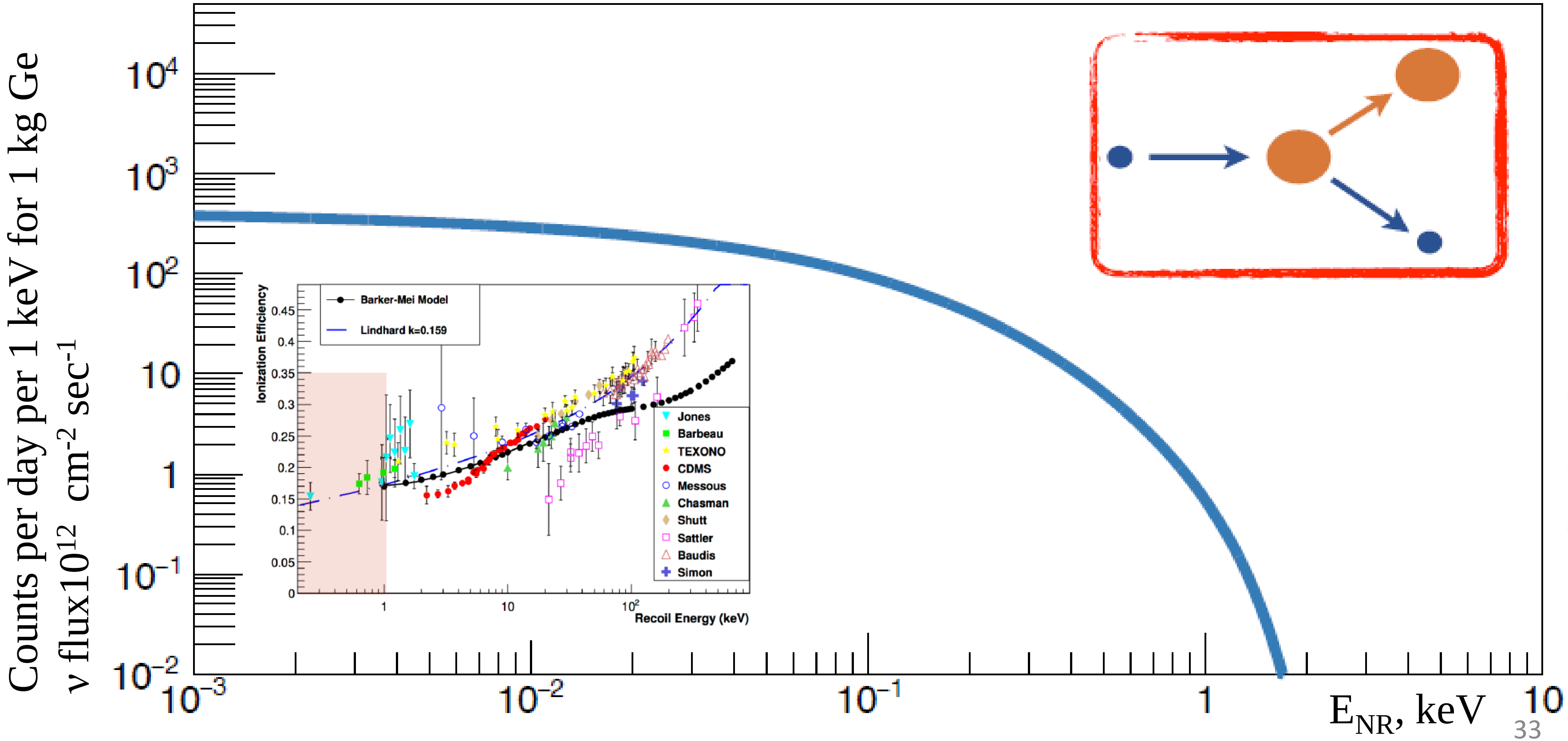
R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)



Coherent elastic neutrino-nucleus scattering (CEνNS)

The use of bolometers makes it possible to measure the energy of the nucleus directly (heat signal), in contrast to semiconductor detectors that measure ionization.

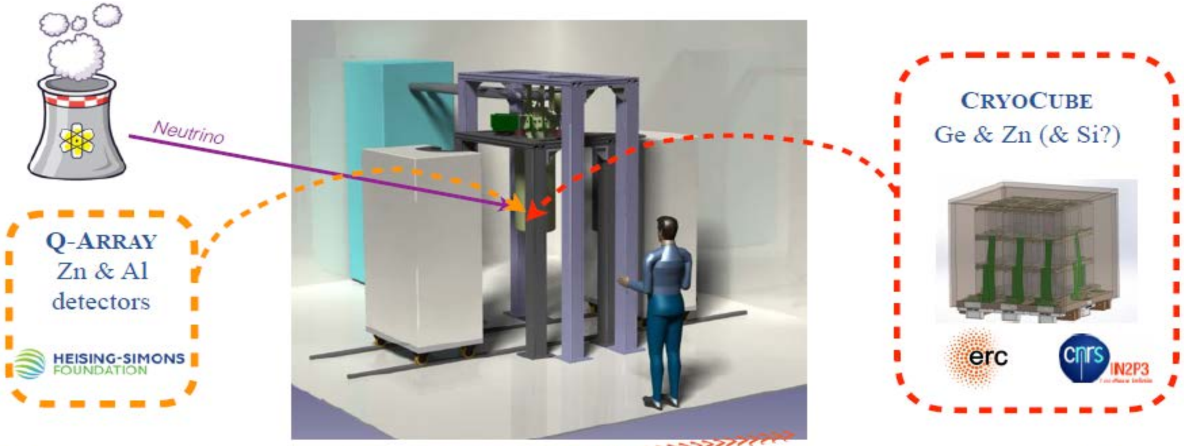
This it the way to the precision measurements.



J. Billard et al., JCAP 11 (2018) 016

RICOCHET experiment: New physics with precision measurements of CEvNS at reactors.

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



RICOCHET
A Coherent Neutrino Scattering Program

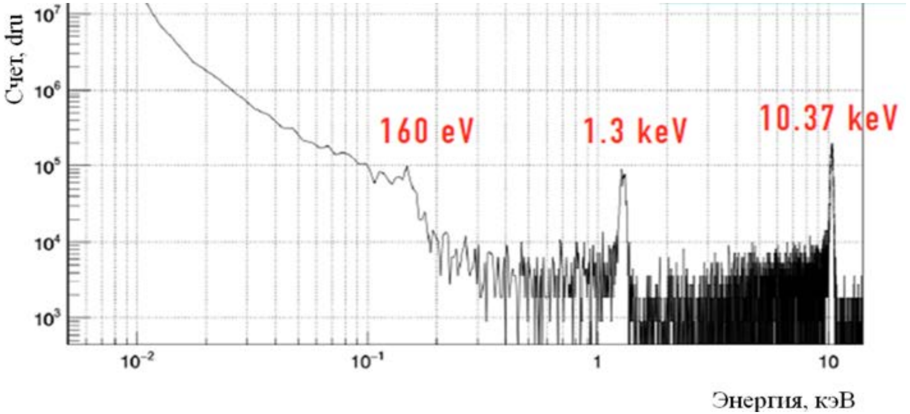
50 eV energy threshold with a 10^3 background rejection down to the threshold

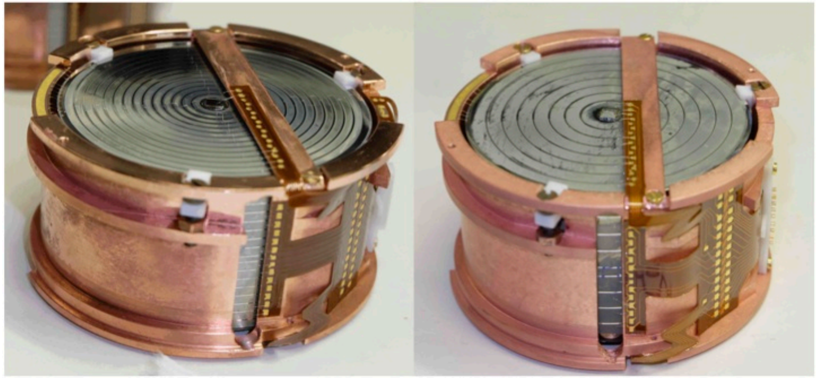
The first key feature of the RICOCHET program, compared to other planned or ongoing CEvNS projects, is to aim for a kg-scale experiment with significant background rejection down to the O(10) eV energy threshold.

The CRYOCUBE: a compact tabletop size setup

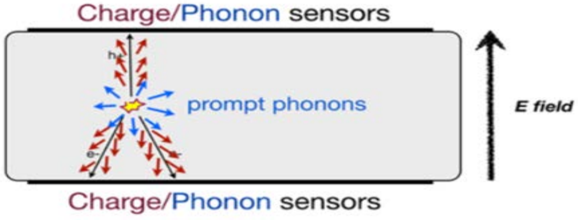
27 x 33 g detectors
8 x 8 x 8 cm^3
radio-pure infrared-tight copper box

Detector-bolometers developed by Dark Matter search experiment EDELWEISS-LT



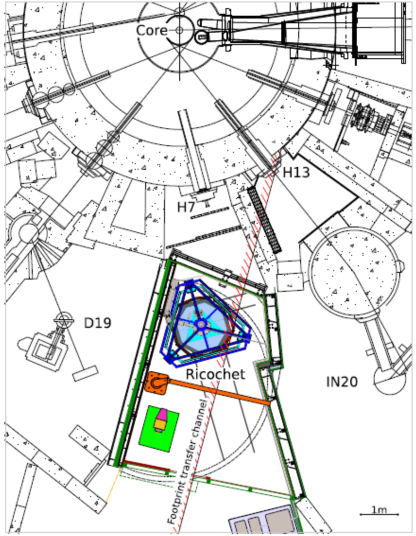


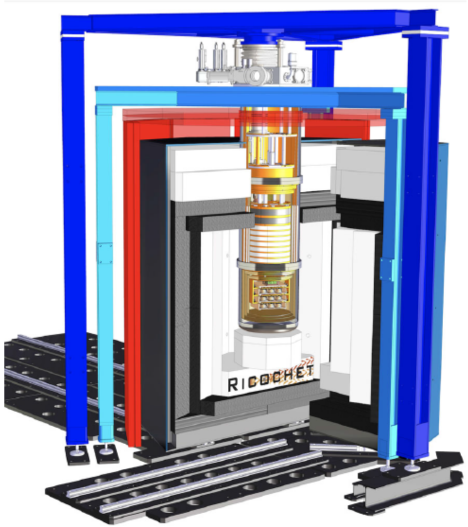
$$E_t = E_r + \frac{1}{3\ eV} E_Q \Delta V$$

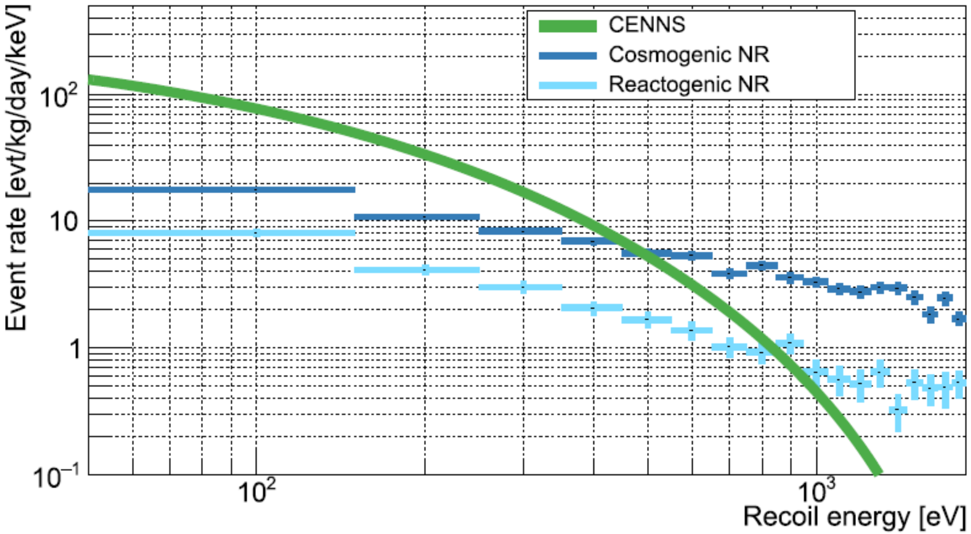


An unprecedented **charge resolution of 0.53 electron-hole pairs** (RMS) has been achieved using the Neganov-Trofimov-Luke internal amplification.

The experiment will deploy a kg-scale low-energy-threshold detector array combining Ge and Zn target crystals 8.8 m away from the 58MW research nuclear reactor core of the ILL

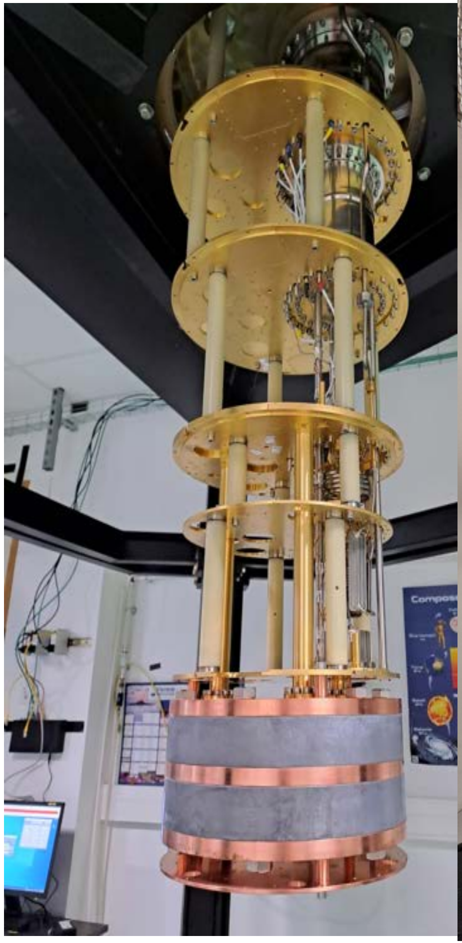


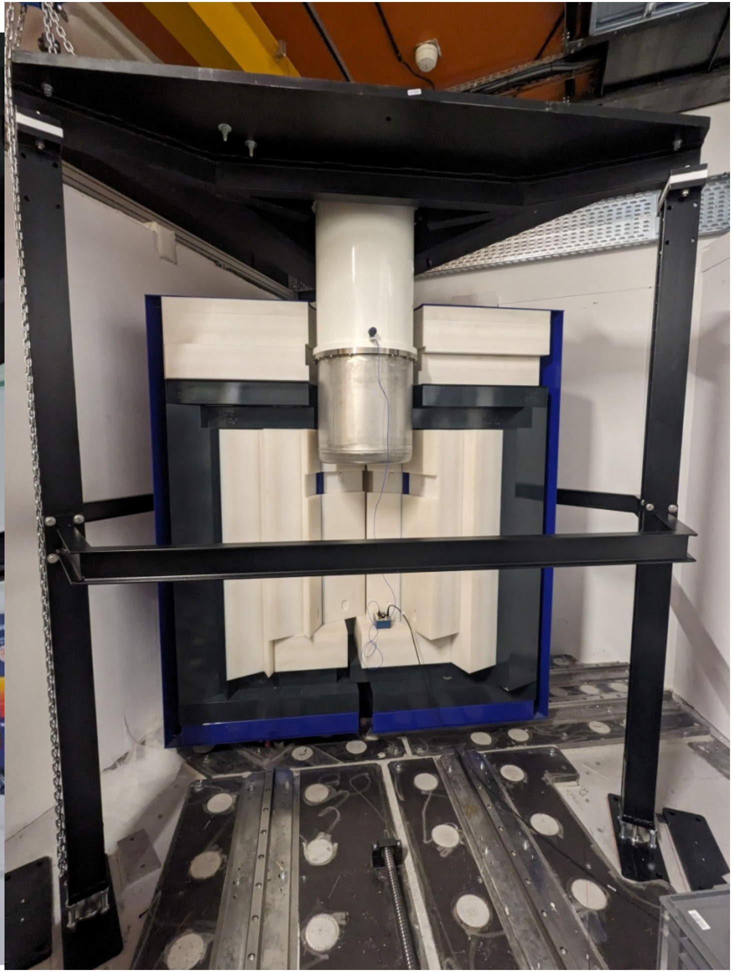


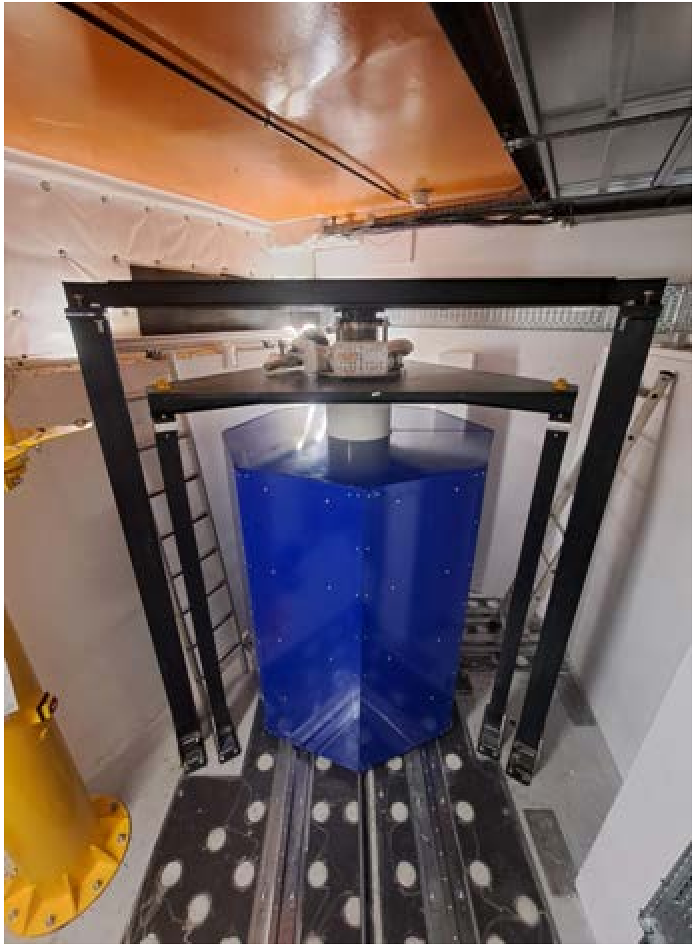


	Cosmogenic	Reactogenic	Total (MC)	**CENNS (Ge/Zn)**
Nuclear recoils [50 eV, 1 keV] (evts/day/kg)				
No shielding (I)	1554 ± 12	53853 ± 544	55407 ± 545	–
Passive shielding (II)	42 ± 3	2.4 ± 0.3	44 ± 3	–
Passive + μ-veto (III)	7 ± 2		9 ± 2	12.8 / 11.2

The Ricochet experiment should reach a statistical significance of 4.6 to 13.6 σ for the detection of CENNS after one reactor cycle. The start of the data taking in the experiment is planned for 2024.







- Comprehensive nuclear physics and nuclear physics based scientific program at DLNP;

- Basic facilities, methods+detectors and scientists are the three pillars that for years have underpinned research at DLNP;

- Creation of infrastructure at JINR, include building and commissioning of new basic facilities to ensure current and future projects at a modern level;

- Participation in world leading experiments.

We would like to ask the Programme Advisory Committee to support our nuclear physics program and will report about progress of individual projects conducted in the frame of the JINR 7-year development plan during the future PAC meetings.