Нейтринные исследования в ОИЯИ

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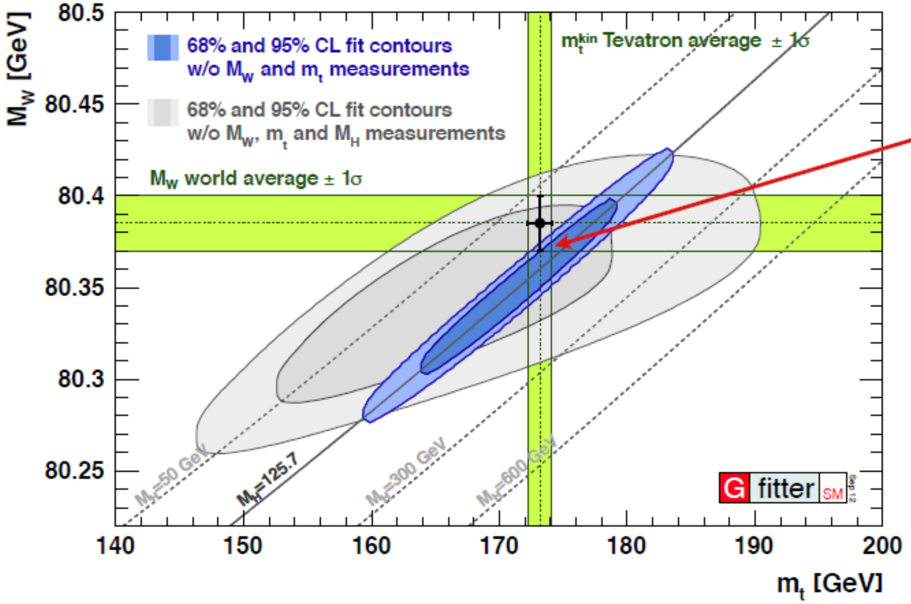
33-я Всероссийская конференция по космическим лучам

Дубна, 13 августа 2014

Стандартная Модель сегодня

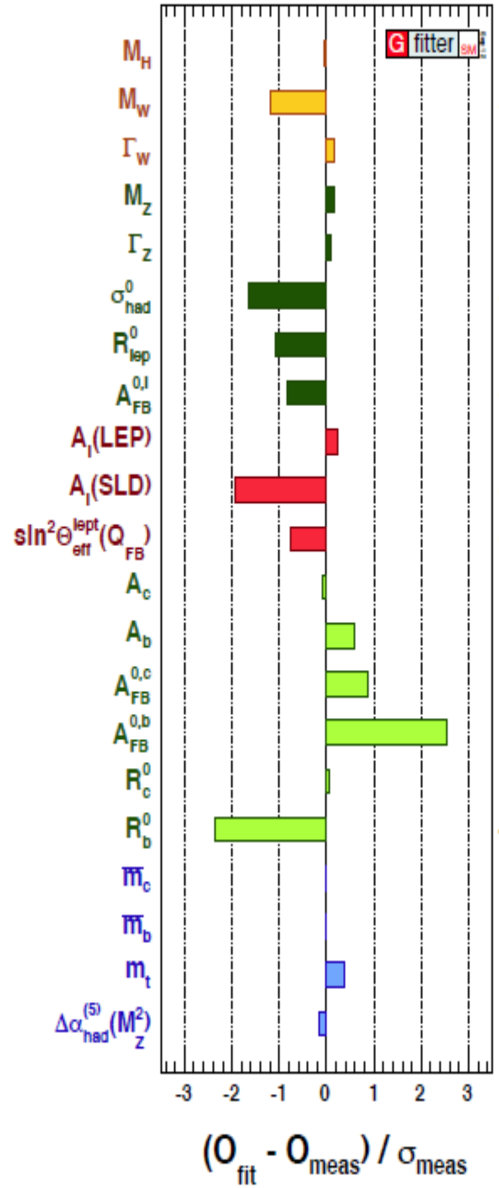
Impressive consistency of the SM



Once M_H is fixed, we cornered the SM!

Effects of new physics through loop corrections!

⇒ improve measurements of EW precision observables



- ✓ Открытие векторных промежуточных бозонов W и Z на ускорителе SPS
- ✓ Детальное исследование свойств Z и W на LEP и предсказание диапазона масс для t-кварка и H-бозона
- ✓ Открытие t-кварка на Тэватроне
- ✓ Открытие бозона Хиггса на LHC

Свойства и роль нейтрино

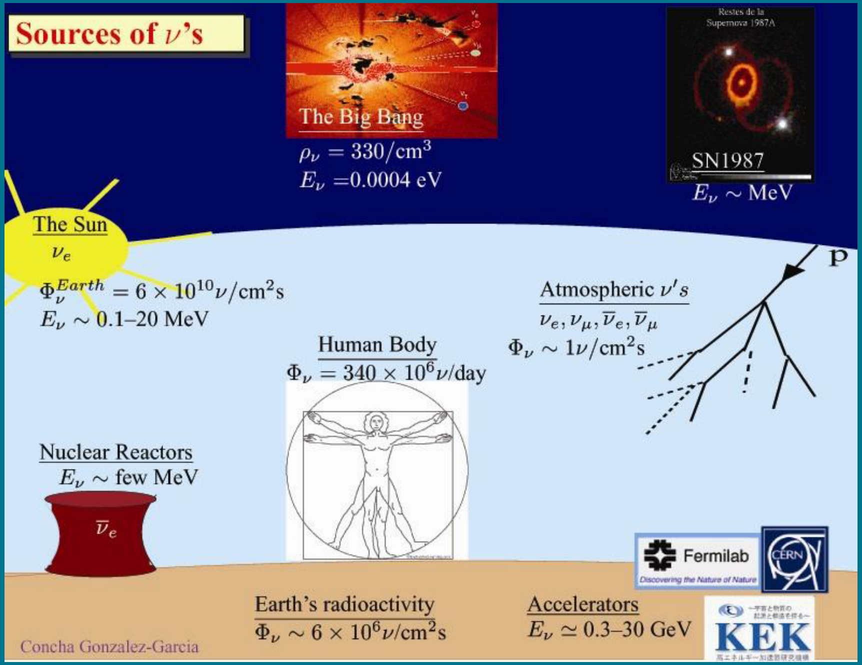
- ✓ Processes (decays, scattering) with neutrinos pushed forward the **Fermi theory, SM.**
- ✓ Neutrinos (together with photons) are the **most abundant particles in the Universe.**
- ✓ Relic neutrinos **should be after Big Bang (together with relic background radiation).**
- ✓ Massive neutrinos are crucial for **construction of theories beyond the SM.**
- ✓ They are **hot Dark matter and responsible for Large scale Structure.**
- ✓ Solar neutrinos inform us about the **Sun interior and how the Sun works.**
- ✓ Supernovae exposures are **impossible without neutrinos, there are nuclear synthesis r-processes governed by neutrinos.**
- ✓ Only neutrinos could supply us with the **most distant cosmic signals.**
- ✓ Neutrinos are **very accurate probes of the structure of hadrons (strangeness, charm, spin, 5Q, ...), they allow test of QCD.**
- ✓ There is already **practical use of neutrinos: nuclear plant control (diagnostics),outer space, geo-neutrinos, communications (“neutrino” was coded and decoded!)…..**

- ✓ Why are neutrino mixing angles **so large (contrary to quarks)?**
- ✓ What is a **source of too small neutrino masses, is it connected with a new huge mass scale?**
- ✓ What is a correct **ordering (hierarchy) of neutrino masses?**
- ✓ Do neutrinos have **CP-phases and could they “save” Baryogenesis (by means of Leptogenesis)?**
- ✓ Could we check directly that the **matter effect really works?**
- ✓ Is the neutrino **mass term Majorana or Dirac (neutrino = antineutrino, or not)?**
- ✓ How does the **Sun really shine?**
- ✓ Is oscillation already a **unique description of neutrino flavor changes?**
- ✓ How do the neutrino properties affect the **other (very)rare weak processes?**
- ✓ Where are the **relic neutrinos?**
- ✓ Do neutrinos have **magnetic moments (diagonal or transition)?**
- ✓ When we measure **coherent low-energy neutrino scattering off nuclei?**
- ✓ Could neutrinos explain **beyond-GZK Cosmic Rays?**
- ✓ Is there any **real possibility of seeing new (heavy) neutrinos with the LHC?**

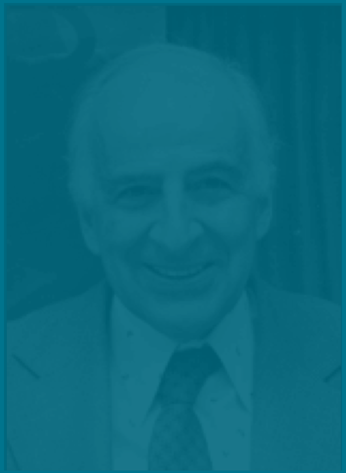
Нейтрино являются наиболее фундаментальным междисциплинарным объектом, роль которого ещё предстоит осознать. Ответы на (хотя бы некоторые) вопросы в физике нейтрино существенно изменят наше представление о картине мироздания.

Источники и регистрация нейтрино

F. Reines, *Ann. Rev. Nucl. Sci.* **10** (1960) 1–26.



- ✓ fission reactors are the best source of low energy antineutrinos
- ✓ muon-neutrinos can be produced by allowing pions to decay in flight
- ✓ the Sun is a “most copious source of neutrinos”
- ✓ cosmic rays striking the Earth’s atmosphere should produce a significant flux of neutrinos from pion decay
- ✓ high-energy neutrinos produced by astrophysical objects would provide information not available from cosmic rays



B.Pontecorvo:

- ✓ proposed the first (radiochemical) method of neutrino detection and possibility of reactor experiments.
- ✓ was the first who came to an idea of *μ – e universality of the weak interaction.*
- ✓ proposed the experiment with accelerator neutrinos to prove that ν_μ *and* ν_e *are different particles.*
- ✓ was the first who came to idea of neutrino oscillations and proposed many experiments to check it.

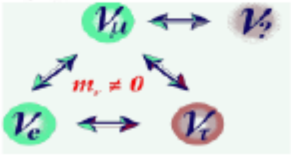
Neutrino history in Dubna — B. Pontecorvo and M.Markov!

About 55 years ago the idea of neutrino oscillation was born in Dubna!

Bruno Pontecorvo:

"The oscillations are very simple trick: 1–2–3 and … all OK!"

Бруно Понтекорво



$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix} \begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{-i\delta} & 0 & c_{13}\end{pmatrix} \begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Weak eigenstates

Atmospheric

$c_{ij}=\cos\theta_{ij}$, $s_{ij}=\sin\theta_{ij}$

CP phase

Sub-dominant θ_{13} oscillations

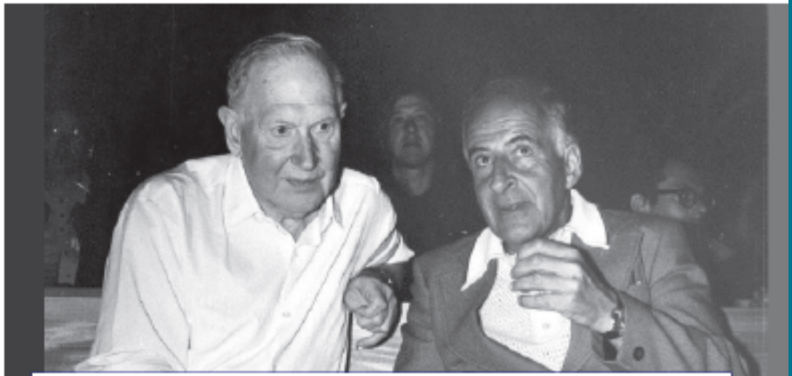
Solar

Mass eigenstates

The beginning of neutrino astrophysics ...

M.A.Markov had proposed for the first time to define incoming directions of a cosmic ray charged particle in water by means of its Cherenkov radiation.

The first realization of this idea was the Baikal neutrino telescope NT-200. This is foundation of the IceCude success of today!

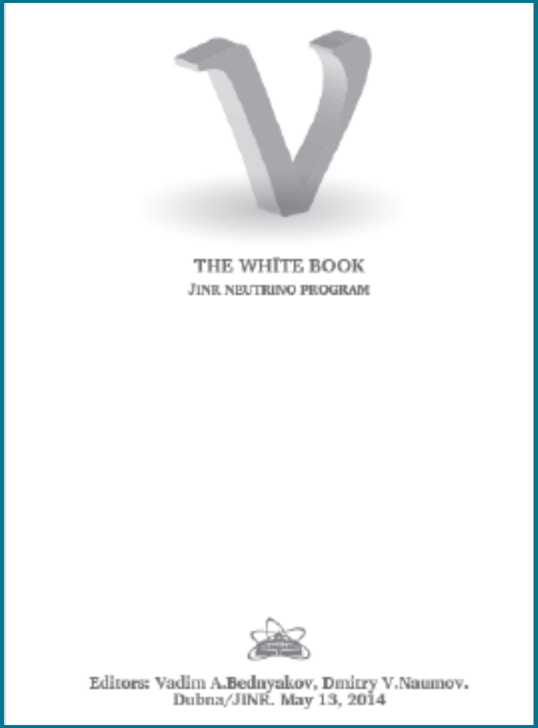


M.Markov, 1960:

„We propose to install detectors to determine the direction of charged particles deep in a lake or in the sea and with the help of Cherenkov radiation" Proc. 1960 ICHEP, Rochester, p. 578.

”White Book” — the JINR neutrino programme runs

Every experiment in which JINR participates in the framework of the neutrino programme is described in a uniform format in the Book on about 300 pages:



THE WHITE BOOK
JINR NEUTRINO PROGRAM

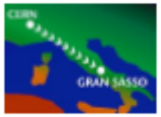
Editors: Vadim A.Bednyakov, Dmitry V.Naumov.
Dubna/JINR. May 13, 2014

Contents

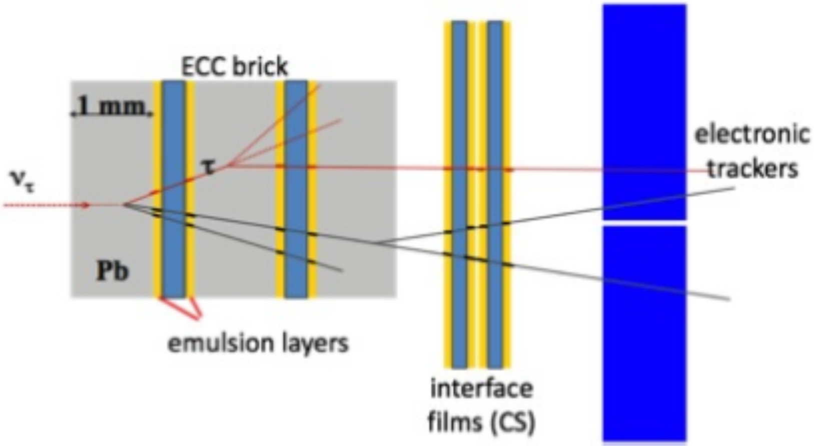
About 200 (100) participants (scientists) take part in the JINR neutrino programme, 60 of them are younger 35 years old. JINR member-states are strongly involved. Internationality — NOνA, JUNO, EDELWEISS, SuperNEMO, ...

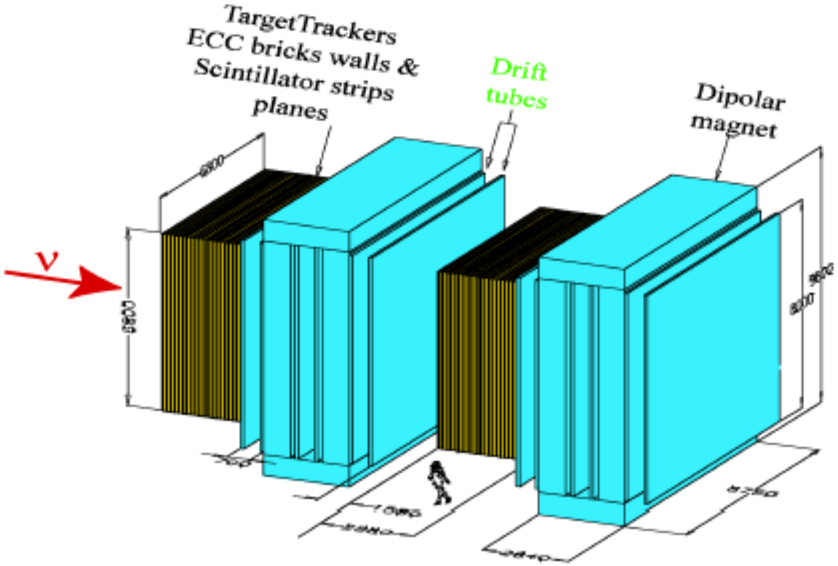
Neutrinos international — OPERA. Goals. Setup

The OPERA goal — observation of $\nu_\mu \rightarrow \nu_\tau$ oscillation via registration of ν_τ appearance in ν_μ beam from CERN (17 GeV, 732 km).



The experiment is located 1400 m underground In the Gran Sasso Laboratory.





— *Emulsion Cloud Chamber (ECC) detector is a modular structure made of a sandwich of passive material plates interspaced with emulsion layers (bricks).*

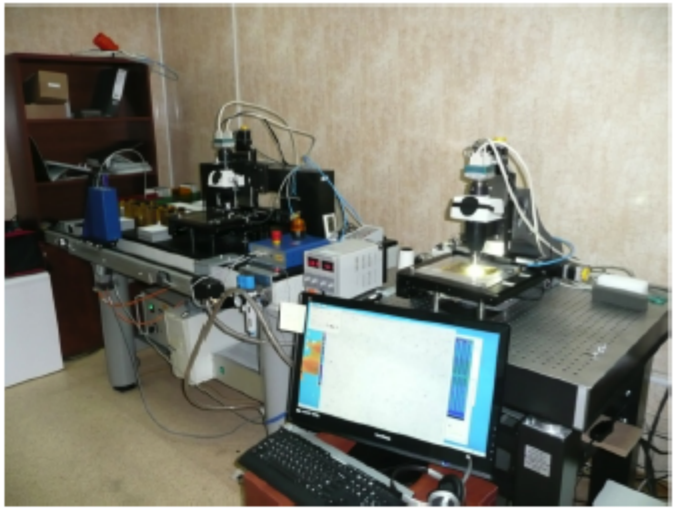
— *A wall made of 3264 bricks accompanied by two planes of electronic Target Tracker (for the real time determination of the event position) comprises a module.*

— *Two supermodules are made of a target section which is a sequence of 31 modules, and of downstream muon spectrometer for muons identification and for the reconstruction of their charge and momentum.*

Neutrinos international — OPERA. Results. JINR

OPERA main results:

1. So far 4 ν_τ-events were identified.
2. Number of observed $\nu_\mu \to \nu_e$ events is in agreement with expectation from the beam contamination, no oscillated events observed in this sample.



— Duration of the project in JINR is 1998–2016

— Annual budget is 55k$ (JINR 1099 + extra-budget)

— JINR team (leader Yu. Gornushkin): A. Chukanov, S. Dmitrievsky, Z. Krumstein, D. Naumov, A. Nozdrin, A. Olchevsky, G. Ososkov, Yu.Petukhov, A. Sadovsky, A. Sheshukov, A.Sotnikov, S. Zemskova, I. Bondarchuk.

— About 15 paper were published + 5 talks were given by JINR at the major international conferences (3 years).

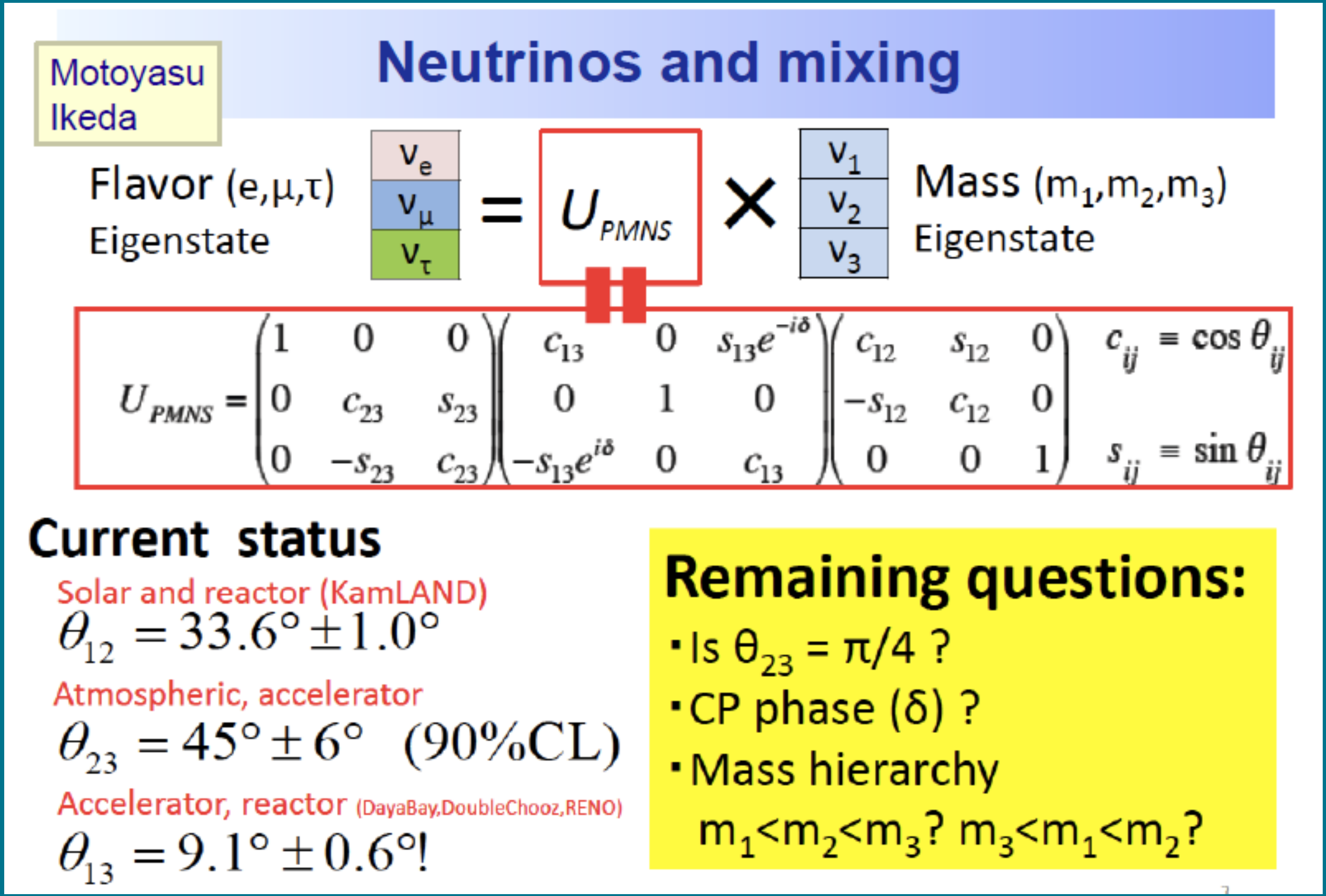
← JINR emulsion scanning station for emulsion processing.

— JINR group participated in the scintillator strip production, in assembly of the Target Tracker planes, their calibration and installation. Software for finding brick with the neutrino vertex was developed at JINR. Group performs the electronic detectors processing and provides identification of the vertex bricks.

— During 2 years, JINR group concentrates on the data analysis of both electronic detectors and emulsions. The final results will be obtained.

Матрица PMNS сегодня

Бруно Понтекорво



Neutrinos and mixing

Motoyasu Ikeda

Flavor (e,μ,τ) Eigenstate $\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$ Mass (m_1,m_2,m_3) Eigenstate

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \begin{matrix} c_{ij} \equiv \cos\theta_{ij} \\ s_{ij} \equiv \sin\theta_{ij} \end{matrix}$$

Current status

Solar and reactor (KamLAND)

$$\theta_{12} = 33.6° \pm 1.0°$$

Atmospheric, accelerator

$$\theta_{23} = 45° \pm 6° \quad (90\%\mathrm{CL})$$

Accelerator, reactor (DayaBay,DoubleChooz,RENO)

$$\theta_{13} = 9.1° \pm 0.6°!$$

Remaining questions:

- Is $\theta_{23} = \pi/4$?
- CP phase (δ) ?
- Mass hierarchy
  $m_1<m_2<m_3$? $m_3<m_1<m_2$?

Neutrinos international — Daya Bay. Goals

The reactor antineutrino experiment Daya Bay (China) with near and far identical detectors.

— The main goal of the Daya Bay experiment is measurement of neutrino mixing angle θ_{13} via observation of the reactor $\bar{\nu}_e$ flux deficit on the far site in comparison to the $\bar{\nu}$ flux in the near site.

— In 2012 using 6 antineutrino detectors the experiment has discovered that $\theta_{13} \neq 0$ with statistical significance higher than 7σ and measured the value of $\sin^2 2\theta_{13} (= 0.089 \pm 0.010)$ with highest precision in the world.

Other targets of the experiment include:

— measurement of neutrino squared mass difference Δm^2_{ee},

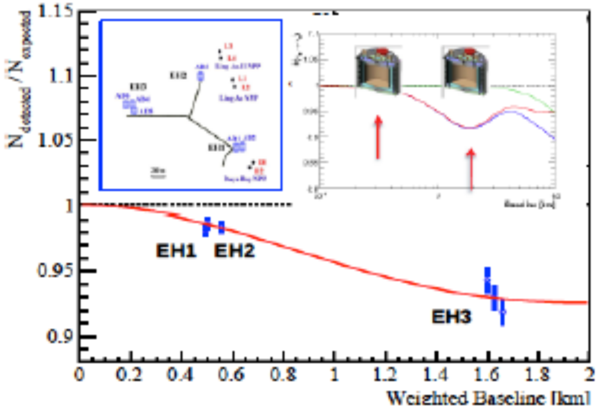
— measurement of the $\bar{\nu}$-flux (normalization and shape),

— sterile neutrino search,

— oscillation analysis based on hydrogen capture of recoil neutron from IBD reaction $\bar{\nu}_e + p \rightarrow n + e^+$,

— oscillation analysis using 8 antineutrino detectors,

— SuperNovae ν-s detection.

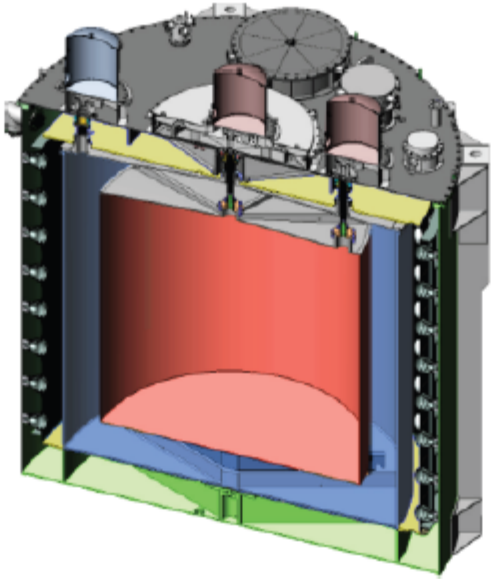


Reactor antineutrinos are recorded by near and far identical detectors.

Apparent deficit of number of antineutrinos in the far detectors lead to discovery of new type of oscillations due to $\theta_{13} \neq 0$.

Neutrinos international — Daya Bay. Setup

Electron antineutrinos are detected via the inverse β-decay reaction: $\bar{\nu}_e + p \rightarrow e^+ + n$. The positron almost immediately releases its energy and annihilates with an electron (prompt signal). The prompt signal visible energy is $1.02 \div 10$ MeV. The neutron is thermalized in an average of 28μs and is captured by a Gd nucleus, which then emits several γs with a total energy of 8 MeV (delayed signal).



The "geometry" of Daya Bay experiment.

The $\bar{\nu}$-detector utilizes the 3-zone scintillator detector structure (3 concentric cylindrical volumes). The innermost volume is the target: 3.1×3.1 m acrylic vessel, filled with 20 t of liquid scintillator, doped by 0.1% of gadolinium. Next volume (4×4 m) is filled with 21 t of undoped LS used to catch γs. It is located in a stainless steel vessel of 5×5 m. The outermost volume is filled with 37 t of mineral oil used as shield against the radiation. 192 8-inch PMT collect the light emitted by scintillation of LS.

Neutrinos international — Daya Bay. JINR

The JINR contribution to the Daya Bay project is important:

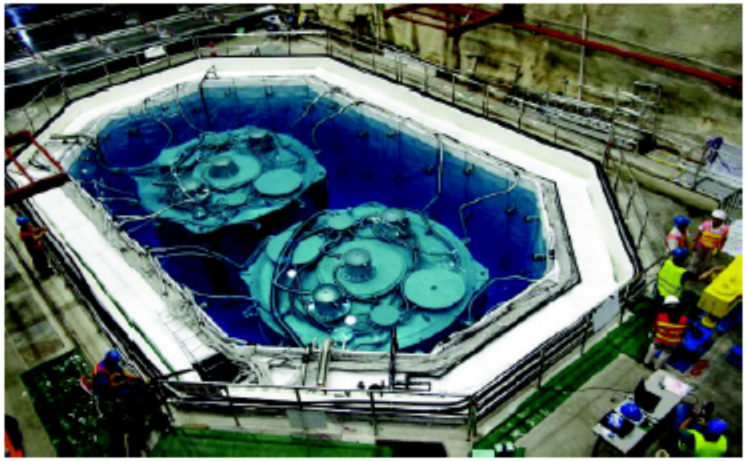
— Development of the liquid scintillators suitable for the large-scale Daya Bay experiment was the JINR team activity.

— PPO (2,5-diphenyloxazole) production for the liquid scintillator (1.5 tons) and delivery to Daya Bay.

— New method of tagging fast neutron events based on Flash ADC signals was suggested.

— A dedicated software package for the oscillation analyses was developed by JINR team.

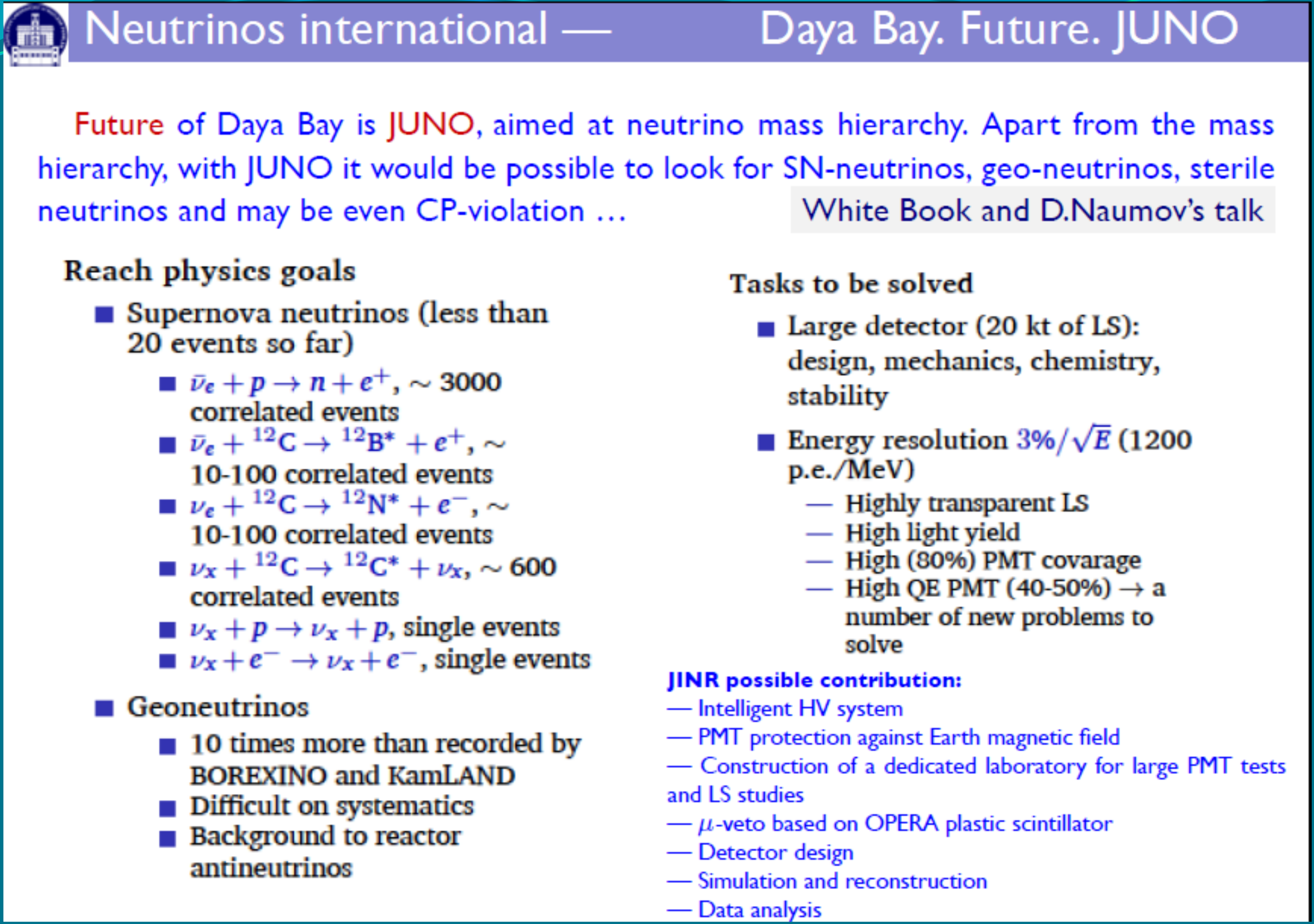
— With the package 3-ν rate+shape oscillation analysis and search for sterile neutrino were conducted at JINR.



— Duration of the project is 2009–2014

— JINR team (D. Naumov): M. Gonchar, Yu. Gornushkin, I. Nemchonok, E. Naumova, A. Olshevskiy, O. Smirnov, O. Samoylov, D. Korablev, I. Butorov

— Annual budget is 20k$ (JINR, 1099)



Neutrinos international — Daya Bay. Future. JUNO

Future of Daya Bay is JUNO, aimed at neutrino mass hierarchy. Apart from the mass hierarchy, with JUNO it would be possible to look for SN-neutrinos, geo-neutrinos, sterile neutrinos and may be even CP-violation …

White Book and D.Naumov's talk

Reach physics goals

- Supernova neutrinos (less than 20 events so far)
  - $\bar{\nu}_e + p \rightarrow n + e^+$, $\sim$ 3000 correlated events
  - $\bar{\nu}_e + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{B}^* + e^+$, $\sim$ 10-100 correlated events
  - $\nu_e + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{N}^* + e^-$, $\sim$ 10-100 correlated events
  - $\nu_x + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{C}^* + \nu_x$, $\sim$ 600 correlated events
  - $\nu_x + p \rightarrow \nu_x + p$, single events
  - $\nu_x + e^- \rightarrow \nu_x + e^-$, single events
- Geoneutrinos
  - 10 times more than recorded by BOREXINO and KamLAND
  - Difficult on systematics
  - Background to reactor antineutrinos

Tasks to be solved

- Large detector (20 kt of LS): design, mechanics, chemistry, stability
- Energy resolution $3\%/\sqrt{E}$ (1200 p.e./MeV)
  - — Highly transparent LS
  - — High light yield
  - — High (80%) PMT covarage
  - — High QE PMT (40-50%) → a number of new problems to solve

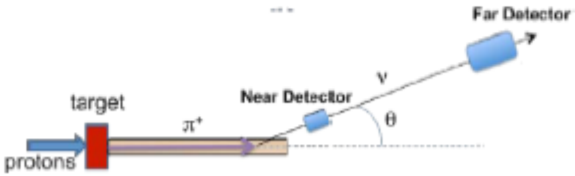
JINR possible contribution:

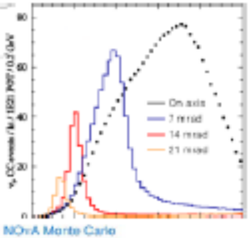
— Intelligent HV system
— PMT protection against Earth magnetic field
— Construction of a dedicated laboratory for large PMT tests and LS studies
— μ-veto based on OPERA plastic scintillator
— Detector design
— Simulation and reconstruction
— Data analysis

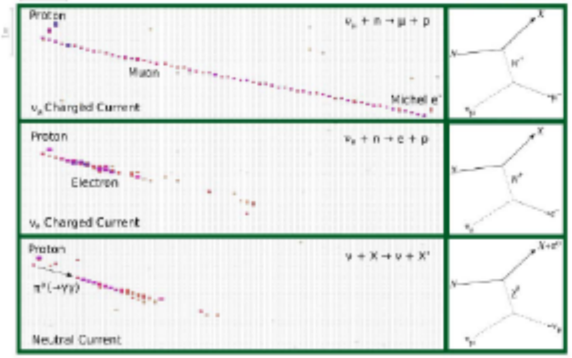
Neutrinos international — NOvA. Goals. Setup

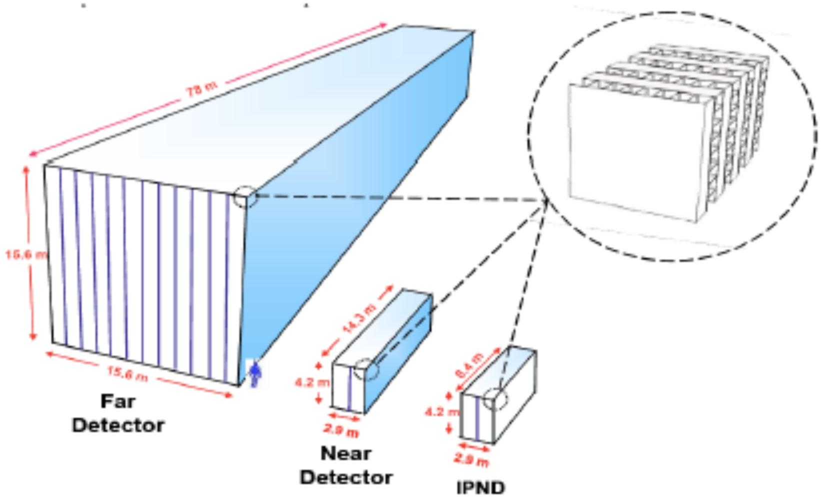
NOvA (NuMI Off-Axis ν_e Appearance) — a new generation accelerator long baseline experiment for study $\nu_\mu \to \nu_e$ oscillations.

The goal is to precisely measure the parameters of the neutrino mixing matrix, the neutrino mass hierarchy and CP violation effects in the lepton sector.







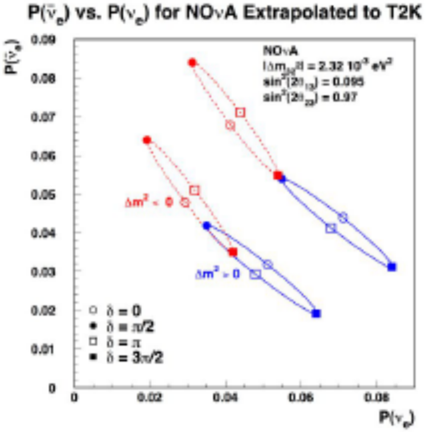


The NOvA apparatus consists of a Near Detector (220 ton) on the Fermilab site where the ν_μ-s are produced, and a Far Detector (14 kton) 810 km distant, both filled with liquid scintillator, have similar construction and situated 14 mrad off-axes to the ν beam. Detectors will be ready to reach full data-taking capability in 2014. The following 6 years of data taking are optimized for running with ν and $\bar{\nu}$ beams.

Neutrinos international — NOvA. JINR

Joining the NOvA the Dubna group can make an important contribution to the detector commissioning, calibration, development of data quality control tools, running and physics analysis.

Significant expertise was gained by JINR team in previous neutrino and particle physics experiments: the work on novel photo-detectors for calorimeters, construction of OPERA Target Tracker detector, development of algorithms and tools for alignment and data quality monitoring, physics analysis of neutrino interaction measurement of hadron production cross sections, etc.



— Duration of the project in JINR is 2014–2016

— Annual budget is 90k$ (JINR 1099)

— JINR team (leader A.G. Olchevsky): N.V. Anphimov, S.M. Bilenky, A.E. Bolshakova, S.G. Dmitrievskiy, A.G. Dolbilov, A.A. Dolmatov, Yu.A. Gornushkin, V.V. Korenkov, C.T. Kullenberg, K.S. Kuzmin, V.A. Matveev, D.V. Naumov, V.A. Naumov, O.N. Petrova, A.B. Sadovsky, O.B. Samoylov, I.M. Shandrov, A.P. Sotnikov

The JINR group is primary involved in the following:

— Electronics tests: parameters studying, cross-talk investigation, optimization of photodetectors.

— Data processing, developments of the DAQ formats and multipoint algorithm.

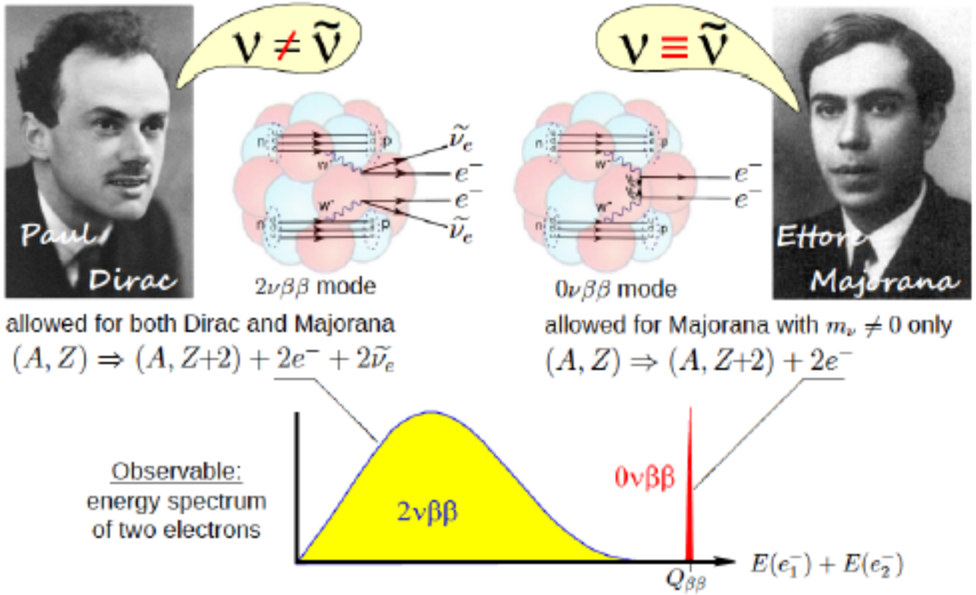
— Reconstruction and event topology identification.

— Theoretical studies for cross-sections and neutrino propagation through the matter.

Neutrinos international — SuperNEMO. Goals

Search for neutrinoless double beta decay with NEMO-3 and the next generation 2-beta decay experiment SuperNEMO.

Search for the $0\nu\beta\beta$-decay is the most direct way to establish the Nature of the neutrino. It violates the total lepton number conservation law by 2 units and is possible only if the neutrino is a Majorana particle ($\nu \equiv \bar{\nu}$) with nonzero effective mass.



$2\nu\beta\beta$ mode

allowed for both Dirac and Majorana

$(A,Z) \Rightarrow (A,Z{+}2) + 2e^- + 2\tilde{\nu}_e$

$0\nu\beta\beta$ mode

allowed for Majorana with $m_\nu \neq 0$ only

$(A,Z) \Rightarrow (A,Z{+}2) + 2e^-$

Observable:
energy spectrum
of two electrons

Probability of $0\nu\beta\beta$-decay is given by

$$W = G_{0\nu} \cdot |\mathcal{M}_{0\nu}|^2 \cdot \langle m_\nu \rangle^2,$$

$G_{0\nu} \sim Q^5_{\beta\beta}$ is a phase space factor and $\mathcal{M}_{0\nu}$ is the nuclear matrix element.

An observation of $0\nu\beta\beta$-decay would allow determination of the absolute neutrino mass scale — $\langle m_\nu \rangle$.

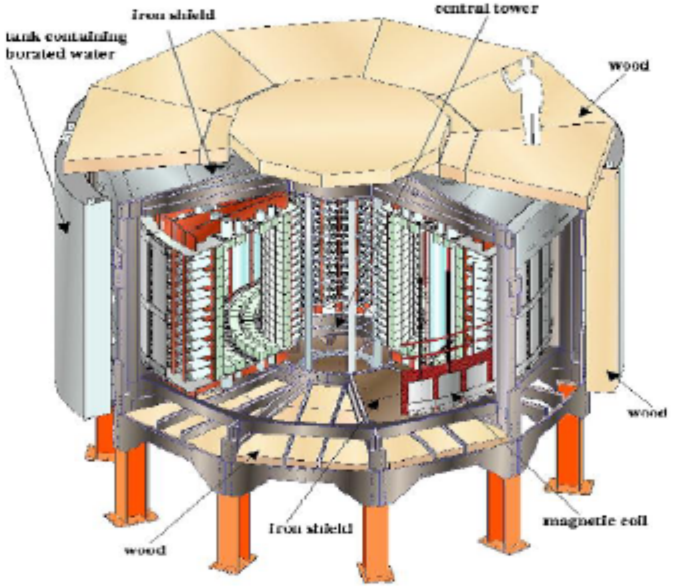
Two-neutrino double beta decay ($2\nu\beta\beta$) is an allowed, very rare weak interaction process. The measurement of its rate is important because it constitutes the main background for the $0\nu\beta\beta$-decay signal, and provides with valuable input for the nuclear structure $\mathcal{M}_{0\nu}$ theoretical calculations.

Neutrinos international — NEMO-3 Results

The NEMO experiment worked with NEMO-3 setup in the Modane Undeground Laboratory (France, Frejus tunnel) at 4800 m w.e. depth from Feb. 2003 → Jan. 2011.

The NEMO low-background spectrometer detected $\beta\beta$-decays with tracking and calorimetric techniques. A thin $\beta\beta$-samples were surrounded with tracking volume and an outer scintillator calorimeter. Tracking, calorimetric and time-of-flight information provides very precise $\beta\beta$-event signature, suppressing the background.

$\beta\beta$-detector $\neq$ $\beta\beta$-source.



NEMO-3 $2\nu\beta\beta$-decay results:

Isotope	Mass (g)	$Q_{\beta\beta}$ (keV)	S/BG	$T_{1/2}$ (10^{19} years)		
^{100}Mo	6914.0	3034	76	0.711	$\pm\,0.002$(stat)	$\pm\,0.054$(syst)
^{82}Se	832.0	2998	3	9.6	$\pm\,0.3$(stat)	$\pm\,1.0$(syst)
^{116}Cd	405.0	2813	10.3	2.88	$\pm\,0.04$(stat)	$\pm\,0.16$(syst)
^{150}Nd	37.0	3371	2.8	0.911	$^{+0.025}_{-0.022}$(stat)	$\pm\,0.063$(syst)
^{96}Zr	9.4	3350	1.0	2.35	$\pm\,0.14$(stat)	$\pm\,0.16$(syst)
^{48}Ca	7.0	4263	6.8	4.4	$^{+0.5}_{-0.4}$(stat)	$\pm\,0.4$(syst)
^{130}Te	454.0	2527	0.5	70	$\pm\,9$(stat)	$\pm\,11$(syst)

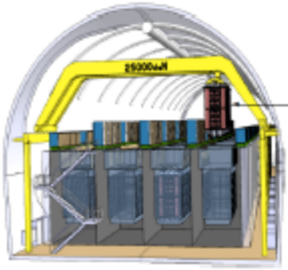
Obtained (90% CL) limit on the $0\nu\beta\beta$-decay of ^{100}Mo and upper limit on the effective neutrino mass:

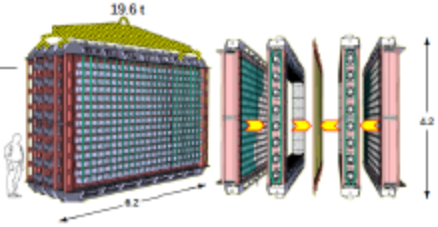
$$\mathrm{T}_{1/2}(0\nu\beta\beta) \geq 1.1 \times 10^{24}\mathrm{y},\ \langle m_\nu \rangle < 0.3 \div 0.9\,\mathrm{eV}.$$

The NEMO-3 detector had a cylindrical shape and was composed of 20 sectors. It contained 9 kg of 7 different $\beta\beta$ isotopes in the form of thin (50 mg/cm^2) source foils located vertically in the middle of tracking volume surrounded by a calorimeter.

Neutrinos international — SuperNEMO. Setup

The SuperNEMO will measure individual electron tracks, vertices, energies and time of flight (full kinematics and topology of an event). The background rejection is based on identification of γ-rays, α-particles, and distinguishing e^- from e^+ with a magnetic field. The $\beta\beta$-decay source separation from the detector allows several different isotopes to be studied.



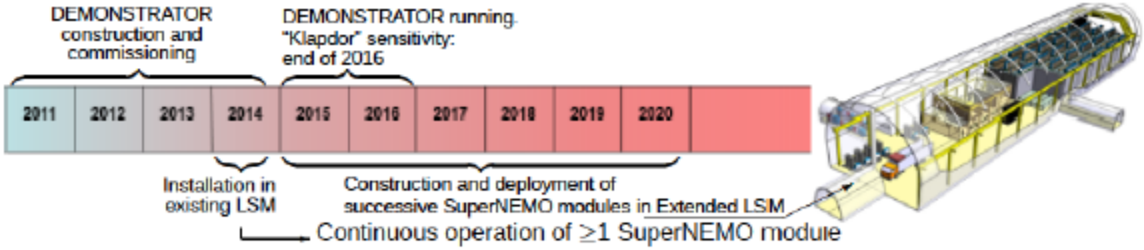


Parameter	NEMO-3	SuperNEMO
Isotope and its mass	^{100}Mo, 7 kg	^{150}Nd or ^{82}Se, 100 - 200 kg
Efficiency	8%	$\sim$30%
Energy resolution (FWHM)	8% @ 3 MeV	4% @ 3 MeV
Internal ^{208}Tl contamination in $\beta\beta$ foil	$< 20\ \mu$Bq/kg	$< 2\ \mu$Bq/kg
Internal ^{214}Bi contamination in $\beta\beta$ foil	$< 300\ \mu$Bq/kg	$< 10\ \mu$Bq/kg (if ^{82}Se)
Internal Radon contamination in tracker	~ 5 - 6 mBq/m^3	< 0.1 mBq/m^3
$T_{1/2}(0\nu\beta\beta)$ sensitivity	$> 1 \times 10^{24}$ y	$> 2 \times 10^{26}$ y
$\langle m_\nu \rangle$ sensitivity	$\leq$ (310 - 790) meV	$\leq$ (30 - 100) meV

The expected (factor 10) improvement in performance.

The SuperNEMO consists of 20 independent modules. Each module contains 5-7 kg of a thin sample foil surrounded by a gas tracking chamber followed by calorimeter walls. The tracking contains more than 2000 wire drift chambers operated in Geiger mode and arranged in 9 layers parallel to the foil. The calorimeter is divided into 1000 blocks which cover most of the detector outer area and are read out by low background PMT. The main candidate isotopes are ^{82}Se, ^{150}Nd and ^{48}Ca.

The first trial module of the SuperNEMO (Demonstrator) is being built now. It will replace NEMO-3 in the LSM in 2014. All 20 modules will be running in 2017–2020 in the extended LSM.



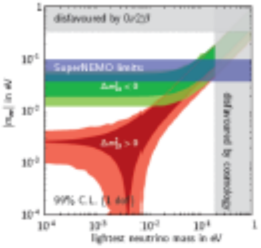
DEMONSTRATOR construction and commissioning

DEMONSTRATOR running. "Klapdor" sensitivity: end of 2016

Installation in existing LSM

Construction and deployment of successive SuperNEMO modules in Extended LSM

Continuous operation of ≥1 SuperNEMO module



Neutrinos international — SuperNEMO. JINR

The JINR contribution into the NEMO project is very important :

— MC simulation of the SuperNEMO detector design, performance evaluation.

— Development of tracking software, $\beta\beta$-event selection criteria, background estimations, databases, data acquisition, slow control, and data analysis software.

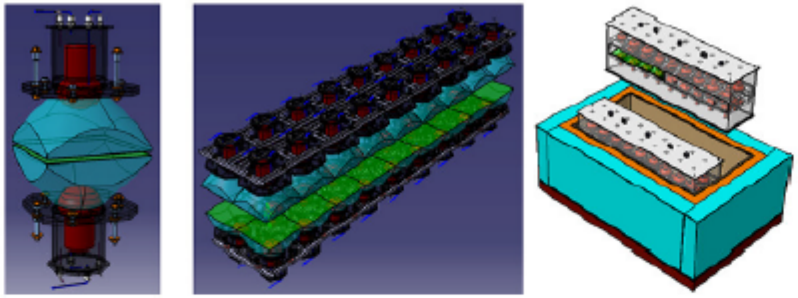
— Development and creation of the calorimeter and veto systems based on plastic scintillators.

— Development of calibration and monitoring system on the basis of JINR radioactive sources.

— Conduction of low background measurements screening radioactive purity of enriched $\beta\beta$-decay sources and structural materials for the Demonstrator with a big JINR HPGe-detector (600 cm^3).

— Creation of the electromagnetic source of mono-energetic electrons for quality control of plastic scintillators used in the calorimeter and the veto system.

— Participation in the development and creation of the ultra low-background BiPo-3 spectrometer aimed to measure radiopurity of $\beta\beta$-decay source foils.



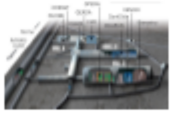
— Duration of the project is 2003–2015

— JINR team (O. Kochetov): V. Brudanin, V. Babin, V. Egorov, D. Filosofov, D. Karaivanov, A. Klimenko, V. Kovalenko, I. Nemchenok, A. Rahimov, Yu. Shitov, A. Shurenkova, A. Smolnikov, V. Timkin, V. Tretyak, Yu. Yushkevich

— Annual budget is about 50k$ (JINR, 1101)

Neutrinos international — GERDA. Goals

GERmanium Detector Array (GERDA) to search for neutrinoless double beta decay in ^{76}Ge.



The leader of Heidelberg-Moscow experiment, Prof. H.V.Klapdor-Kleingrothaus, published a claim on observation of $0\nu\beta\beta$ decay in ^{76}Ge (6.4 σ). The claim is very intriguing and has to be verified. Only GERDA is able to test directly the claim with ^{76}Ge.

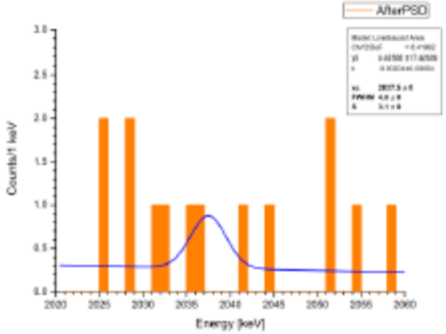
— The goal of GERDA Phase-I stage (finished in 2013) was to scrutinize the claim with a total exposure of 21 kg yr.

— The next Phase-II aims at exploring $T^{0\nu}_{1/2} > 10^{26}$ yr, with 100 kg yr of exposure and a background index 10^{-3} counts/(keV kg yr).

— To reach such a background the collaboration is going to operate 30 extra detectors (20 kg of ^{76}Ge) with a new electrode geometry (BEGe detectors), providing superior pulse shape discrimination.

— New devices will be installed to identify energy depositions in the liquid argon surrounding the detector array, through the detection of the induced LAr scintillation light. These events are due to background sources. In coincidence with a Ge detector signal they can be used as anti-Compton or anti-coincidence veto.

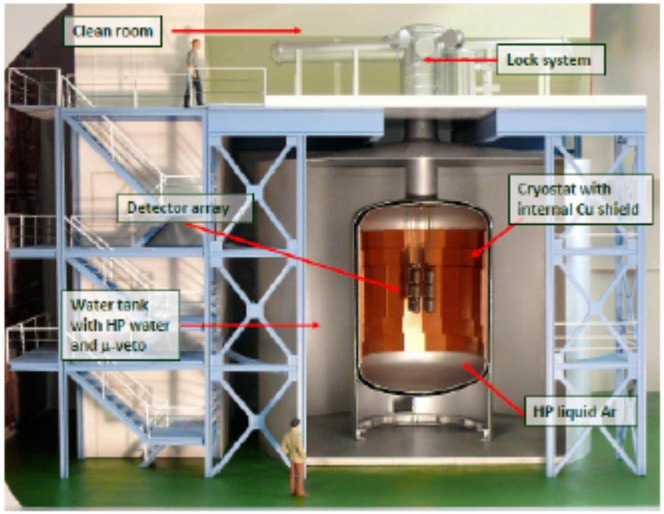
The signature of $0\nu\beta\beta$ in ^{76}Ge is a peak at the Q-value of the decay (2039.061 ± 0.007 keV).

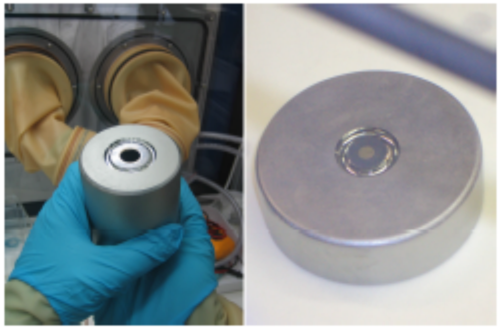


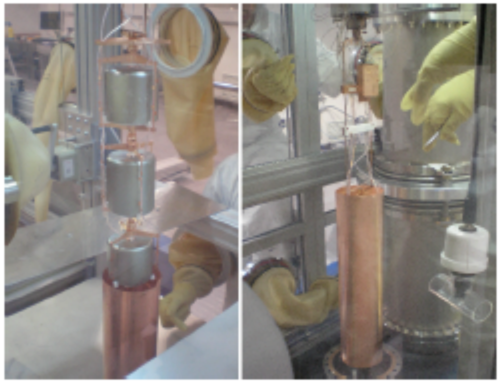
H.V. Klapdor-Kleingrothaus: $T^{0\nu}_{1/2} = (2.23^{+0.44}_{-0.31}) \cdot 10^{25}$ yr.

Neutrinos international — GERDA. Setup

The GERDA experiment is located at the Laboratori Nazionali del Gran Sasso (Italy). The setup has an array of Ge detectors, mounted in low-mass supports and immersed in a 64 m^3 cryostat filled with liquid argon. The LAr serves as cooling medium and shield against external backgrounds. The cryostat is located inside a water tank of 10 m in diameter. $\beta\beta$-detector = $\beta\beta$-source.




A semi-coaxial Phase I (Left) and BEGe Phase II (Right) detectors.

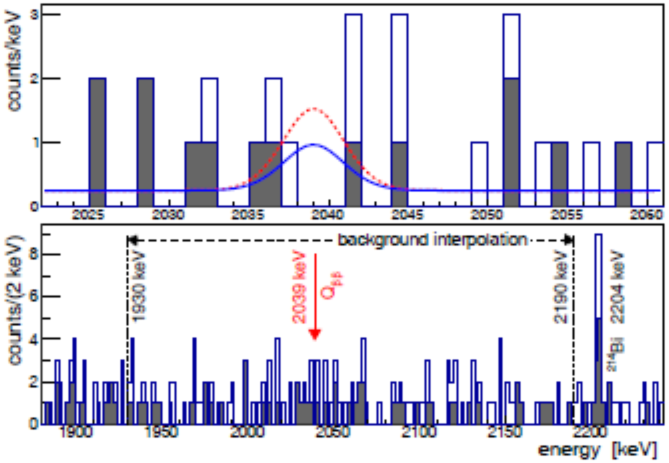

A string of 3 $^{\mathrm{enr}}$Ge detectors.

In Phase I, the Ge semi-coaxial and BEGe detectors were mounted into 4 strings. A 30 μm thin copper cylinder with a diameter of 75 cm encloses the detector array.

In Phase II, 7 strings of the detectors will be installed (30 new BEGe + 7 semi-coaxial from Phase I, about 35 kg of $^{\mathrm{enr}}$Ge) in ultra low background holders made from intrinsically pure mono crystalline silicon. Entirely new electronics will provide better energy resolution and PSD capability. The LAr instrumentation will be implemented in GERDA cryostat in order to detect the scintillation light of the Ar as an additional background rejection tool.

Neutrinos international — GERDA-I. Results

Phase I started in Nov. 2011 with 8 enriched Ge detectors. The data were collected until May 2013 (492.3 live days, or 21.6 kg yr). The exposure-averaged energy resolutions at $Q_{\beta\beta}$ are 4.8 ± 0.2 keV for the semi-coaxial detectors, and 3.2 ± 0.2 keV for the BEGe detectors.



The GERDA finds no indication of a peak at $Q_{\beta\beta}$ and not supported the claim of $0\nu\beta\beta$ decay in ^{76}Ge. The limit on the half-life is $T^{0\nu}_{1/2} > 2.1 \times 10^{25}$y (90% CL) including the systematic uncertainty.

In Fig. The combined energy spectrum from all $^{\rm enr}$Ge detectors without (with) PSD is shown by the open (filled) histogram. Given are expectations (with PSD) based on $T^{0\nu}_{1/2} = 1.19 \times 10^{25}$ y (KK, red dashed) and derived from GERDA result $T^{0\nu}_{1/2} = 2.1 \times 10^{25}$ y (blue solid). The lower panel shows the region used for the background interpolation.

Intensive preparation for Phase-II of GERDA has been started, 30 new BEGe detectors from ^{76}Ge already produced and tested (about 20 kg ^{76}Ge), in total about 40 kg of detectors will be used.

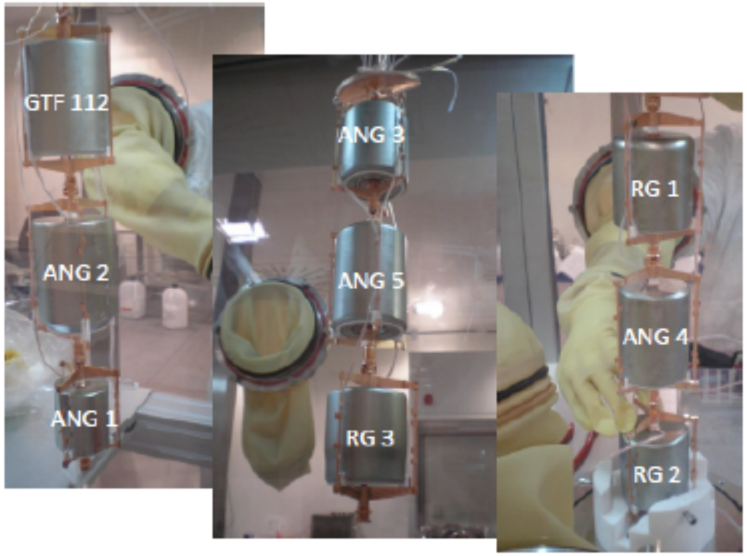
Due to the unprecedented low background and the HPGe detectors good energy resolution, GERDA has already reached stringent $0\nu\beta\beta$ half-life limit for ^{76}Ge.

Nevertheless, I believe, it is too early to conclude that the claim for the $0\nu\beta\beta$ signal in ^{76}Ge is strongly disfavored. Therefore in nearest 5 years GERDA has a very good perspective with its Phase II, which is aimed for a sensitivity increased by a factor of 10!

Neutrinos international — GERDA. JINR

JINR members are playing significant roles in all key parts of GERDA experiment:

— JINR was responsible for design, production, testing and installation of plastic muon veto system on the top of GERDA cryostat. This veto will be also used for Phase II.
— JINR specialists participate heavily in the development of LAr instrumentation.
— Physicists from JINR are strongly involved in the analysis of GERDA data, especially for Phase II (BEGe) detectors and this contribution will be increased.
— JINR members play the central and leading role in the core of GERDA experiment — operations with bare germanium detectors.



— Duration of the project is 2006–2018
— JINR team (A. Smolnikov, K. Gusev): V. Brudanin, D. Borowicz, V. Egorov, A. Klimenko, O. Kochetov, A. Lubashevskiy, I. Nemchenok, N. Rumyantseva, E. Shevchik, M. Shirchenko, I. Zhitnikov, D. Zinatulina
— Annual budget is about 50k$ (JINR, 1101)

”A neutrino interdisciplinary laboratory at the

Kalinin Nuclear Power Plant

could be the Next Russian mega-project”...

From the decision of the RAS Scientific Council “Neutrino Physics and Neutrino Astrophysics” 26.06.2012

JINR neutrino laboratory for the KNPP

The RAS Scientific Council stresses that …

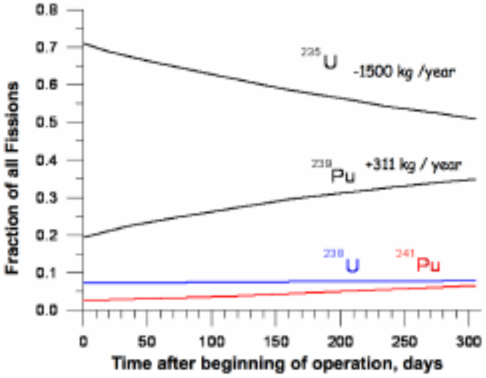
— "Special attention should be paid to the unique opportunity to accomplish a new modern neutrino interdisciplinary project in Russia at the Kalinin Nuclear Power Plant".

— "This modern neutrino laboratory will really allow Russia to be the world leader, both in fundamental research on reactor antineutrinos and in applied research for nuclear energy industry and safety of nuclear reactors."

Kalinin Nuclear Power Plant (KNPP) is a standard 3GWth (VVEP-1000) water-moderated and water-cooled Power reactor. Core diameter 3.12 m, height 3.5 m.

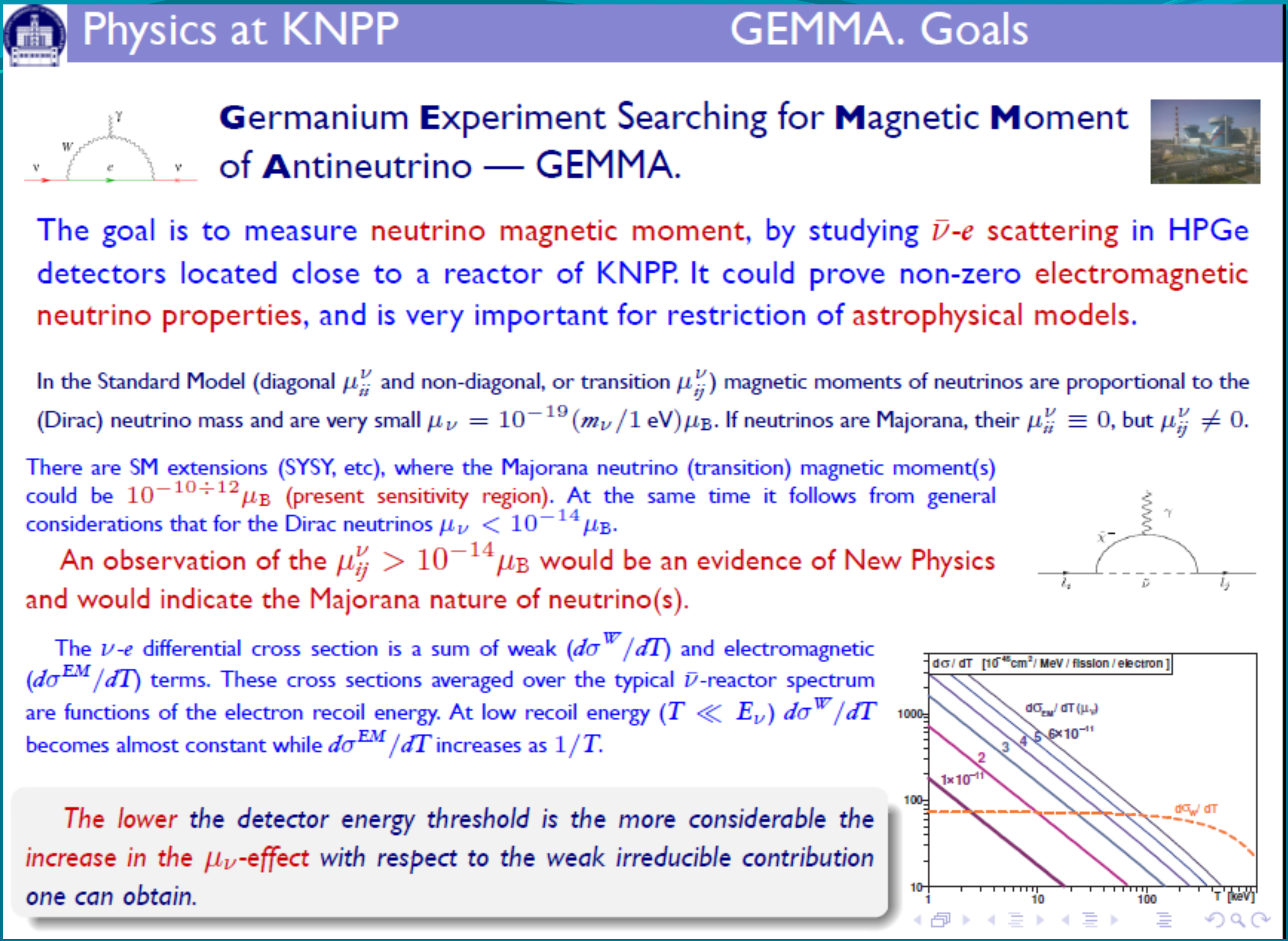
Fuel is U-238 (97.7%) and U-235 (3.3%). Operation during 320 days (to be increased). Fuel recharge every 50 days. 1500 kg of U-235 is burned out and 311 kg of Pu-239 is produced which changes (by 10%) the flux and energy spectrum of the neutrinos emitted.

Full KNPP flux is about 10^{21} antineutrinos per sec into 4π.



UNIQUE FLUX, 5×10^{13} neutrinos per sec and cm^2, is available at 10 m from the core!

GEMMA and DANSSino work well at the KNPP.



Physics at KNPP GEMMA. Goals

Germanium **E**xperiment Searching for **M**agnetic **M**oment of **A**ntineutrino — GEMMA.

The goal is to measure neutrino magnetic moment, by studying $\bar{\nu}$-e scattering in HPGe detectors located close to a reactor of KNPP. It could prove non-zero electromagnetic neutrino properties, and is very important for restriction of astrophysical models.

In the Standard Model (diagonal μ_{ii}^{ν} and non-diagonal, or transition μ_{ij}^{ν}) magnetic moments of neutrinos are proportional to the (Dirac) neutrino mass and are very small $\mu_{\nu} = 10^{-19}(m_{\nu}/1\text{ eV})\mu_{\mathrm{B}}$. If neutrinos are Majorana, their $\mu_{ii}^{\nu} \equiv 0$, but $\mu_{ij}^{\nu} \neq 0$.

There are SM extensions (SYSY, etc), where the Majorana neutrino (transition) magnetic moment(s) could be $10^{-10\div12}\mu_{\mathrm{B}}$ (present sensitivity region). At the same time it follows from general considerations that for the Dirac neutrinos $\mu_{\nu} < 10^{-14}\mu_{\mathrm{B}}$.

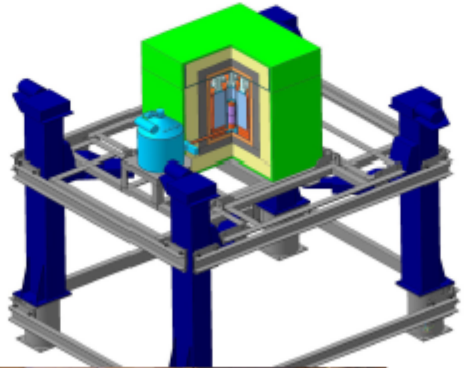
An observation of the $\mu_{ij}^{\nu} > 10^{-14}\mu_{\mathrm{B}}$ would be an evidence of New Physics and would indicate the Majorana nature of neutrino(s).

The ν-e differential cross section is a sum of weak ($d\sigma^{W}/dT$) and electromagnetic ($d\sigma^{EM}/dT$) terms. These cross sections averaged over the typical $\bar{\nu}$-reactor spectrum are functions of the electron recoil energy. At low recoil energy ($T \ll E_{\nu}$) $d\sigma^{W}/dT$ becomes almost constant while $d\sigma^{EM}/dT$ increases as $1/T$.

The lower the detector energy threshold is the more considerable the increase in the μ_{ν}-effect with respect to the weak irreducible contribution one can obtain.

GEMMA. Setup

GEMMA-II is located 10 m below the center of the core of reactor N3 (KNPP). Enormous flux of 5.4×10^{13}/cm^2/s $\bar{\nu}$-s is available. The mass of the detector is 6 kg (2 detectors of 3 kg each). The γ-background conditions in the new site are much better (by an order of magnitude vs reactor N2 of GEMMA-I).



The detector is movable due to a special lifting mechanism that can vary the distance between the detector and the center of the reactor core from 10 to 12 m.

It allows on-line variation of the $\bar{\nu}$-flux significantly and thus suppresses the main systematic errors caused by the possible long-term instability and uncertainties of background.

A special U-type low-background cryostat is used to improve the passive shielding and to reduce the external background down to $0.5 \div 1.0$ keV·kg·day^{-1}.

Special care is taken to improve antimicrophonic and electric shielding. The energy threshold is reduced to 1.5 keV.

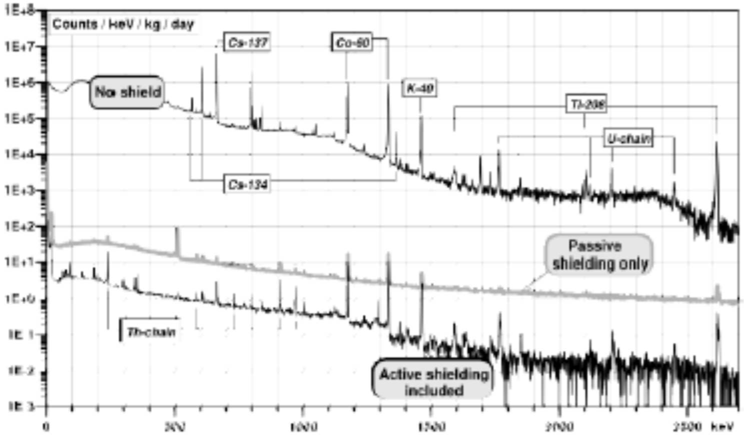
U-type low-background cryostat (left) and the scheme of its detector part.

These improvements will allow us to suppress the systematic errors and expect the GEMMA-II sensitivity at a level of $1 \times 10^{-11} \mu_B$.

Physics at KNPP GEMMA. JINR+ITEP

The GEMMA-II detector is placed inside a cup-shaped NaI crystal with 14 cm thick walls surrounded by 5 cm of electrolytic copper and 15 cm of lead. Being located just 10 m under the reactor core center the detector is well shielded against the hadronic component of cosmic rays by the reactor body and technological equipment (70 mwe). The μ-component is reduced by a factor of 10 (3) at 20° (80°) with respect to vertical line. Nevertheless, a part of residual muons are captured in the shielding and produce neutrons that scatter in the detector and raise the low energy background.

To suppress this effect the spectrometer is covered with additional plastic scintillator plates which produce relatively long μ-veto signals.



The effectiveness of the passive and active shieldings

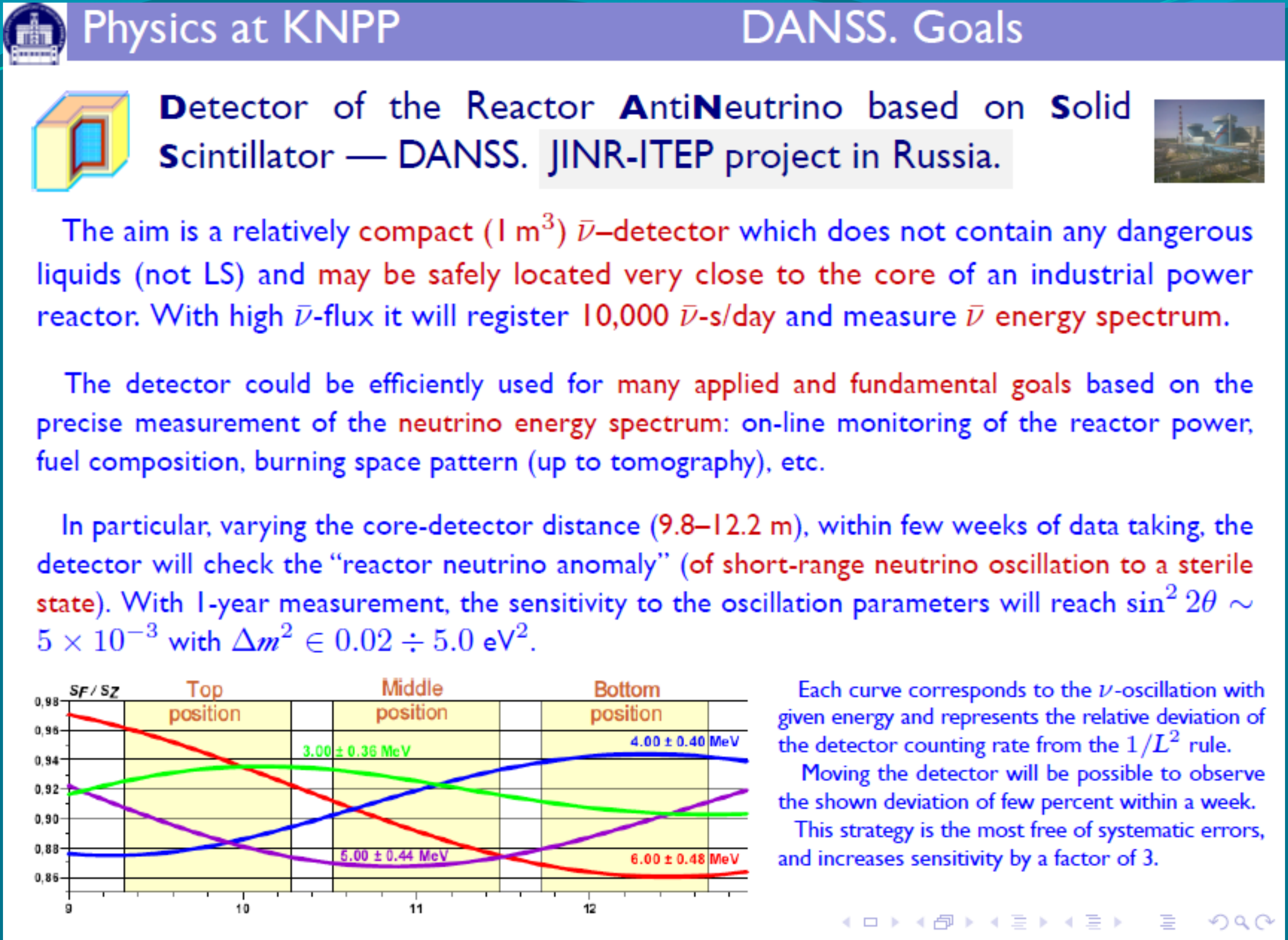
GEMMA — the JINR+ITEP project.

— Duration of the project is 2005–2018.

— JINR team (V. Brudanin, V. Egorov): V. Belov, D. Medvedev, E. Shevchik, M. Shirchenko, I. Zhitnikov

— Annual budget is about 100k$ (JINR, 1101)

In 2016–2018 a new type of detector with point contacts will be used. This will allow an ultralow effective threshold of about 300 eV. Several detectors with total mass about 5 kg will give an opportunity to reach the sensitivity at a level of $5 \div 10 \times 10^{-12} \mu_B$.



Physics at KNPP — DANSS. Goals

Detector of the Reactor **A**nti**N**eutrino based on **S**olid **S**cintillator — DANSS. JINR-ITEP project in Russia.

The aim is a relatively compact (1 m^3) $\bar{\nu}$–detector which does not contain any dangerous liquids (not LS) and may be safely located very close to the core of an industrial power reactor. With high $\bar{\nu}$-flux it will register 10,000 $\bar{\nu}$-s/day and measure $\bar{\nu}$ energy spectrum.

The detector could be efficiently used for many applied and fundamental goals based on the precise measurement of the neutrino energy spectrum: on-line monitoring of the reactor power, fuel composition, burning space pattern (up to tomography), etc.

In particular, varying the core-detector distance (9.8–12.2 m), within few weeks of data taking, the detector will check the "reactor neutrino anomaly" (of short-range neutrino oscillation to a sterile state). With 1-year measurement, the sensitivity to the oscillation parameters will reach $\sin^2 2\theta \sim 5 \times 10^{-3}$ with $\Delta m^2 \in 0.02 \div 5.0$ eV^2.

Each curve corresponds to the ν-oscillation with given energy and represents the relative deviation of the detector counting rate from the $1/L^2$ rule.

Moving the detector will be possible to observe the shown deviation of few percent within a week.

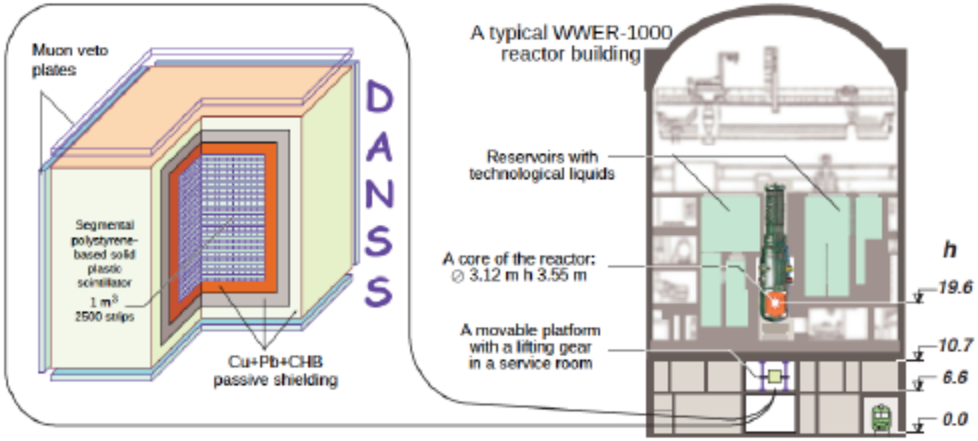
This strategy is the most free of systematic errors, and increases sensitivity by a factor of 3.

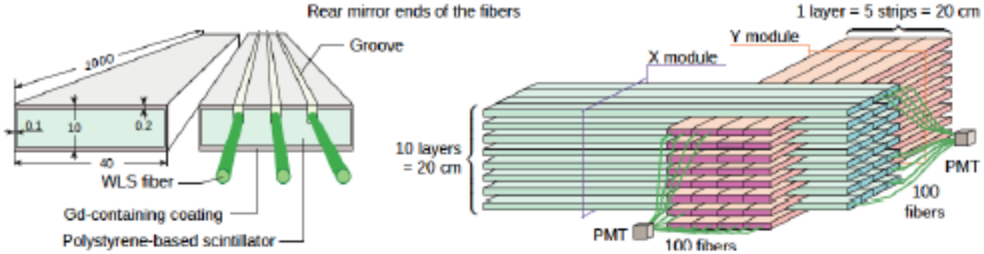
DANSS. Setup

The DANSS detector consists of highly segmented plastic scintillator surrounded with a composite shield of copper, lead and borated polyethylene (CHB), and vetoed against cosmic μs with external scintillator plates.

It's location very close to the core of the reactor allows extremely high $\bar{\nu}$-flux and provides very good shielding against cosmic rays (50 mwe) which completely removes fast cosmic neutrons and suppresses μ-component by a factor of 6.

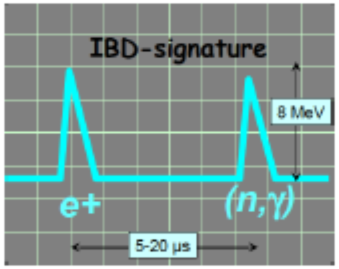
High segmentation of the plastic scintillator allows background suppression down to a 1% level.





The basic element of DANSS is a polystyrene-based extruded scintillator strip ($1 \times 4 \times 100$ cm^3) with a thin Gd-containing surface coating, which is a light reflector and an (n, γ)-converter simultaneously.

Each set of 50 parallel strips are combined into a module, so that the whole detector (2500 strips) is a structure of 50 intercrossing modules.



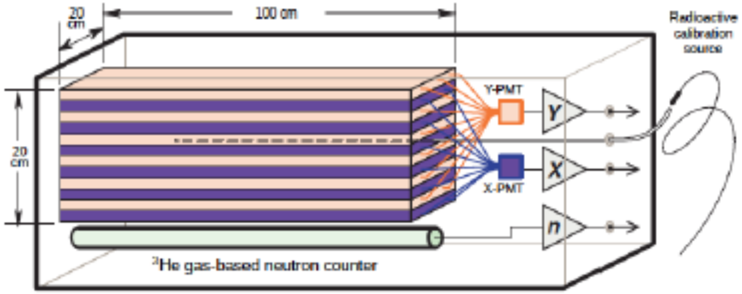
The inverse beta-decay ($\overline{\nu}_e p \rightarrow e^+ n$) of hydrogen is used to detect $\overline{\nu}$-s. The energy threshold is 1.8 MeV, and most of the remaining $\bar{\nu}_e$-energy is transferred to the e^+. This e^+ deposits its energy within a short range (few cm) and annihilates into two 511-keV γ-s — the 1st (prompt) energy deposition.

The second (delayed) deposition is due detection of the neutron. Initial energy of the neutron is only few keV. After some traveling in the plastic scintillator it is captured by gadolinium with a very high cross-section. As a result, a cascade of γ-rays is emitted with a total energy of about 8 MeV.

Physics at KNPP DANSSino. Results

To check the DANSS design, a pilot version —

DANSSino (DANSS/25) was created →

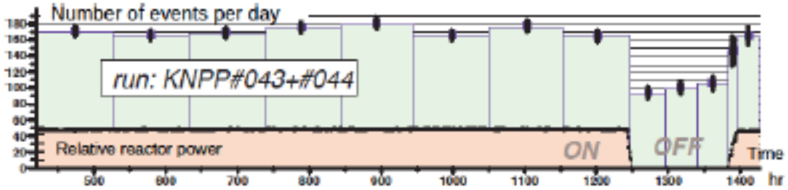


One hundred strips of DANSSino form a bar $20 \times 20 \times 100$ cm^3 divided into two modules: the odd strip layers are coupled to the X-PMT and the even ones to the Y-PMT. Together with an additional neutron counter both modules are equipped with preamplifiers and placed into a light-tight box.

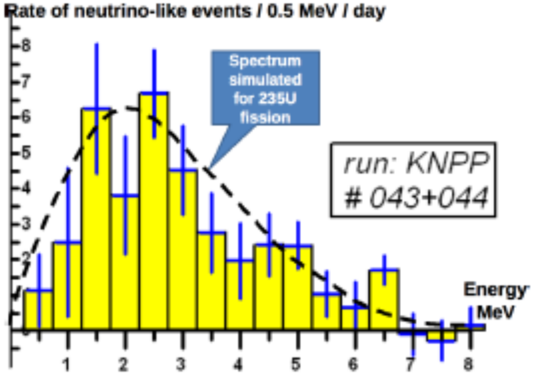
The DANSSino, unshielded and shielded with CHB against neutrons.

Young generation strongly involved!

Despite of its small size, DANSSino has detected about 70 events per day (S/B$\simeq$1). Energy and time distribution of the neutrino-like events are in a good agreement with MC simulations, confirming true observation of the $\bar{\nu}$-events.

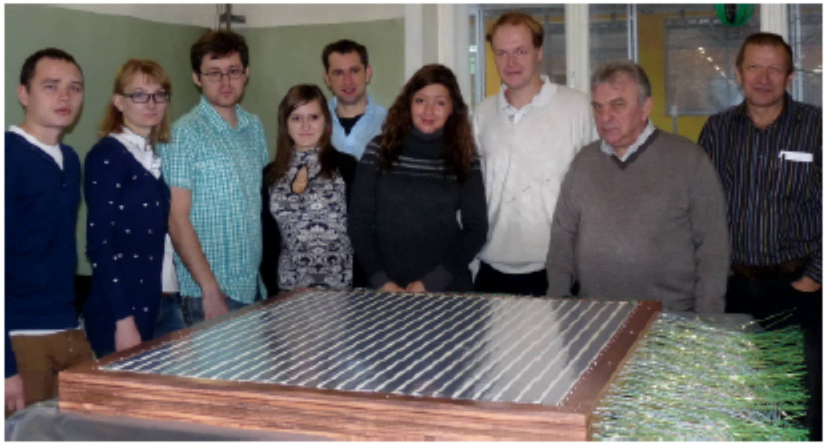


This is already measured reactor $\bar{\nu}$-spectrum! →



Physics at KNPP DANSS. JINR+ITEP

— Duration of the project is 2006–2018.
— JINR team (V.B. Brudanin, V.G. Egorov): V. Belov, M. Fomina, Z. Hons, A. Kuznetsov, D. Medvedev, A. Olshevsky, N. Rumyantseva, Ye. Shevchik, M. Shirchenko, Yu. Shitov, I. Zhitnikov, D. Zinatulina
— Annual budget is about 200k$ (JINR, 1101 +extra budget)



The DANSS detector is under responsibility of our young generation — guarantee of the future success.

JINR plays a leading role in the Project.

Most work was performed in Dubna by the JINR staff: design and creation of the entire mechanical structure (detector strips with WLS fibers, passive and active shielding, lifting system), light extraction system, PMT front-end electronics, data acquisition system, design and creation of the prototype (DANSSino) and test measurements with it.

ITEP is responsible for managing with SiPM (front-end electronics and data taking).

Parallel to the main DANSS detector creation, the next trial version DANSSino-2 is under mounting now in order to test other signal extraction and another basic element, the scintillator plate made by ENVINET firm (Czech Republic). This work is done together with the Institute of Experimental and Applied Physics, CTU in Prague.

νGEN. JINR Setup!

The νGEN experiment is based on:

— JINR expertise in the production of unique low-threshold HPGe detectors (masses of 240 and 450 grams). Four point contact detectors already built at JINR with total mass 1.8 kg (up to 5 kg), and energy threshold of 350 eV.

— The low-background cryostat for detectors built by Baltic Scientific Instruments (BSI). The setup has also integrated low-noise FET and preamplifiers.

— The background $\simeq$ 0.5 events/kg/keV/day.

— The possibility to work on the KNPP, where ν-flux is $> 5.4 \cdot 10^{13}$ cm^{-2}/sec (best with factor 10).

The 4 HPGe point contact 450-g detectors built at JINR.

The low background cryostat built by BSI. Internal part; Assembled, test of low radioactive shield at LSM.

— Location just under the reactor $\rightarrow$ about 70 m.w.e. shielding from cosmic rays. The shield will be improved with active μ-veto system (plastic scintillator) and with active anti-compton shield.

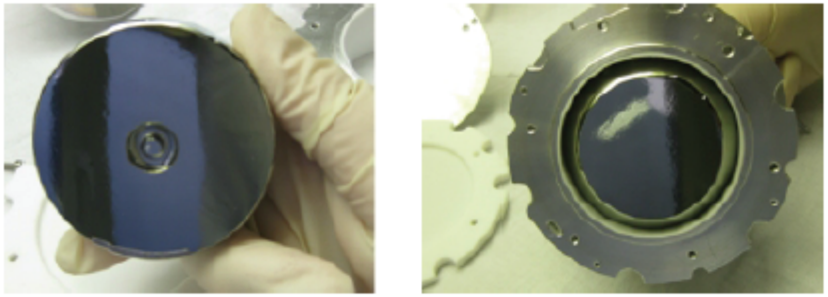
— Important: JINR team already has unique experience in conducting low-background $0\nu2\beta$-search experiments and low-threshold experiments (search for neutrino magnetic moment) at the KNPP.

Physics at KNPP νGEN. JINR (MEPhI will join)

— Duration of the project is 2014–2018.

— JINR team (V. Brudanin, E. Yakushev): V. Belov, V. Egorov, D. Filosofov, M. Fomina, Yu. Gurov, A. Lubashevskiy, D. Medvedev, I. Rozova, S. Rozov, V. Timkin, I. Zhitnikov.

— Annual budget is about 10k$ (JINR, 1101)

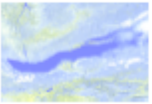

The detector with point contact created by BSI with JINR participation and JINR technology (left — without holder, right — in the low radioactivity holder).

For the νGeN setup (with 4 HPGe low-energy-threshold-of-300 eV detectors, 450 grams each) placed at 10 m from the center of reactor core up to 10 events of the CNNS in Ge are expected for detection per day.

Therefore, JINR team, with the νGeN experiment at the KNPP, expects to detect the coherent neutrino-nucleus scattering and measure CNNS cross-section in Ge during the nearest 3–5 years.

JINR-INR joint facility — Baikal-GVD. Goals

BAIKAL Experiment. Deep underwater muon and neutrino detector in the Baikal Lake.



The next generation neutrino telescope, BAIKAL–Gigaton Volume Detector, is aimed at studying astrophysical neutrino fluxes and, mapping the high-energy neutrino sky in the Southern Hemisphere including the region of our galactic center.

Other topics include:

— Search for neutrinos from point-like sources,

— Neutrinos from GRB and AGN,

— Diffuse flux of HE-neutrinos,

— Atmospheric neutrinos, oscillations, mass hierarchy,

— Neutrinos from DM annihilation in the Sun and Earth,

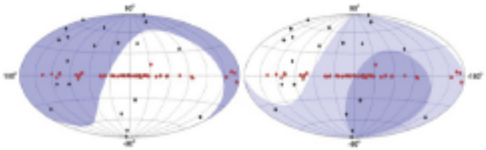
— Non-SM neutrino interactions,

— Magnetic monopoles, Q-balls, etc,

— Global ν Network,

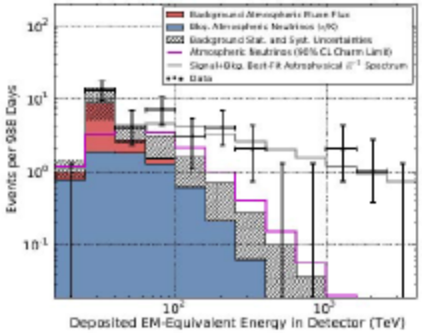
— CERN-to-GVD LBL ν-beam?

— IceCube PeV-νs?



IceCube (left) and Baikal-GVD (right) are complimentary to cover the all neutrino Sky.

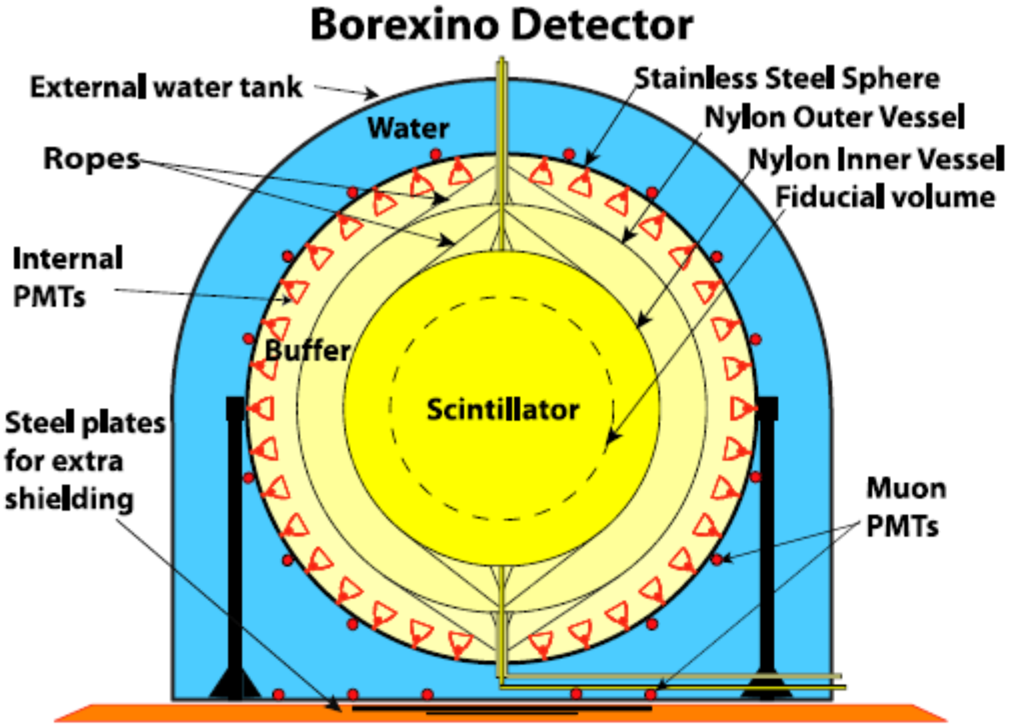
IceCube, KM3Net and Baikal-GVD have jointed into Global Neutrino Network. It is extremely important international project for future astronomy!

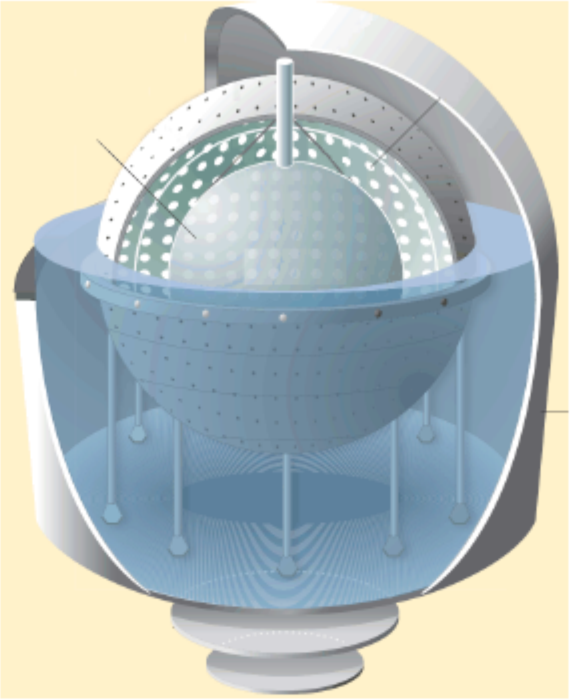


IceCube sees (extra)galactic neutrinos, but not very good.
The key parameter of the BAIKAL-GVD is angular resolution, which should be much better than 1°!

Neutrinos international — Borexino. Setup

The detector is located deep underground (3800 m of water equivalent) in the Hall C of the Laboratori Nazionali del Gran Sasso (Italy), where the muon flux is suppressed by a factor of 10^6.

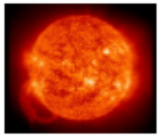




Borexino uses 278 t of HP liquid organic scintillator to register νe-scattering with 200 keV threshold. The base of the dome-like structure is 18 m in diameter. The scintillation light is collected by 2212 photomultipliers (PMT). The Borexino has an excellent energy resolution (6.6%) for its size, due to the high light yield of 500 p.e./MeV/2000 PMT.

Neutrinos international — Borexino. Goals

The BORon solar neutrino EXperiment, BOREXino, at the Gran Sasso underground laboratory.



The first stage goal of Borexino experiment — solar ^{7}Be ν-flux measurement with 5% precision was achieved in 2011.

To reduce main contaminants in the sub-MeV range repurification was completed in 2011–2013.

At the second stage, with the high radiopurity Borexino can perform new investigations:

Solar Neutrino study, solar models discrimination.

— Improvement of ^{7}Be neutrino flux measurement (3%)

— pp-neutrino flux measurement with 10% precision

— pep neutrino measurement with better precision (>3σ)

— ^{8}B neutrino measurement with 4-fold statistics (10%)

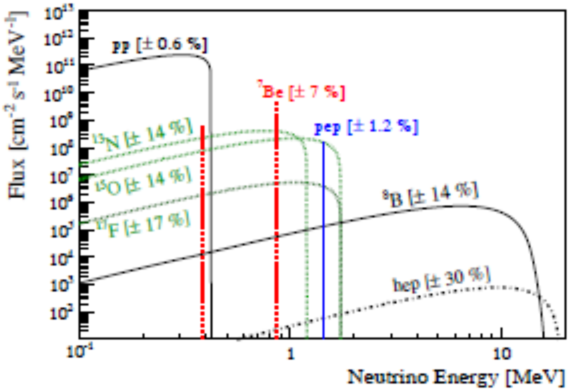
— measurement (or limits) on the CNO neutrino flux.

Search for non-standard interactions of neutrino.

Search for dark matter with modified Borexino-CTF.

Supernova neutrino detection.

There are no competing projects existing at the moment.



Geoneutrino flux measurement with higher statistics.

Project SOX (Short distance Oscillations with BoreXino). Measurements with artificial neutrino source (search for sterile neutrino, neutrino magnetic moment).

Neutrinos international — Borexino. JINR

First observation of geoneutrino (10 events) in 2010,
Study natural radioactivity of the Earth,
Measurement of ^{7}Be solar neutrino flux with 5%-precision,
First direct pep solar neutrino measurement,
Test of seasonal and diurnal variations of the solar neutrino flux —

— were obtained with significant JINR contribution to the detector running and data analysis.

— Duration of the project at JINR is 1992–2016
— JINR team (O. Smirnov): K. Fomenko, A. Sotnikov, D. Korablev, O. Zaimidoroga
— Annual budget is 10k$ (JINR, 1099)
— No hardware contribution. The contribution is in 38 papers by the development of the software, simulation tools, physical analysis, and by paper refereeing.

JINR team participates in:
Software development for Borexino. Data taking shifts (experts level). Analysis of the Borexino data: Be-7 flux, antineutrino fluxes (geo and limits on the solar neutrino fluxes), seasonal variations, limits on the effective neutrino magnetic moment, pp-neutrino flux, rare processes.
Participation in the software development for the prototype Dark Side -10, etc. PMT testing for Dark Side (for muon veto and neutron veto) …

Теоретические исследования и подготовка кадров

- ✓ Развитие феноменологии и теории нейтринных осцилляций

- ✓ Расчёты матричных элементов двойного бета-распада

- ✓ Предложение новых и расширение физической программы существующих экспериментов

- ✓ Создание математических и программных средств для моделирования и анализа данных

- ✓ Анализ дополнительных данных, важных для интерпретации результатов нейтринных экспериментов

- ✓ Чтение лекций, проведение семинаров, конференций и школ

Заключение

- *Физика нейтрино и Астрофизика являются сегодня динамично развивающейся перспективной областью, имеющей принципиальное значение для физики элементарных частиц*

- *ОИЯИ и его страны-участницы вносят в эти исследования существенный вклад, основанный на традиционно развиваемых теоретических идеях, экспериментальных программах и технологиях*