PARTICLE PHYSICS AT PIK REACTOR COMPLEX

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Abstract:

The Standard Model provides estimations on neutron EDM (nEDM) value on the level inaccessible for the modern experiment: $10^{-30} – 10^{-33}$ e·cm. CP-violation (and nEDM) arises only in the second order of smallness on the weak interaction constant. SM fails to account for baryon asymmetry of Universe. Search for nEDM is expected to be search for some phenomena beyond the framework of SM. To improve limitation on nEDM accuracy more intense UCN source is needed. UCN source with superfluid He which is preparing at PNPI will make it possible to reach the highest UCN density $10^3 – 10^4$ cm^{-3}.

Reactor Antineutrino Anomaly gives new average ratio of the observed antineutrino flux to the expected 0.934 ± 0.024 (2σ accuracy). The possible reason for deficiency is oscillations of neutrino into the fourth, sterile state which has considerably less cross-section of interaction with known particles. This assumption requires extension of ideas of the elementary particles interaction, and in case of its detection, a new state of neutrino would be the way to a new physics.

Predicted and discovered electric fields in noncentrosymmetric crystals which may act on a neutron, provide new possibilities for measuring the neutron electric dipole moment (nEDM) by the crystal-diffraction method with the sensitivity about UCN method.

Recent detection of gravitational waves raised the question of the place of this phenomenon in the process of matter generation in the Universe. The project PITRAP proposes to combine a powerful source of exotic nuclides with ultra-sensitive detection of studying this phenomenon for the experimental determination of the mass landscape of exotic nuclides involved in the process of fast neutron capture.

Search for neutron–antineutron oscillations is another possibility of employing UCN in fundamental experiments at new UCN source. A transition of a neutron to an antineutron is possible only under conditions of baryon-number violation, which is one of Sakharov's conditions for the formation of the Universe.

INTRODUCTION

The neutron research reactor PIK is going to become an up-to-date large-scale user facility based on the most powerful steady-state flagship neutron source, capable of meeting major national and worldwide demands for neutron beams research for several decades to come.

The high-flux research neutron-beam PIK Reactor represents a compact source of neutrons with active core volume about 50 L, surrounded by a heavy water reflector. The maximum density of the undisturbed thermal neutron flux in the central experimental channel is close to the value of $5 \cdot 10^{15}$ n/cm^{2}s and $1.2 \cdot 10^{15}$ n/ cm^{2}s in the reflector at 100 MW.

At the end of 2018 the program of reactor PIK commissioning is started. The full power is going to reach in 2-3 years.

The presented program is part of whole reactor scientific program concerned with the physics of elementary particle.

1. NEUTRON EDM SEARCH WITH HIGH INTENSITY UCN SOURCE AT WWR-M REACTOR

We perform neutron EDM measurement for long time. Our last published result [1] set an upper limit $|d|<5.5\ 10^{-26}$ e·cm. Since then our measurements at ILL is suspended, because a platform in reactor hall at ILL has to be reinforced according to new anti-seismic rules in France and this work still is not performed.

Now we are preparing new UCN source for UCN on the base of superfluid helium at the PNPI. According to modelling calculations new source should provide much higher UCN density for experiments and we expect improving the accuracy of the neutron EDM measurement to level less than 10^{-27} e·cm. The scheme of future facilities is shown in Fig. 1.1.

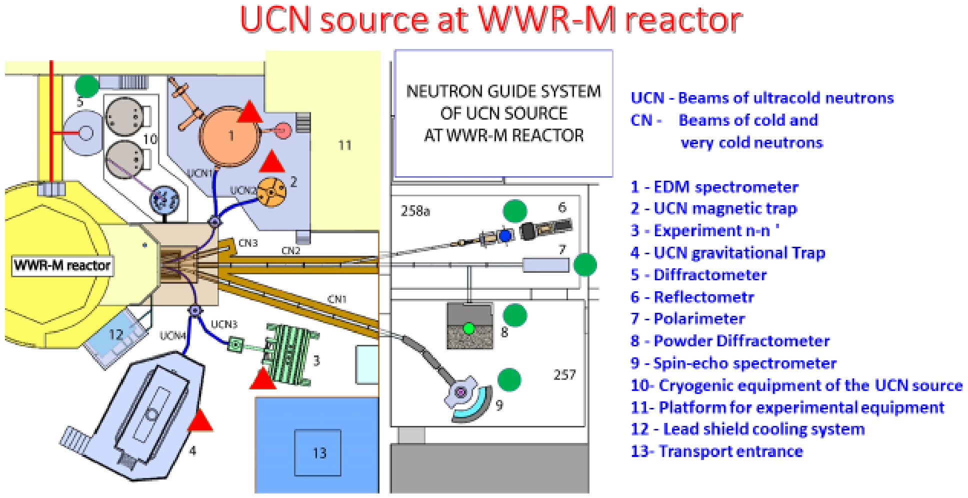
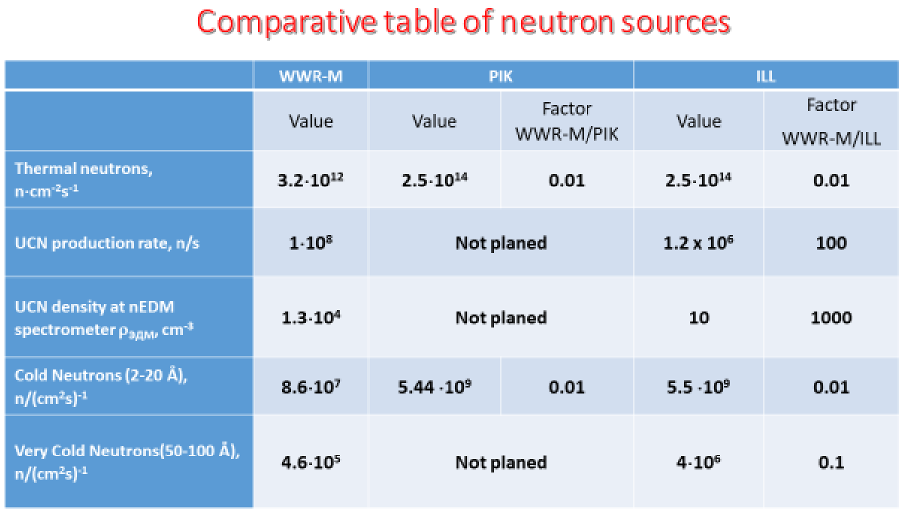


Fig. 1.1. UCN source at WWR-M reactor.

The parameters of new source are given in the table.



Comparative table of neutron sources

	WWR-M	PIK		ILL	
	Value	Value	Factor WWR-M/PIK	Value	Factor WWR-M/ILL
Thermal neutrons, n·cm^{-2}s^{-1}	$3.2 \cdot 10^{12}$	$2.5 \cdot 10^{14}$	0.01	$2.5 \cdot 10^{14}$	0.01
UCN production rate, n/s	$1 \cdot 10^{8}$	Not planed		1.2×10^{6}	100
UCN density at nEDM spectrometer $\rho_{ЭДМ}$, cm^{-3}	$1.3 \cdot 10^{4}$	Not planed		10	1000
Cold Neutrons (2-20 Å), n/(cm^{2}s)$^{-1}$	$8.6 \cdot 10^{7}$	$5.44 \cdot 10^{9}$	0.01	$5.5 \cdot 10^{9}$	0.01
Very Cold Neutrons(50-100 Å), n/(cm^{2}s)$^{-1}$	$4.6 \cdot 10^{5}$	Not planed		$4 \cdot 10^{6}$	0.1

The construction of new source is in progress and we plan to accomplish it in nearest few years.

Approximate number of researchers involved in EDM project is of about 10. More people are engaged in construction of new source and in preparation of other experiments on it.

[1] Serebrov A.P., et al., JETP Letters, **99** (2014) 7

2. SEARCH FOR STERILE NEUTRINO AT PIK AND SM-3 REACTORS

The results of LSND experiment, Gallium Anomaly [1] and, especially, Reactor Antineutrino Anomaly (RAA), claimed in 2011 [2], gave impetus to the discussion on possibility of existence of the sterile neutrino having considerably less cross-section of interaction with matter than, for example, the reactor electron antineutrino. It is assumed, that due to transition of reactor antineutrino into a sterile state, one can observe the oscillation effect at short distances from the reactor and deficiency of the reactor antineutrino flux at large distances. The assumed properties of a new particle make it one of the candidates for dark matter and require extension of the framework of elementary particles interaction theory beyond the Standard Model. Thus, the researches related to reactor antineutrino have potential to find a new physics.

Neutrino laboratory at SM-3 reactor has been operating since 2013. Results obtained with full-scale detector will be published in JETF Letters in February 2019 [3]. Using experimental spectrum, we performed the model independent analysis of restrictions on oscillation parameters Δm_{14}^2 and $\sin^2 2\theta_{14}$. The results of this analysis exclude area of reactor and gallium anomaly at CL more than 99.7% ($> 3\sigma$) for values $\Delta m_{14}^2 < 3eV^2$ and $\sin^2 2\theta_{14} > 0.1$ However, we observed an oscillation effect at CL 2.8σ in vicinity of $\Delta m_{14}^2 \approx 7.34eV^2$ and $\sin^2 2\theta_{14} \approx 0.39$. Coherent addition technique was developed. This method allows us to direct observation of oscillation effect which is shown in Fig.2.1.
The future plans of Neutrino-4 experiment are the improvement of current setup and creation of new neutrino lab with new detector system at SM-3 reactor to increase experimental accuracy, see Fig.2.2.
At the same time project of neutrino laboratory at PIK reactor was developed. Main advantages of PIK reactor are compact core size and possibility to measure antineutrino flux and spectrum in wide distance range (4 – 25 m). It is very important minimum distance is 4 meters, which is closest distance as possible for measurements at the reactors. Neutrino detector layout plan at PIK reactor is in Fig. 2.3.

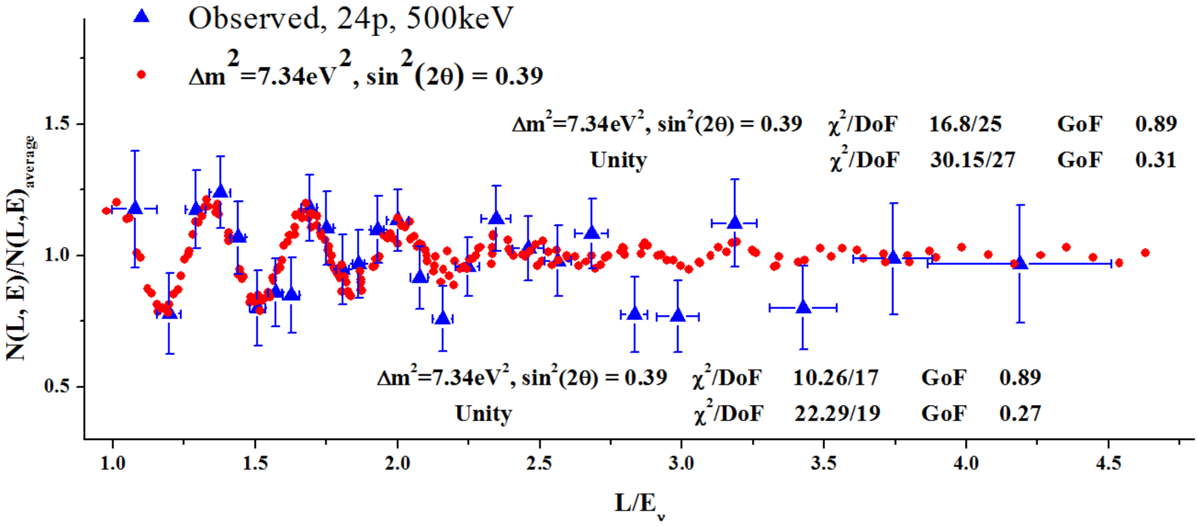


Fig. 2.1. Coherent addition of the experimental result with data selection by variable L/E for direct observation of antineutrino oscillation. Comparison of left (blue triangles) and right (red dots, with optimal oscillation parameters).

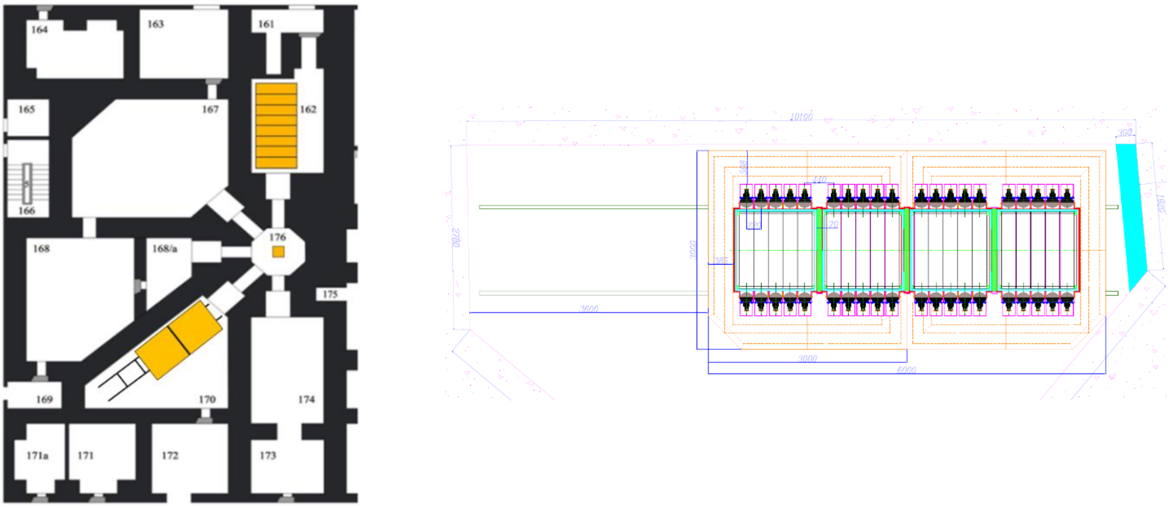


Fig. 2.2. Scheme of SM-3 reactor building with new neutrino laboratory in room 170 (on the left). Scheme of moveable detector system in room 170 (on the right).

Firstly, the improvement of current setup requires replacing of currently used scintillator with a new highly efficient liquid scintillator with capability of pulse-shape discrimination, and with an increased concentration of gadolinium up to 0.5%. It is expected that the accidental coincidence background will be reduced by factor of 3 and measurement accuracy will be doubled. Moreover, anti-coincidence shielding will be increased. In the project on new detectors, it is also planned to use a sectioned structure, which gives a different detector response on the positron event, compared to that on recoil proton from the fast neutron. Using a scheme with two PMTs for each side of the section, along with a scintillator with Ultima Gold scintillation fluid addition, with good properties of PSD, will make possible employing this technique for separation of neutrino events from the background ones related to fast neutrons. The project is planned to be implemented with participation of colleagues from JINR and NEOS collaboration.

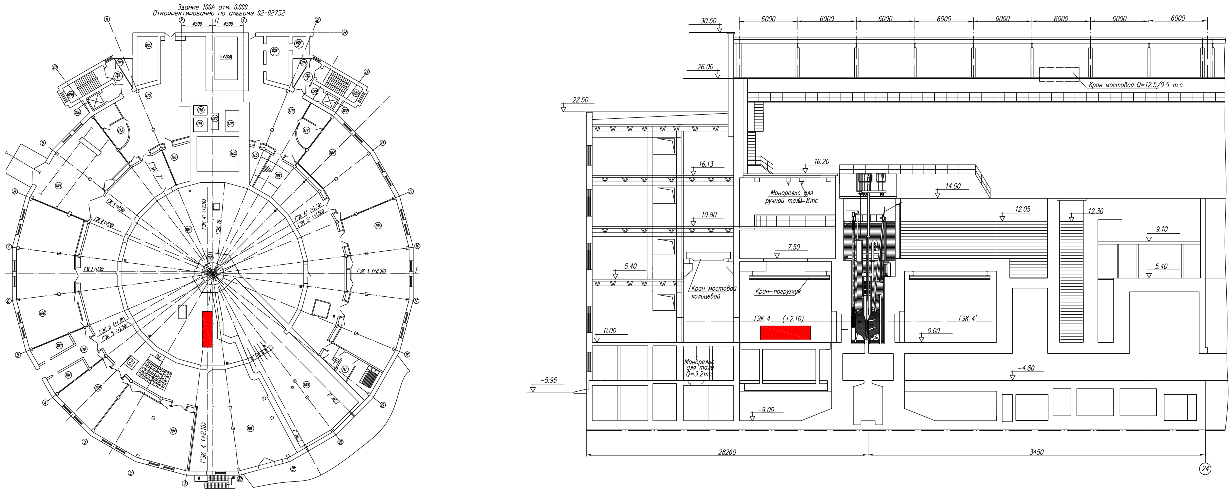


Fig. 2.3. Detector layout plan at PIK reactor.

According to preliminary estimations, in two years of collecting data, we expect to obtain statistical accuracy at the level of 1-2% by measuring an antineutrino flux from the reactor. Thus, the question of possible existence of a sterile neutrino with parameters of $\Delta m_{14}^2 \approx (0.5 \div 10)\mathrm{eV}^2$and $\sin^2(2\theta_{14}) > 0.05$ will be resolved.

[1] J. N. Abdurashitov, et al. (SAGE), Phys. Rev. C **73**, 045805 (2006).
[2] G. Mention, et al., Phys. Rev. D **83**, 073006 (2011).
[3] Serebrov A.P., et al., accepted for publishing in JETP Letters in 2019, arXiv:1809.10561

3. NEUTRON EDM SEARCH BY CRYSTAL-DIFFRACTION METHOD

The creation of an equipped experimental position at the PIK reactor of PNPI NRC «Kurchatov institute” on a beam of cold neutrons with a large aperture and record intensity in the neutron-guide hall to perform a wide range of experiments applicable to elementary particle physics and physics of atomic nucleus. This instrument will represent a universal position for investigating the properties of a neutron and fundamental interactions.

A high-priority task is to conduct an experiment on the neutron electric dipole moment (nEDM) search using the diffraction in a noncentrosymmetric quartz crystal at DEDM spectrometer. The nEDM is one of very sensitive probes for CP violation beyond the Standard Model of particle physics [1]. The importance of nEDM searches is additionally highlighted by an additional possibility to reach understanding a nature of baryon-antibaryon asymmetry in the Universe that is one of the most exciting puzzle in modern physics. The most precise experiments today use Ramsey’s magnetic resonance method and ultra cold neutrons (UCNs) [2, 3]. Further progress is presently limited by systematics [4] and the low density of UCNs available. It is very important that this is a fundamentally different method of searching the nEDM with other, compared with the method of UCN, systematic errors.

The basic idea of crystal diffracting method is to use the giant electric fields of a noncentrosymmetric crystal. The value of the fields on the entire way of the neutron through the crystal amounts to 10^8-10^9 V/cm, which is higher than the fields attainable in the laboratory by conventional methods. The experimental value obtained for the electric-field strength from the measured angle of neutron-spin rotation because of Schwinger interaction agrees with the calculated field strength and with the field strength measured earlier by different methods [5].

Series of test experiments was carried out on the reactors WWR-M (PNPI, Russia) and HFR (ILL, France) and shown:

- The electric field acting on a neutron in a quartz crystal is $E_{exp} = (0.7\pm0.1)\cdot10^{8}$ V/cm [6].
- It is shown that this scheme of experiment has a high selective ability to nEDM. It has the ability to control the false effects caused by residual magnetic fields and Schwinger interaction without loss of statistical sensitivity.

Test experiments [7-9] demonstrated that the method sensitivity can be at the level of about $2\cdot10^{-26}$ e·cm for the 100 days of the statistic accumulation for the available quartz crystal and PF1b cold neutron beam of ILL reactor. Essential advance of the method can be reached by using others crystal.
The first stage is to achieve the accuracy of $\sim10^{-26}$ e·cm by using the quartz crystal. In this case the sensitivity to neutron EDM will amount to $\sim10^{-25}$ e·cm per day. The second stage is to achieve the accuracy $(2\text{-}3)\cdot10^{-27}$ e·cm by using the new class of crystals (BSO, BGO).

The experimental station is being created as a platform with unique characteristics of the neutron beam: the maximum neutron flux density, the maximum possible integral neutron flux. There is a possibility to work with polarized and non-polarized neutrons, with a monochromatic and white beam.
DEDM instrument layout at reactor PIK shown at Fig. 3.1. There is a casemate, which accommodates all the equipment exposed to the neutron flux radiation and activation, includes: a polarizer, a velocity selector, various collimators, double monochromator. In addition to that, there is a beam monitor in the casemate.

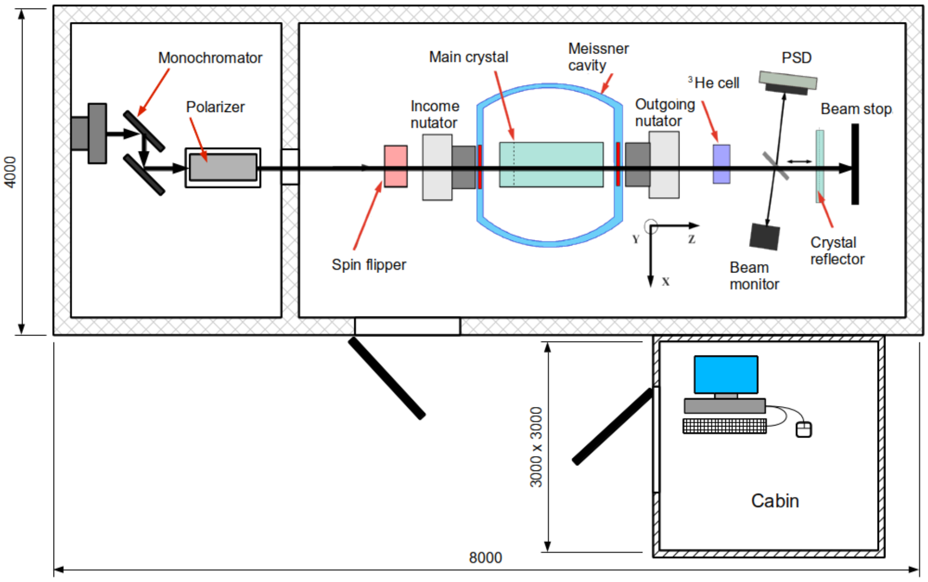


Fig. 3.1. DEDM instrument layout at reactor PIK

The experimental station uses a 3D-polarization analysis system like proposed and developed in the PNPI. A superconducting version of such a system CRYOPAD is implemented in the ILL [10]. This design allows you to carry out simultaneously with the main experience of a number of test experiments and get rid of some false effects.

It also will planed use this station to studies of gravitational interaction and tests on neutron electroneutrality, the experiments in the field of fission physics, the study of the weak interaction in nuclear reactions, angular correlations in neutron decay, and so forth. The station can be used to test new equipment too.

[1] M. Pospelov, A. Ritz, Annals of Physics **318** (2005) 119.
[2] I.S. Altarev, et al., Yad. Fiz. **59** (1996) 1204.
[3] C.A. Baker, et al., Phys. Rev. Lett. **97** (2006) 131801.
[4] J.M. Pendlebury, et al., Phys. Rev. A **70** (2004) 032102.
[5] V.L. Alexeev, et al., Nucl. Instr. Meth. A **284** (1989) 181; V.L. Alexeev, et al., JETP **69** (1989) 1083.
[6] V.V. Voronin, et al., JETP Lett. **74** (2001) 251.
[7] V.V. Fedorov, et al., Phys. Lett. B **694** (2010) 22.
[8] V. V. Fedorov, et al., Nucl. Instr. Meth. A **611** (2009) 124.
[9] V.V. Fedorov, et al., Nucl. Instr. and Meth., B **252** (1) (2006) 131.
[10] F.Tasset, et al. Physica B, **267-268** (1999) 69-74.

4. EXOTIC NUCLIDES UNDER EXTREME

Observation of gravitational waves and a tail of “post-gravitational” emission as a result of the neutron star merging have ignited the version of possible syntheses of nuclear composition of the nature via this merging channel. Though this phenomenon is not expected to appear often in comparison to the supernovae explosions, the synthesis of heavy nuclides can have specific features. The rapid neutron capture (r-process) is still thought the main driver of heavy nuclides production in the hot stellar conditions, however the exact trajectory of it in the map of nuclides is not known. This process should propagate along the border of existence of nuclides (so called neutron drip-line). However as can be seen from Fig. 4.1 the predicted positions of this border are strongly scattered from one to another theory, thus the r-process theoretical pathway also should be indefinite. The key parameter which should govern the nuclear composition of r-process is the mass-landscape of nuclides (i.e. the total binding energies), which have to be measured.

Many planned accelerator facilities (FAIR, FRIB, ARIEL etc.) are intended to produce exotic neutron-rich nuclides, however as Fig. 4.2 shows the best production yields for unknown yet nuclides are expected with the high-flux reactor. Though the reactor has a privilege only in the fission mass region, many expected r-process species are located just in this part of nuclear chart.

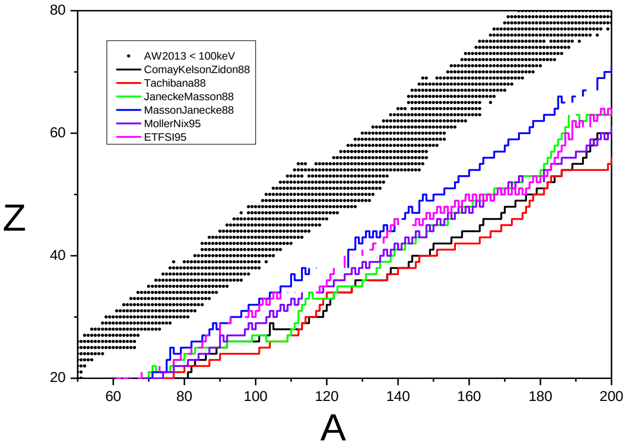


Fig. 4.1. Neutron drip-line(colored) on the nuclear chart

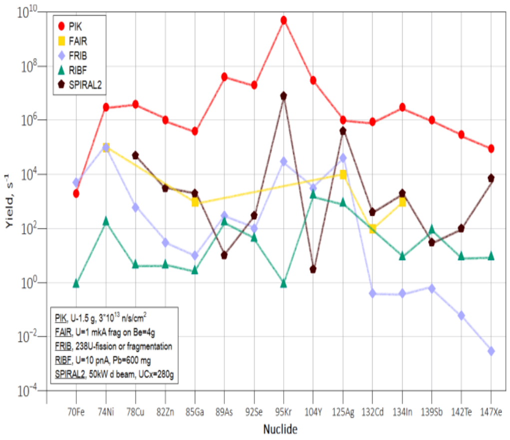


Fig. 4.2. Yields of nuclides with unknown masses

Success in experiments with nuclides of an exotic proton/neutron composition depends on the intensity of the producing primary beam as well as the sensitivity of the measuring setup. The new PIK reactor which is under commissioning at the PNPI NRC “Kurchatov institute” is expected to be a high-flux facility [1, 2] with a powerful production of such exotic nuclides by thermal neutron irradiation of the external uranium target. A Penning ion trap is an ultrasensitive apparatus capable of operating with a single ion [3]. This combination named PITRAP provides synergy and a unique possibility for studying exotic nuclei [4]. Fig 4.3 shows the scheme of proposed installation of Penning ion trap (4) based on the use of mass selected ion beam from the planned mass-separator IRINA(1) [5]. The ion channel (3), providing the low energy bunched ion beam, and itself the trap layout (4) is shown in an enlarged view in Fig. 4.4.

Fig. 4.3. Collage of the reactor PIK properties [1, 2] with basic characteristics: power: 100 MW; thermal neutron flux: 5×10^{15} n/cm^{2}sec. In the bottom of figure - arrangement of the setup PITRAP (4) is shown. It will use the horizontal channel ГЭК 5 and the electromagnetic mass separator (1) followed by ion channel (2) and bending dipole magnet (3).

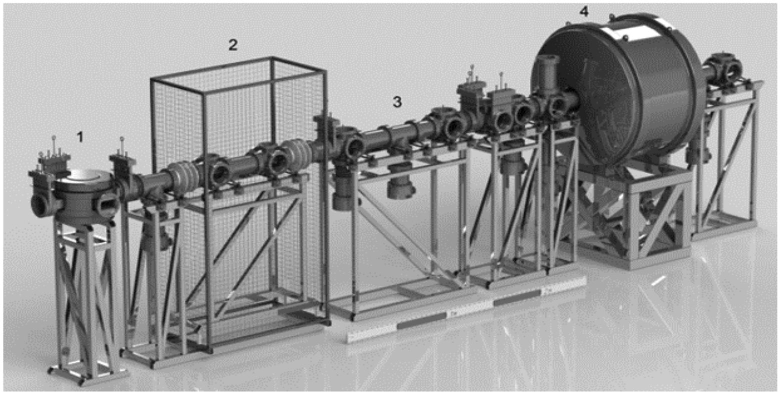


Fig. 4.4. Model of the measuring facility with a Penning ion-trap (4). (1) is a turning magnet, (2) indicates the gas-filled RFQ, (3) is the multi-ToF system.

The design of the first Penning trap in Russia was developed using the many years of experience gained in working with different ion traps in foreign laboratories. The technical design project is presented in [4]. The construction work in the reactor channel aimed at the target and ion-source unit installation have been started.

The experimental determination of the landscape of exotic nuclide masses will allow us to accurately determine the nuclide pathway of the r-process, which is crucial for determining astrophysical properties of the medium and the place of the process origin, including the generation of matter when neutron stars merge. The experimental data obtained will also make it possible to find a more reliable position of the neutron boundary of the existence of a nuclear substance.

Another block of problems is associated with the high-precision off-line measurements of long-lived radionuclides with the Penning trap at the PITRAP. They can be produced by irradiating targets in the PIK reactor. The measurements can be performed after this irradiation in a trap independently of the reactor operation. High-precision measurements of the masses of long-lived nuclides can open up an entire strata of problems in fundamental physics ranging from neutrino physics to cosmochronology [6,7]. As it was shown by our group [6], the Penning traps can be very useful in a searching for the candidates for the neutrinoless double electron capture in nuclides which could be an indicator of Majorana type of neutrinos and a violation of the leptonic number conservation in the weak channel.

[1] K.A. Konoplev, Main scientific results of the PNPI in 2000−2004, 18-23, Gatchina, 2005.
[2] V.L. Aksenov and M.V. Kovalchuk, www.NIKIET.ru (2015).
[3] K. Blaum, Yu. Novikov, and G. Werth, Contemp. Phys., **51**, 149–175 (2010).
[4] Yu.N. Novikov, Yu.I. Gusev, S.A. Eliseev *et al*., Report № Ф-310. B.P. Konstantinov PNPI NRC “Kurchatov Institute”, Gatchina, 2016.
[5] V. Panteleev, A. Barzakh, D. Fedorov, *et al.*, PNPI, High Energy Physics Division, Main Scientific Activities 2007–2012 , 274–277 (2013).
[6] S. Eliseev, Yu. Novikov, and K. Blaum, J. Phys. G: Nucl. Part. Phys., **39**, 124003 (2012).
[7] H.-J. Kluge and Yu. Novikov, Nucl. Phys. News, **17**, No. 4, 48–50 (2007).

6. HUNTING BARYON NUMBER VIOLATION WITH ULTRACOLD NEUTRONS

We present a project of experiment aimed on search for neutron-antineutron oscillation of free neutrons. $n - \bar{n}$ oscillation is a hypothetical process in which neutron spontaneously transforms into antineutron. Neutron and antineutron are both electrically neutral particles, hence only the conservation of baryon number forbids a neutron from transforming into an antineutron. But, according to A. Sakharov [1], baryon number violation is one of three conditions which are essential to explain observed matter-antimatter or baryon number asymmetry of the Universe.

Firstly, it was suggested to search for neutron-antineutron oscillations in beam experiments. In this experiment beam of neutrons after long flight base hits target where annihilation reaction is searched. All flight base should have shielding from the Earth’s magnetic field because it suppresses amplitude of oscillations. Such experiment was realized at beam of cold neutrons at Institute Laue-Langevin (ILL) [2]. In this experiment current limit on period of neutron-antineutron oscillations of $8.6 \cdot 10^7$ s was obtained. Sensitivity of experiment depends on so called discovery potential Nt^2, where N is number of neutrons reaching the target per second and t is time of neutron flight to the target. Discovery potential of ILL experiment was $1.5 \cdot 10^9$ n·s.

In the case of experiment with UCN stored in a material trap the walls of UCN trap play the role of annihilation target. Time of flight is the time between two collisions with trap walls. The sensitivity of experiment with UCN mostly depends on the trap size and number of UCN in it. Increase in sensitivity is possible only with creation of a powerful source of ultracold neutrons.

In our works [3-6] we estimated possible sensitivity of experiment on search for $n - \bar{n}$ oscillations at the new UCN source. According to available area we accepted UCN trap in form of horizontal cylinder with diameter of 2 m and length of 4 m. The calculations show that the sensitivity can be increased by ~ 10–40 times compared to sensitivity of ILL experiment depending on the model of neutron reflection from walls. We used two models of neutron reflection from trap walls: with partial accumulation of the antineutron phase and without it. Real parts of the reflection potential are close or coinciding for the first case. For the second case - real part of the reflection potential for antineutron is close to zero. In the first case, one expects antineutrons to reflect from walls and the antineutron phase to be accumulated in contrast to the second case, in which no such accumulation can take place because the antineutrons immediately annihilate upon entering the matter. However, the coefficient of antineutron reflection in the first case cannot be sufficiently high because of a large imaginary part of the reflection potential for antineutron due to a large annihilation cross section. Dependence of sensitivity on diameter of UCN trap is shown in Fig. 6.1.

The design of the setup is shown in Fig. 6.2. UCN in the experiment are stored in the trap, which is a cooper cylinder with length of 4 m and diameter of 2 m. UCN are transported to the trap by the neutron guide through hole in a side of the cylinder. The UCN trap is mounted in an aluminum vacuum chamber. Pumping the vacuum chamber is implemented through a pipe of 200 mm in an upper side of the setup. For suppress the Earth’s magnetic field the vacuum chamber is surrounded by magnetic shield. To reconstruct the position where annihilation takes place the vertex detector is used. The calorimeter is used to reconstruct energies of annihilation reaction products.

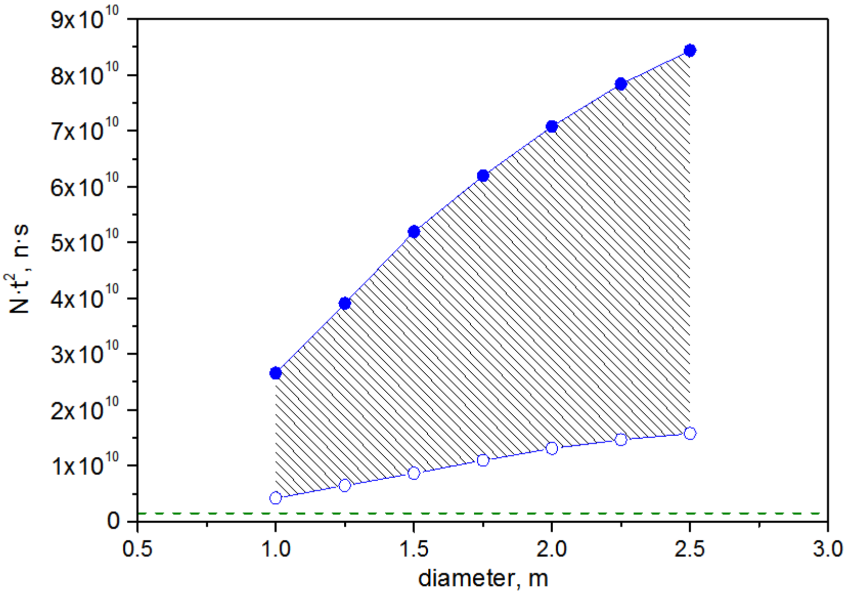


Fig. 6.1. Sensitivity of experiment depending on diameter of UCN trap. Length of the trap is 4 m. Filled signs correspond to the case with partial accumulation of the antineutron phase. Empty signs correspond to the case without accumulation of the antineutron phase. Dashed horizontal line corresponds to sensitivity of the ILL experiment.

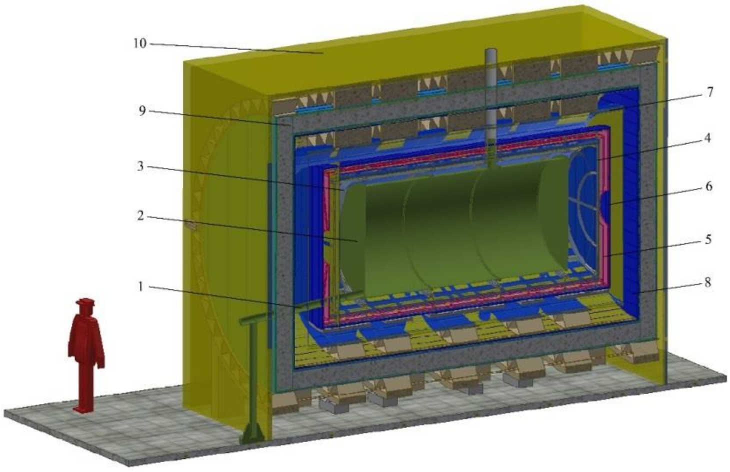


Fig. 6.2. Scheme of experimental setup: 1 – neutron guide, 2 - UCN trap, 3 - vacuum chamber, 4 – trek detector (inner part), 5 - magnetic shield, 6 - hodoscope (internal part), 7 - trek detector (middle part), 8 - hodoscope (external part), 9 - trek detector (external part), 10 – active shielding.

The estimated cost of the experiment is at least an order of magnitude less then cost of NNbar experiment at cold neutron beam at European Spallation Source [7].

[1] A.D. Sakharov, JETP Lett. **5**, 24 (1967)
[2] M. Baldo-Ceolin, P. Benetti, T. Bitter et al., Z. Phys. C **63**, 409 (1994)
[3] A.P. Serebrov, A.K. Fomin, Yu.A. Kamyshkov, Tech. Phys. Lett. **42**, 99 (2016)
[4] A.K. Fomin, A.P. Serebrov, O.M. Zherebtsov et al., J. Phys.: Conf. Ser. **798**, 012115 (2017)
[5] A. Fomin, PoS INPC2016, 189 (2017)
[6] A.K. Fomin, A.P. Serebrov, O.M. Zherebtsov et al., KnE Energy & Physics 3, 109 (2018)
[7] D.G. Phillips, W.M. Snow, K. Babu et al., Physics Reports **612**, 1 (2016)