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Fundamental interactions involving neutrons and neutrinos: reactor-based studies led by Petersburg Nuclear Physics Institute (National Research Centre 'Kurchatov Institute') [PNPI (NRC KI)]

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Contents

Abstract. Neutrons of very low energy ($\sim 10^{-7}$ eV), commonly known as ultracold, are unique in that they can be stored in material and magnetic traps, thus enhancing methodical opportunities to conduct precision experiments and to probe the fundamentals of physics. One of the central problems of physics, of direct relevance to the formation of the Universe, is the violation of time invariance. Experiments searching for the nonzero neutron electric dipole moment serve as a time invariance test, and the use of ultracold neutrons provides very high measurement precision. Precision neutron lifetime measurements using ultracold neutrons are extremely important for checking ideas on the early formation of the Universe. This paper discusses problems that arise in studies using ultracold neutrons. Also discussed are the currently highly topical problem of sterile neutrinos and the search for reactor antineutrino oscillations at distances of 6 – 12 meters from the reactor core. The field reviewed is being investigated at multiple facilities globally. The present paper mainly concentrates on the results of PNPI-led studies at WWR-M PNPI (Gatchina), ILL (Grenoble), and SM-3 (Dimitrovgrad) reactors, and also covers the results obtained during preparation for research at the PIK reactor which is under construction.

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1. Introduction

Studies of the fundamental interactions between elementary particles are successfully under way at accelerators and colliders, where the production of new elementary particles at energies up to 10^{13} eV opens up new horizons in our understanding of the fundamentals of Nature. Astrophysics, cosmology, cosmic ray physics, and neutrino physics make extremely profound complementary contributions to the general picture of the world and are also related to the fundamental interactions of elementary particles. However, there are methods of precision studies, methods of searching for small deviations from the Standard laws of physics. They permit us to obtain information on fundamental interactions within other experimental approaches. One such line of research consists of studies involving ultracold neutrons, those of very low energy, on the order of magnitude of 10^{-7} eV. Section 2 of this review deals precisely with this line of research in physics. Section 3 is devoted to studies with reactor antineutrinos, since recently the issue also arose of the possible existence of a sterile neutrino and oscillations of reactor antineutrinos at small distances (6–12 m) in the vicinity of the reactors. This issue is extremely important in the physics of fundamental interactions, and it deserves particular attention.

This review is based on material included in the author's talk presented at a conference dedicated to the 80th birthday of Academician V M Lobashev.

2. Studies involving ultracold neutrons

2.1 Properties of ultracold neutrons

Neutrons are commonly considered to be particles that penetrating matter without difficulty, since they are neutral. Indeed, they were actually discovered owing to this experimental fact. However, neutrons of very low energies with large de Broglie wavelengths of $\sim 500-1000$ Å interact with matter in a coherent manner and are reflected from matter with a very high probability of $\sim 99.9\%$. This effect allows storage of neutrons in material traps and transporting ultracold neutrons (UCNs) along pipes (neutron guides) like a gas at an extremely low pressure. The effective temperature of such neutrons reaches 10^{-3} K and for this reason they are called ultracold. The aforementioned properties of ultracold neutrons were first noted by Ya B Zel'dovich in 1959 [1].

The coherent scattering of low-energy neutrons on the nuclei of a material leads to emerging an effective potential within the material at a level of $(1-2) \times 10^{-7}$ eV. Neutrons with energies below the potential of the material turn out to be confined to a potential box, i.e., in a trap made of the material. Thus, one can store neutrons.

Neutrons can also be confined in a magnetic trap of a complex multipole shape owing to interaction of the neutron magnetic moment with the magnetic field. Such a trap will only retain neutrons of the same polarization. The potential on the wall of such a magnetic bottle will also approximately amount to 1×10^{-7} eV. The possibility of confining ultracold neutrons in magnetic traps was noted by V V Vladimirskii in 1960 [2]. Ultracold neutrons can indeed be transported along pipes (neutron guides), since the UCN reflection coefficient is very high. Therefore, UCNs are capable of undergoing several thousand collisions before being lost (absorbed or scattered inelastically) on the walls of the trap. While the range between the walls is ~ 10 cm, the total path length of an ultracold neutron may amount to several dozen meters. It is important to ensure the neutrons travel in the same direction from the source to the experimental facility, so the neutron guides must have a specular surface with a high reflection potential.

Finally, ultracold neutrons are quite sensitive to Earth's gravitational field. The height that an ultracold neutron 'flying upward' can overcome amounts to 1–2 m. So the energy of UCNs can be measured applying gravitational spectrometers.

Thus, ultracold neutrons are the most controllable and safest neutrons, although the same cannot be said of other neutrons pertaining to the neutron spectrum.

2.2 History of the discovery of ultracold neutrons and the development of ultracold neutron sources at PNPI

The first experiment designed for extracting ultracold neutrons from a reactor was performed in 1968 at JINR (Dubna) by F L Shapiro and his coworkers [3]. The goal was to make use of ultracold neutrons to search for the neutron electric dipole moment (EDM). This is a fundamentally important task in the physics of elementary particle interactions, which we shall discuss below.

Abroad, ultracold neutrons were also singled out a year later from the neutron spectrum for a more prosaic purpose, namely, for studying neutron scattering at low energies (A Steyerl, Münich, 1969) [4].

During the 1970s and 1980s, experimental methods for making use of ultracold neutrons underwent extensive development. Numerous institutions in our country and abroad were engaged in this process. The experimentally obtained density of the ultracold neutron gas was increased by 8 orders of magnitude, as compared to the first experiment in Dubna, and amounted to 10–40 cm^{-3}. An effective method for producing UCNs consists in the thermalization of neutrons in a medium with a low temperature, due to which the fraction of ultracold neutrons in the spectrum can be enhanced by factors of tens or hundreds.

The first cooled UCN source at PNPI was constructed in 1974 on the base of a beryllium convertor. The source was situated in a lead cavity at the center of the reactor core region (Fig. 1). Given the total reactor power of 18 MW, a thermal power of 1200 W was released into it and a temperature of 30 K was sustained due to cooling by gaseous helium from a refrigerator. The temperature gain factor in the UCN flux amounted to 10 [5]. Such was the ratio of low-temperature and room-temperature UCN fluxes for this source. In 1980, a liquid-hydrogen UCN source having a volume of 150 cm^3 was installed in the beryllium reflector of the reactor. A highly efficient and very compact cooler was placed immediately within the source, as shown in Fig. 1. It permitted the construction of a source involving a small volume of liquid hydrogen. The temperature gain factor in the UCN flux amounted to 25 [6]. In 1986, a liquid-hydrogen source [7] was placed at the center of the reactor core, which permitted obtaining, besides UCNs, the most intense beam of polarized cold neutrons. The temperature gain factor in the UCN flux was 50, and the UCN density amounted to 8 cm^{-3}. A very complex engineering and technical problem had to be resolved in the course of constructing this source. It was necessary to ensure 2-kW heat removal from 1 litre of liquid hydrogen at a temperature of 18–20 K. For a liquid-hydrogen temperature level and a 1-l volume, such a problem proves to be extremely difficult. Such a heat release can only be removed by a fast liquid-hydrogen flow through the source. For this purpose, a circulatory loop (6 litres of liquid hydrogen) was developed, with one arm containing the heat exchanger, which was cooled by a 3-kW cryorefrigerator. Circulation of the hydrogen in the loop is via natural convection and asymmetry in the position of the cooler. The hydrogen flow rate in a pipe 30 mm in diameter amounts to approximately 1 m s^{-1} for a thermal load of 2 kW. Such a system requires no use of circulation pumps for liquid hydrogen and is quite effective. At the ILL (Institute Laue–Langevin, Grenoble, France) reactor, removal of 5-kW heat power was achieved from a 25-l volume of liquid deuterium situated in the heavy-water reflector of the reactor. The total heat release in the ILL is 2.5 times higher, but the specific heat release level is 10 times higher in the WWR-M reactor. Such a level of specific heat removal at hydrogen temperatures has not yet been attained anywhere.

Right up to 1986, PNPI, which has a reactor of medium power, occupied a leading position in the UCN density

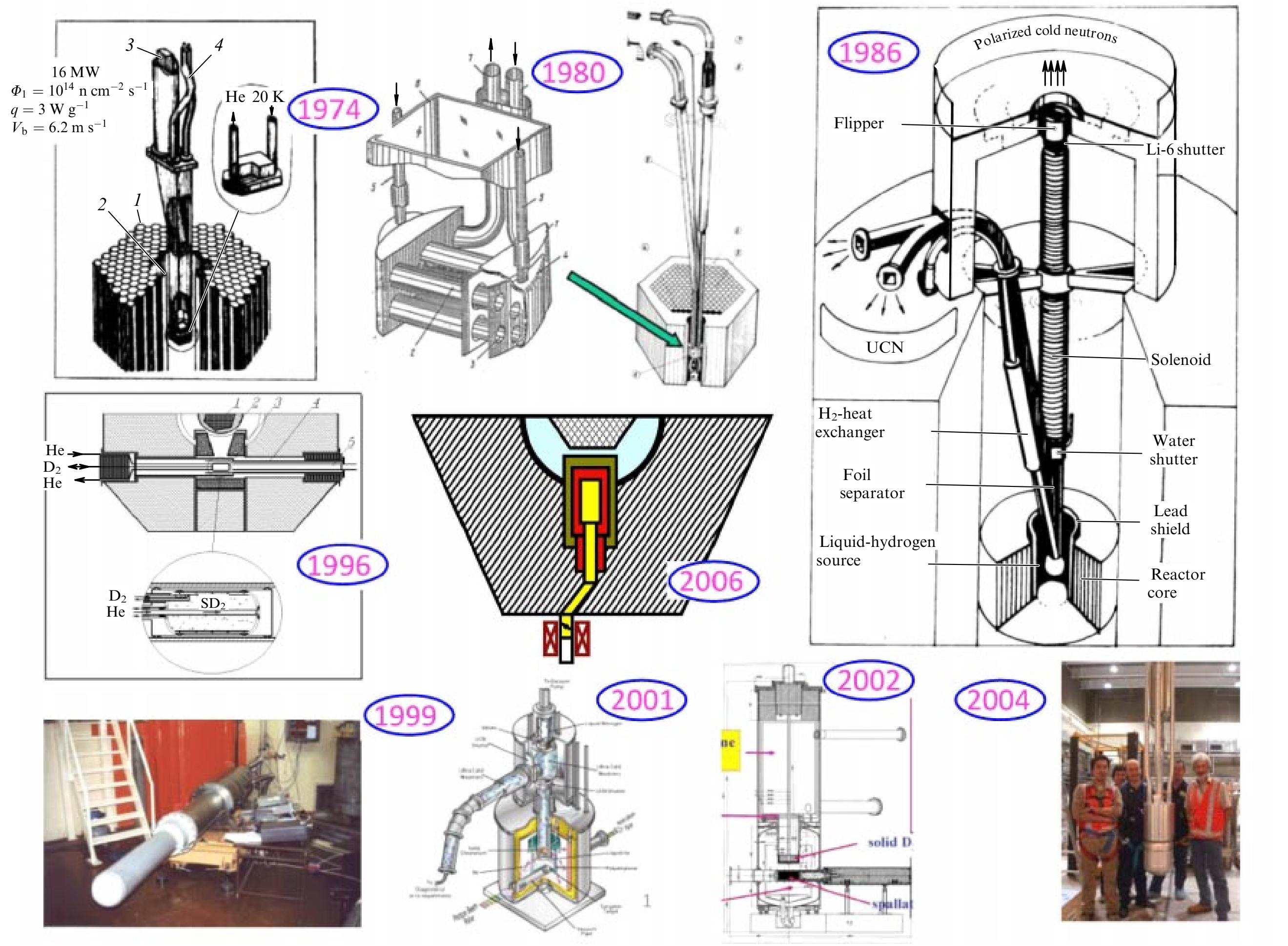


Figure 1. (Color online.) Intensive UCN sources designed by PNPI: 1974 — beryllium convertor of thermal neutrons to UCN; 1980 — liquid-hydrogen UCN source in the beryllium reflector of the WWR-M reactor; 1986 — universal source of ultracold and of polarized cold neutrons (CNs) at the center of the WWR-M reactor core; 1996 — solid-deuterium source of UCNs in the thermal column of the WWR-M reactor; 1999 — hydrogen source of cold neutrons based on a compact cooler for the WWR reactor in Budapest (PNPI project); 2001 — solid-deuterium UCN source with spallation neutron source in a proton beam at the Los Alamos National Laboratory (USA) in collaboration with PNPI; 2002 — solid-deuterium UCN source with spallation in the proton beam of the Paul Scherrer Institute (PSI, Switzerland) in collaboration with PNPI; 2004 — source of cold neutrons in the Australian reactor ANSTO (PNPI–INVAP project), and 2006 — project of a UCN source on the base of superfluid helium in the thermal column of the WWR-M reactor.

achieved (Fig. 2). In 1986, however, a liquid-deuterium UCN source was installed in the ILL high-flux reactor [8]. Ultracold neutrons were obtained from a source of cold neutrons by transformation of the neutron velocity from 50 m s^{-1} down to 5 m s^{-1} at the turbine, where the reflection of a neutron from a retreating blade produces additional neutron 'cooling'. The UCN density relative to the source in Gatchina was increased by a factor of 5 and amounted to 40 cm^{-3}.

Figure 2 shows the growth diagram of UCN density during the past 46 years. Regretfully, no progress has been observed in UCN density enhancement in the last 25 years. The point is that direct and quite effective methods, namely, the use of maximum neutron fluxes in reactors at temperatures of 15–20 K, had already been mastered. Future progress requires alternative methods of obtaining UCNs. Mastering lower temperatures in powerful fluxes of neutrons and of γ-radiation is not possible, so we have undertaken studies in our solid-deuterium source, situated in a beryllium reflector, at low reactor powers (1 MW). The gain factor was found to grow rapidly as the temperature decreases [6]. A question arose concerning the possibility of employing solid deuterium in conditions of low heat release due to the application of a

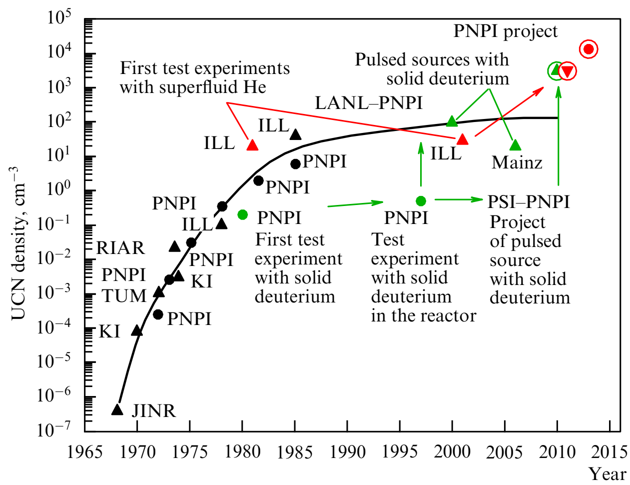


Figure 2. (Color online.) Plot elucidating the progress in UCN source development. The last point in this diagram concerns the designed parameters of the new source in the PNPI WWR-M reactor based on superfluid helium; indicated is the possible UCN density in the trap of the EDM spectrometer.

bismuth shield [9]. Calculations revealed the theoretically achievable UCN density at the level of 10^3-10^4 cm^{-3}. In this connection, a 6-litre solid-deuterium UCN source cooled to a temperature of 4.5 K was placed inside the thermal column of the WWR-M reactor [10]. The gain factor obtained experimentally in the UCN flux with respect to room temperature amounted to 1230. A significant role in providing the UCN yield from solid deuterium was found to be played by the ortho-para-state of molecules of the material, as well as by the homogeneity of the solid-deuterium density. More detailed studies of these issues were performed by passing very cold neutrons through solid deuterium [11]. A compromise between the high heat release level and the low temperature of the source was found applying the idea of a pulsed mode [12] with a spallation neutron source in a proton beam. In this method, a low-temperature moderator is irradiated with neutrons for several seconds, and ultracold neutrons fill an intermediate trap up to a density proportional to the density of thermal neutrons in the pulse. At the end of the pulse, the shutter to the source is closed and experimentalists can use the UCNs from the trap for several hundred seconds, while the low-temperature moderator cools. Thus, owing to the pulsed mode, a compromise was found between the power and low temperature. Solid deuterium at the liquid-helium temperature of 4.5 K can be used as the moderator and the UCN source [11]. In studies performed by our team with a six-litre solid-deuterium moderator in the thermal column of the WWR-M reactor, the temperature gain factor in the UCN density due to the temperature being lowered from 20 K to 4.5 K was shown to amount to 10–12.

A method making use of solid deuterium with a neutron source based on nuclear spallation in a proton beam was realized at the Los Alamos National Laboratory (USA) in 2001, and the density obtained was 100 cm^{-3} [13]. A more large-scale project was developed at PSI (Switzerland), involving the active participation of PNPI [14]. The density expected is approximately 10^3 cm^{-3}; at present, however, it only amounts to a value inferior by at least an order of magnitude. Thus, solid deuterium can be applied in a pulsed mode in accelerators. Such a project is not appropriate for Russia, since no high-current (several milliamperes) accelerators with an energy of 600–800 MeV exist.

But there is another method that can be successfully applied in the WWR-M reactor. This method is based on obtaining UCNs with the aid of superfluid helium. Superfluid helium constitutes a remarkable quantum liquid possessing the amazing properties of superfluidity and of heat superconductivity. Although the peculiarities of the interaction of superfluid helium with neutrons are not so well known, they are no less surprising. Superfluid helium is extremely transparent to neutrons of low energies. This property was noted in a paper by I Ya Pomeranchuk and A I Akhiezer in 1945 [15]. But at the time, Ya B Zel'dovich had not yet said anything about the possibility of UCN storage, and ultracold neutrons were not given consideration so actively from the point of view of performing fundamental experiments. Attention was drawn to the possibility of utilizing superfluid helium to obtain UCNs by R Golub and J M Pendlebury in 1977 [16].

The essence of the issue is quite simple. The famous Landau curve relating the energy and momentum of excitations (phonons, rotons) in superfluid helium intersects the curve $E = p^2/2m$ for the neutron. The intersection point corresponds to an excitation energy (in units of temperature) of 12 K. This means that a UCN can only 'absorb' a phonon of energy 12 K. Such phonons are practically absent at the liquid-helium temperature of 1 K, since the Boltzmann factor is an exponential of power -12. Precisely this circumstance explains the extraordinary transparency of superfluid helium to UCNs. Indeed, a UCN can 'live' in superfluid helium tens or hundreds of seconds until a phonon is absorbed. Ultracold neutrons are 'produced' in helium from cold neutrons with a wavelength of 9 Å or energy of 12 K, which is precisely equal to the energy of the phonon, i.e., a cold neutron excites a phonon and practically comes to a stop itself, becoming ultracold. Cold neutrons penetrate the wall of the trap, while ultracold ones are reflected; therefore, a UCN accumulation effect is possible up to a density determined by the storage time in the helium trap.

Experiments on UCN accumulation in traps with superfluid helium have been successfully performed with beams of cold neutrons in France and Japan [17–19]. UCN densities have been attained in a beam that are comparable to the densities of UCN extracted from sources in reactors. The neutron beam divergence is very small compared to 4π. In conditions of 4π irradiation, it is possible to gain 3–4 orders of magnitude. The questions arise: in what irradiation conditions can a source based on superfluid helium work, and what power can be extracted at a temperature of about 1 K? It is well known that at a temperature of 1.8 K one may extract power values amounting to kilowatts from superconducting magnets. Such installations are cumbersome and very costly. We can state the task of removing a power of 10–20 W at a temperature of 1.2 K; then, this problem is resolved with the aid of an available helium liquefier, producing 50 l of liquid helium per hour, and also with the aid of a system for vacuum pumping of helium vapor, so as to achieve a temperature of 1.2 K. To resolve this problem successfully, it is necessary to find a compromise between the heat release level and the neutron flux density.

The project of a UCN source for the WWR-M reactor was put forward in 2006, and papers devoted to it were subsequently published [20–23]. The conditions at the PNPI WWR-M reactor are quite appropriate for finding a compromise between the heat release and the neutron flux. This is due to the presence of a reactor thermal column, which represents a pipe of a large diameter (1 m) bordering on the reactor core. Such a pipe diameter permits us to install a powerful lead shielding against the γ-radiation of the reactor core, a graphite moderator, and a liquid-deuterium premoderator at a temperature of 20 K to obtain cold neutrons and, finally, the UCN source itself based on superfluid helium at a temperature of 1.2 K. The principle of operation of the UCN source is presented in Fig. 3. Cold neutrons penetrate the wall of the trap, while ultracold neutrons are reflected; therefore, UCN accumulation is possible up to a density determined by the storage time in the helium trap.

The layout of the ultracold neutron source in the vicinity of the WWR-M reactor core is demonstrated in Fig. 4.

At present, the project of a UCN source has been developed for the WWR-M reactor. Detailed calculations have been carried out applying the MCNP code, as a result of which a thermal power of 15 kW was shown to be released in the lead shielding of the source, and the removal of which is readily provided for with the aid of circulating water. The liquid-deuterium moderator will be cooled by the flow of gaseous helium at a temperature of 20 K. Finally, and most importantly, a heat power of 19 W will be released in a source

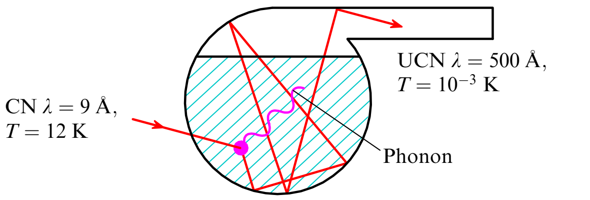


Figure 3. (Color online.) Schematic view of UCN production in superfluid helium and of their extraction toward the experimental facility.

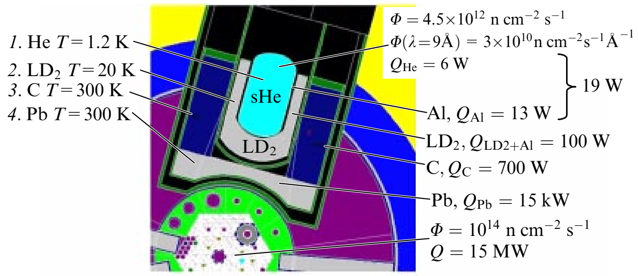


Figure 4. (Color online.) Layout of locating ultracold neutron source in the vicinity of the WWR-M reactor core: *1* — superfluid helium converter of cold neutrons to ultracold neutrons at a temperature of 1.2 K, *2* — liquid-deuterium premoderator at a temperature of 20 K for obtaining cold neutrons, *3* — graphite moderator at room temperature, and *4* — lead shielding.

with superfluid helium. As was already noted, such a power at the level of 1.2 K can be removed with the aid of available cryogenic facilities. Monte Carlo calculations of the UCN density show it to be possible to obtain a UCN density of $\sim 1 \times 10^4$ n cm^{-3} [20–23] in the experimental facilities (for instance, in the trap of an EDM spectrometer). This signifies that the gain factor with respect to UCN density in Grenoble will amount to 1000. Thus, we can restore precedence to Russia in the field of ultracold neutrons and achieve significant advance in fundamental studies with ultracold neutrons. The layout of the beams from the PNPI WWR-M reactor after installation of the UCN source is presented in Fig. 5.

This project gives promise to be exceptionally high-effective from the economic point of view due to a developed infrastructure of the reactor. Its implementation over a course of 5 years will require approximately \$ 4–5 mln. Such a figure is comparable with the reactor operating costs.

The project is based on the employment of high technologies. It could become quite a successful step forward in the program aimed at protecting and developing fundamental and applied research in Russia on the basis of research reactors. The project requires no capital construction and could be realized in 5 years. At present, a full-scale model of the source has been created, which includes all necessary cryogenic and vacuum equipment. A test experiment is planned with the goal of achieving the removal of 20-W heat power at a temperature of 1.2 K. Figure 6 displays the equipment pertaining to the full-scale model. After the

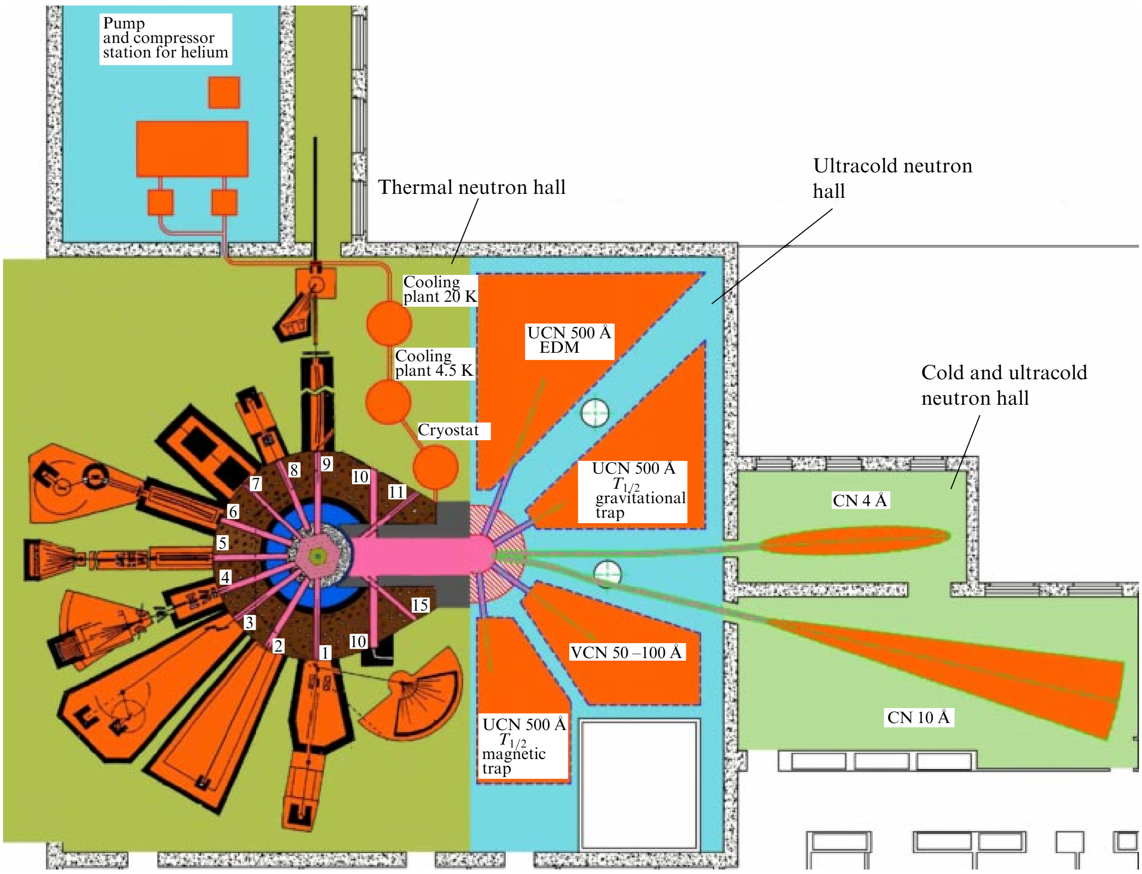


Figure 5. (Color online.) General layout of experimental halls of WWR-M reactor. Position layout of the source of cold neutrons (CN) and of ultracold neutrons of the complex of experimental devices in the main reactor hall and of the complex of experimental devices in the neutron guides chamber.

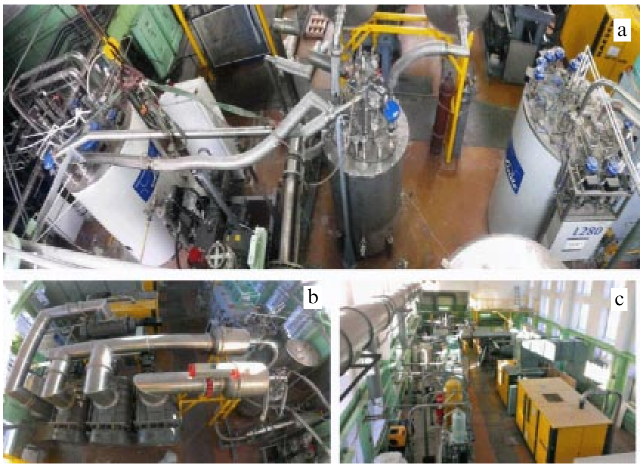


Figure 6. (Color online.) Equipment related to the full-scale source model. (a) Helium liquefier 50 l h^{-1}, cryostat at a temperature of 1 K for UCN supersource, and helium refrigerator with 3000 Wof power for a temperature of 15 K. (b) Set of pumps for evacuation of helium vapor involving vacuum pipes of large diameter. (c) Blocks of helium purification and helium compressors.

aforementioned experimental test is completed, the decision may be taken to implement the project at the WWR-M reactor. Realization of the project with superfluid helium at the WWR-M reactor will make it possible to have the worlds best source of ultracold neutrons in Russia. This important assertion must be discussed in greater detail.

It would seem natural to assume it possible in the future to obtain at the high-flux reactor PIK (or by now at the high-flux reactor ILL) an even higher UCN density for the experiment in search of the neutron EDM. However, careful examination of the issue shows this is not so. Owing to the significance of the problem, it was subjected to a detailed study [24–26], which must be dealt with since it concerns practical strategy. The following questions must be answered. Why is it better to construct a UCN source in the thermal column of the WWR-M reactor instead of the PIK reactor? Why does the UCN density achieved at the ILL reactor in the extracted beam of cold neutrons amount to only 40 cm^{-3} [18]? Is it possible to obtain a significantly higher density at the PIK reactor than at the ILL reactor?

The difference lies in the fact that at the PIK reactor (as well as the ILL reactor) the UCN source based on superfluid helium can only be situated in the extracted neutron beam. But passage to the scheme involving a UCN source in the extracted beam leads immediately to a loss in the initial neutron flux density, which is proportional to the solid angle of the beam relative to 4π. At a distance of 5 m from the source of cold neutrons, this solid angle factor equals 10^{-4}. It is extremely difficult to compensate such a factor. The neutron flux in the thermal column of the WWR-M reactor amounts to 3×10^{12} n cm^{-2} s^{-1}, while the neutron flux in the cold neutron source of the PIK reactor amounts to approximately $(3-5) \times 10^{14}$ n cm^{-2} s^{-1}. Thus, passage in the PIK reactor to the setup of a UCN source in the extracted beam leads to a loss of four orders of magnitude in the neutron flux density owing to the solid angle of the beam, but only two orders of magnitude can be compensated by the high neutron flux in the PIK reactor. It turns out to be possible to compensate for the total UCN productivity by a factor of several times through increasing, for instance, by 5 times the volume of the converter with superfluid helium placed along the beam of cold neutrons. However, this concerns enhancement of the total productivity, but not the UCN production density at the source.

Finally, one can discuss the UCN density accumulation mode within the source volume at the very low temperature of 0.6–0.8 K for achieving a very low UCN loss coefficient in helium. We can assume that a very small loss coefficient ($\eta \approx 10^{-5}$) may be obtained in the case of UCN reflection from the walls of the source. Increasing the UCN storage time in the source makes it possible to increase their accumulation time in the source. Then, in a time of about 1000 s the possibility appears for attaining a UCN density of approximately 10^5 cm^{-3}. However, this result, even if it can be obtained, has no direct practical significance for the experiment in search of the neutron EDM. In such an experiment, the UCN density must be maintained in the trap of the EDM spectrometer, and its accumulation has to be performed every 100 s. During this time period, a UCN density that is one tenth as great, i.e. only 10^4 cm^{-3}, will be accumulated. While UCNs undergo accumulation in the trap of an EDM spectrometer, their density decreases in proportion to the ratio between the source volume and the total volume of the source, the trap, and the neutron guides, and in addition UCN losses occur during transportation. The UCN density loss coefficient also decreases approximately 10-fold, and the UCN density in the trap of the EDM spectrometer will amount to $\sim 10^3$ cm^{-3}, i.e., two orders of magnitude less than the maximum calculated UCN density in the closed source. Regretfully, the UCN density accumulation mode in the source yields no practical effect. Such is the qualitative estimate that is confirmed by more precise Monte Carlo simulations.

Thus, it is possible to obtain a UCN density of 1.3×10^4 cm^{-3} in the trap of an EDM spectrometer with the UCN source in the thermal column of the WWR-M reactor, and 1.3×10^3 cm^{-3} at the reactor PIK [24–26]. Therefore, the UCN source in the thermal column of the WWR-M reactor is 10 times more effective. However, since operation of the WWR-M may be terminated, both projects must be developed. Figure 7 presents the layout of UCN sources at the PIK reactor.

Now, it is necessary to answer the second question: why does the UCN density achieved in the extracted cold neutron beam of the ILL reactor only amount to 40 cm^{-3}, and is it possible to obtain significantly more at the PIK reactor than at the ILL reactor?

The source with superfluid helium at the ILL reactor was situated in a cold neutron beam with a flux of 3×10^7 cm^{-2} s^{-1} Å^{-1} at a wavelength of 9 Å [18]. The use of more powerful beams was not possible owing to the heat release in the source. The heat release in the source in the direct neutron beam in the immediate vicinity of the reactor may amount to tens of watts due to the γ-radiation field from the reactor. The power of such radiation in the direct beam from the reactor amounts to approximately 100 W. About 15% of the power will be released in the low-temperature part of the source. To resolve the cryogenic problem of heat removal of such power at a temperature of 1 K becomes too difficult. Therefore, such a problem was not dealt with in the case of the ILL reactor. However, we propose a solution that permits us to bypass the heat release problem. This solution consists in installing a bismuth filter in front of the UCN source [27]. A bismuth filter 10-cm thick will permit the heat release in the chamber with superfluid helium to be lowered

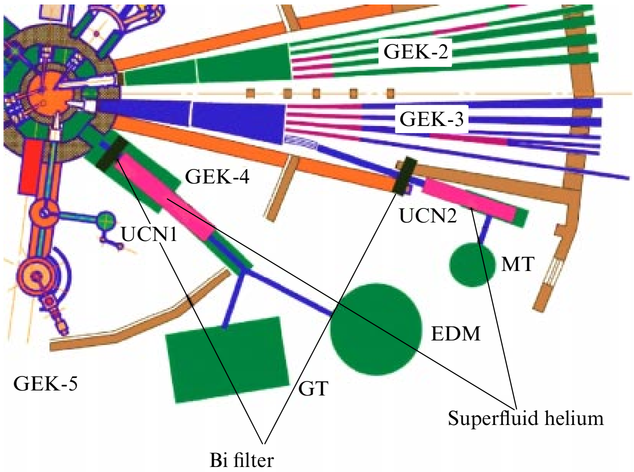


Figure 7. (Color online.) Layout of UCN sources with superfluid helium and of experimental devices in channels GEK-3 and GEK-4 of the PIK reactor: UCN1 — UCN source in channel GEK-4, UCN2 — UCN source in channel GEK-3, EDM — installation for measuring the EDM of the neutron, GT — device for measuring the neutron lifetime involving a UCN gravitational trap, and MT — device for measuring the neutron lifetime involving a UCN magnetic trap.

by a factor of 30 [27]. The flux of neutrons at a wavelength of 9 Å, which are converted to UCNs, will only attenuate by 30%. Thus, the problem of sustaining a low temperature and the superfluid state of liquid helium can be resolved, since the heat power released in the source will only amount to 0.5 W. The UCN density in the trap of the EDM spectrometer from the 100-l source with superfluid helium will reach 1.3×10^3 cm^{-3} [24]. The source will operate in a continuous mode by filling the trap of the EDM spectrometer according to the setup shown in Fig. 7. Utilization of the accumulation mode may permit obtaining a UCN density in the source of up to 10^5 cm^{-3}, but, as pointed out above, this effect has no practical significance for the experiment in search for the EDM of the neutron. In comparing different projects, it is necessary to take into account the UCN density in the experimental trap, as was done in our publications [20–26].

Regretfully, in the project of a source in the extracted beam of thermal neutrons with a solid methane moderator [28], for instance, the UCN density (10^5 cm^{-3}) in the source is indicated, but nothing is said of the UCN density in the trap of the EDM spectrometer. This gives rise to the erroneous impression of an advantage of the project. Indeed, the estimate for the UCN density presented in Ref. [28] was obtained for a UCN source operating in the accumulation mode under the assumption of quite perfect source parameters (a superfluid helium temperature of 0.6–0.8 K, and a loss coefficient $\eta = 10^{-4}$ of UCNs reflected from walls of the source). As was shown above, the expected density in the trap in the case of operation of the EDM spectrometer is two orders of magnitude lower, i.e., $\sim 1 \times 10^3$ cm^{-3}. Obtaining the same UCN density by another, more complex, method (by producing cold neutrons from thermal neutrons in the extracted beam, when cold neutron sources are present in the reactor) does not seem expedient. It should be noted that, if the authors succeed in resolving the problem with a large heat release in the direct beam of thermal neutrons, the project can be applied to reactors where no sources of cold neutrons are present.

Thus, the UCN source in the thermal column of the WWR-M reactor operating in the continuous mode and capable of providing a UCN density of $\sim 1 \times 10^4$ cm^{-3} in the experimental trap may turn out to be the most productive source. The next one in intensity may be the UCN source at the PIK reactor, situated in the extracted beam of cold neutrons, also operating in the continuous mode and capable of providing a UCN density in the experimental trap of $\sim 1 \times 10^3$ cm^{-3}. Finally, it should once more be noted that the accumulation mode is not effective, and that UCN sources must be compared by the resulting density in the experimental trap.

In the following sections, it will be clarified for the solution of which problems of elementary particle physics such efforts are spent in obtaining UCNs.

2.3 Three of A D Sakharov's conditions for the formation of the Universe and the neutron electric dipole moment

At the early stage of formation of the Universe, all processes were determined by the interaction properties of elementary particles. Symmetry laws point to the invariance of interactions relative to three discrete transformations: charge conjugation (C), spatial inversion (P) (specular reflection of space), and time reversal (T). Moreover, there is a most general CPT theorem relative to all three combined transformations. In Ref. [29], published in 1967, A D Sakharov established the relation between baryon asymmetry of the Universe and CP violation. Three conditions were introduced for formation of the Universe: baryon number violation, C- and CP-violations, and the existence of a nonequilibrium thermodynamic process. The problem of CP violation is extremely important for our comprehension of the Universe and must be studied in detail.

In the case of electromagnetic and strong interactions of elementary particle, invariance is fulfilled with respect to each of these operations (C, P, and T). But weak interactions violate the spatial inversion law. There is no symmetry between right and left; our world turned out to be left-handed, since the weak interaction of elementary particles is determined by the left-handed W-boson. It would seem possible to restore symmetry between right and left by considering the world of elementary particles as a whole — particles and antiparticles. Then, invariance will be fulfilled with respect to the joint C and P, i.e., CP, transformations. However, CP invariance is violated in the decays of K-mesons and B-mesons. The violation effects are extremely small ($\sim 10^{-3}$) and, it would seem, do not affect our lives or our existence, but this is not so: on the contrary, they have a very strong impact. Particles and antiparticles annihilate when interacting: transforming into γ-quanta and neutrinos, they destroy each other, so the worlds of particles and antiparticles cannot exist together. Indeed, at the formation of the Universe, annihilation of particles and antiparticles took place. However, it turned out to be incomplete — particles won, and, although the residue only amounted to one part in a billion, it is precisely this peculiarity that makes up our immense Universe. If symmetry laws for particles and antiparticles were strictly obeyed, our Universe would now exist in the form of γ-quanta and neutrinos. Luckily, this is not so. The baryon asymmetry of the Universe (the ratio between the number of baryons, i.e., neutrons and protons, and the number of photons) amounts to 6×10^{-10}. Thus, the process of CP violation (one of

Sakharov's conditions) lies at the base of the Universe existence.

It is now time to explain how CP violation is related to the electric dipole moment of the neutron. The requirement that the CPT theorem be satisfied signifies that CP violation should be accompanied by T violation, so as to retain invariance with respect to the CPT transformation. Therefore, CP violation essentially consists in violation with respect to time reversal. This means that the laws of elementary particle interactions change under time reversal. If we imagine the interaction process involving elementary particles to be recorded on a video and, then, if time $-t$ is substituted for time t and we, conventionally speaking, view the video in the backward direction, we will not see reproducted old events. The time arrow (defining a preferential direction) already exists in acts of elementary particle interactions.

The electric dipole moment of the neutron (if it differs from zero) is an unambiguous signal of T violation. When time is reversed, the electric dipole moment does not change, since it represents a static charge distribution, while the magnetic moment and spin change directions, since they are dynamic characteristics. After such an operation, we have a particle that is not identical to itself, and that will interact differently with electromagnetic fields: before time reversal, the electric dipole and magnetic moments were parallel, while after they became antiparallel.

Since CP or T violation exists, there should be an electric dipole moment differing from zero, and this is just as valid as the existence of the Universe. In this fact, one can perceive the unanimity of the picture of the World: reflection of the large in the small. Here, we see a striking example of how it is possible with the aid of precision measurements to study the most profound issues of the Universe.

2.4 Theoretical predictions for the neutron electric dipole moment

The Standard Model of electroweak interaction provides estimates for the EDM of the neutron at a level inaccessible to present-day experiments: $10^{-30}-10^{-33}$ e cm. CP violation (and the neutron EDM) arise here only in the second order of smallness in the weak interaction constant. Therefore, the Standard Model also encounters certain difficulties in explaining the baryon asymmetry of the Universe. Thus, searches for the neutron EDM actually represent searches for phenomena beyond the Standard Model.

Within the framework of the Standard Model, for example, the baryon asymmetry of the Universe should also be inferior to the observed value by many orders of magnitude. Quite evidently, the Standard Model requires extension. Numerous models of CP violation exist. For example, the neutron EDM in models explaining the baryon asymmetry of the Universe should be at a level of 10^{-26} e cm, i.e., precisely at the limits of even presently current experiments.

Gauge theories involving spontaneous symmetry breaking have led to the construction of models of another sort for explaining CP nonconservation [30, 31]. Such models like supersymmetry, models with multiple Higgs particles, and left-right-symmetric theories include expansion of the Standard Model symmetry and add new particles. The particle EDM in these models arises in the first order in the weak interaction and turns out to be at a level of $10^{-26}-10^{-28}$ e cm. Revelation of the EDM of the neutron at such a level or the establishment of a new limit on its value is important for the

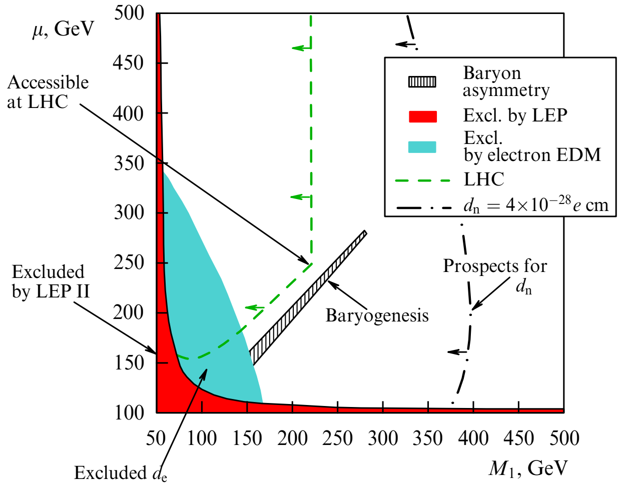


Figure 8. (Color online.) Sensitivity of modern experiments and of planned measurements of the neutron EDM to mass parameters of supersymmetric particles relative to baryogenesis [33].

choice of theory adequately describing phenomena of CP violation.

Electric dipole momenta of any elementary particles serve as a sensitive test of such new physics, and in a certain sense these studies are an alternative to the search for new particles in high energy physics at hadron colliders. The recent measurement of the electron EDM [32] apparently casts doubt on the minimal sypersymmetric models of electroweak baryogenesis [33]. Further development and enhancement of the sensitivity of experiments on search for the EDM of elementary particles and, especially, the EDM of the neutron are necessary in order to reveal and explain this 'additional' CP violation [34].

As an illustration, Fig. 8 shows, in coordinates of the masses of superparticles sought in supersymmetric theoretical models, the regions that have already been 'closed' (to the possible existence of superparticles) by other experiments [33].

On the vertical axis the masses of the supersymmetric higgson/higgsino are plotted, while the mass parameter M_1 $U(1)_Y$ gigino(bino) is plotted on the horizontal axis. The shaded region corresponds to mass values that could explain the observed baryon asymmetry within the framework of these models. The dark gray region is excluded by data obtained at LEP, and the gray region is excluded by the existing limit on the EDM of the electron. The dashed line shows the region accessible to the Large Hadron Collider (LHC, Switzerland). The region accessible to the experiment in search for the EDM of the neutron, if the experimental precision is enhanced by two orders of magnitude, is indicated by the dashed–dotted line. Implementation of such studies will become possible when new high-intensity UCN sources are put into operation.

2.5 Experimental searches for the neutron electric dipole moment involving ultracold neutrons

It is interesting that measurement of the electric dipole moment of the neutron was discussed even before the discovery of spatial parity violation and, all the more, before the discovery of CP violation. E M Purcell and N F Ramsey (who subsequently received the Nobel Prize in Physics) discussed an experiment on searching for the electric dipole moment of the neutron as a possible test of the violation of spatial parity. The experiment was carried out in 1951, but its results were only published in 1957, when active discussions started of the issue of spatial parity violation. It soon became clear that the experiment was essentially more significant, since it was also relevant to the search for CP-violation effects. The precision of the first experiment on search for the neutron EDM ($d_n = -(0.1 \pm 2.4) \times 10^{-20}\, e$ cm) was improved in recent years by 6 orders of magnitude, and the last two orders of magnitude are connected with using ultracold neutrons.

The proposal to use ultracold neutrons in the experiment searching for the electric dipole moment of the neutron was put forward by F L Shapiro [35]. The first experimental evidence of the existence of UCNs was obtained at JINR; also shown was the possibility of their extraction from the reactor. Soon after, work with ultracold neutrons also started at the WWR-M reactor of PNPI under the leadership of V M Lobashev; the first polarized UCN beams were obtained here [36] and high-intensity cooled UCN sources were designed and produced. The possibility was theoretically shown of applying UCNs in experiments on search for the neutron EDM [37].

The first experiment with ultracold neutrons on searching the electric dipole moment of the neutron was realized at PNPI [37]. The technique of working with ultracold neutrons had to be mastered practically from zero, starting from obtaining them, i.e., developing UCN sources, up to constructing a magnetic resonance spectrometer with an energy resolution of $\sim 10^{-17}$ eV (Fig. 9).

Obtaining such a high energy resolution is precisely effected by storing the neutrons in a trap for ~ 100 s ($\Delta E \sim \hbar/\Delta t$). Therein lies an advantage of the method of ultracold neutrons relevant to the beam experiment in which the time of flight through the device only amounts to several milliseconds. The magnetic resonance technique exhibits surprisingly high precision: it is based on measurements of the shift of the resonance frequency under a change in direction of the electric field with respect to the direction of the magnetic field.

The neutron EDM can be revealed by a shift in the magnetic resonance frequency. In a real experiment, however, all is not as simple as in the concept presented above. The first problem lies in the instability of the magnetic field against the background of noises in which it is impossible to single out the sought frequency shift. Therefore, the chamber of the spectrometer must be placed inside a multilayer magnetic screen, but this is insufficient, and the magnetic field inside the screen must be stabilized with the aid of precision cesium magnetometers with optical pumping. The achieved instability of the magnetic field ($\sim 10^{-8}$ Oe in 10 min) is in any case by 5 orders of magnitude smaller than the magnetic noise in the experimental hall of the reactor. Another task consists in creating an extreme electric field strength of 10–15 kV cm^{-1}. A high voltage of ~ 150 kV must be supplied to the spectrometer without creating magnetic instability; therefore, the leakage currents in the insulators must not exceed several nanoamperes. It is even difficult to interpret the result achieved in the measurement precision of the electric dipole moment ($\sim 10^{-25}\, e$ cm), since 10^{-25} cm is much smaller than the dimension of the neutron, $\sim 10^{-13}$ cm. Indeed, if one imagines the neutron to be equal in size to the terrestrial globe, then the shift between the positive and negative elementary charges will only amount to ~ 10 μm.

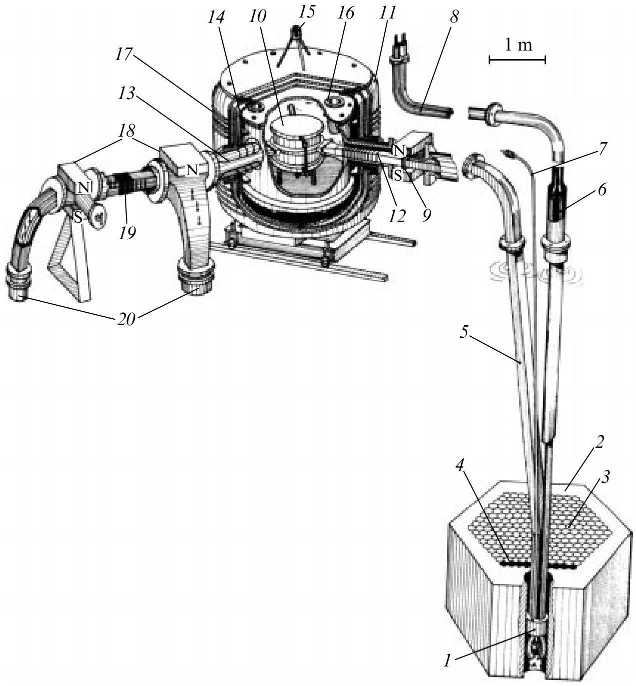


Figure 9. (Color online.) Schematic of a magnetic resonance spectrometer with an electric field for searching for the neutron EDM: *1* — liquid-hydrogen UCN source, *2* — beryllium reflector, *3* — reactor core, *4* — lead shielding, *5* — neutron guide for UCNs, *6* — helium cryopipes, *7* — hydrogen pipe guides, *8* — vacuum pipe guides, *9* — polarizer, *10* — UCN storage chambers with high-voltage electrodes, *11* — magnetic screens, *12* — solenoid with oscillating magnetic field (input), *13* — coil with magnetic field gradient (exit), *14* — coils for a homogeneous magnetic field, *15* — magnetometer of the system for stabilization of the external magnetic field, *16* — magnetometer of the system for stabilization of magnetic field inside magnetic screens, *17* — coils for demagnetization of magnetic screens, *18* — analyzers, *19* — flipper of the system for double analysis of polarization, and *20* — UCN detectors (depicted by author).

The first results of experiments in search for the neutron EDM by the UCN method were obtained in 1980 at PNPI (Gatchina, Russia) [38, 39], and then at ILL (Grenoble, France) [40, 41] as well. The first limit on the neutron EDM obtained in Gatchina by applying UCNs amounted to $|d_n| < 1.6 \times 10^{-24}\, e$ cm (90% C.L.). The Gatchina result was already improved in 1981: $|d_n| < 6 \times 10^{-25}\, e$ cm (90% C.L.) [39]. In the 1990s, both teams achieved a limit for the neutron EDM of $\sim 1 \times 10^{-25}\, e$ cm (90% C.L.) [41–44]. At this stage, measurements in Gatchina stopped owing to termination of the UCN source operation. In Grenoble, the RAL/Sussex/ILL collaboration continued measurements, and in approximately 10 years the limit on the neutron EDM was lowered by a factor of 3 [45]. The best present-day constraint on the electric dipole moment of the neutron was presented in Ref. [45]: $|d_n| < 2.9 \times 10^{-26}\, e$ cm (90% C.L.). Here, a single chamber was used for the storage of UCNs, and a mercury comagnetometer was exploited for monitoring magnetic conditions (polarized mercury atoms are within the same volume as the UCNs). Regretfully, the mercury magnetometer is not an absolute comagnetometer owing to the so-called geometric phase effect [46], which differs from neutrons to mercury atoms. This leads to a systematic error occurring in the presence of a magnetic field gradient.

In 2008, the PNPI EDM spectrometer was installed at the UCN beam port PF2/MAM of the ILL reactor (Fig. 10). The

Figure 10. (Color online.) General view of the PNPI differential spectrometer in the ILL experimental hall.

work was performed by the PNPI–ILL–PTI collaboration. In 2013, this collaboration imposed the following bound on the neutron EDM value: $|d_n| < 5.5 \times 10^{-26}\,e$ cm at a 90% confidence level [47]. The result reported in Ref. [47] is somewhat inferior to the one achieved in Ref. [45]; however, it was obtained with an experimental device based on a methodically different technique. We use a differential magnetic resonance spectrometer involving two UCN storage chambers with a common constant magnetic field and oppositely directed electric fields in the neutron storage volumes. Such a setup of the experiment provides a substantially different possibility for controling systematic errors. In the course of measurements, we revealed no systematic effects at the achieved level of precision.

A specific feature of our spectrometer lies in the presence of two UCN storage chambers with a common system of magnetic fields and electric fields equal in value but oppositely directed (Fig. 11). When the electric field polarity is reversed, the effects due to the neutron EDMs will be of opposite signs in different chambers, while instability of the common magnetic conditions leads to a shift in the resonance frequency of the same sign. The results of these measurements being different lead to effects due to the neutron EDMs adding up, while the effects caused by correlated changes in the count not related to the EDMs are strongly suppressed.

Another peculiarity enhancing the sensitivity of the facility is in the double polarization analysis system. At the exit from each storage chamber of the spectrometer there are two detectors, each of which registers the projection of a certain neutron polarization component onto the guiding field direction. Since the direction of the guiding field in the exit neutron guides is conserved, a spin flipper is positioned in front of the second pair of detectors for registration of the second polarization component. This increases the total number of neutrons in the measurement process and permits compensating the spread of results related to fluctuations in the neutron source intensity. Analysis of data from the four detectors allows the revelation of systematic effects.

The result recently obtained by the PNPI–ILL–PTI collaboration, $|d_n| < 5.5 \times 10^{-26}\,e$ cm, is planned to be improved in precision by approximately threefold owing to a higher intensity of the UCN beam from the PF2/MAM port and a new layout of the spectrometer. The main prospect for improving the precision up to the level of $5 \times 10^{-28}\,e$ cm is related to the UCN source at the WWR-M reactor.

Figure 12 illustrates the chronology of how the upper limit on the value of the neutron EDMs was lowered in experiments performed in Gatchina and Grenoble and further research plans at the WWR-M reactor in Gatchina.

At present, the use of UCNs for experiments on searching the neutron EDM remains the most promising method. A significant enhancement of the UCN source intensity will also improve the sensitivity of the facility, i.e., the prospects for developing the experiment on search of the neutron EDM are related to the creation of a new generation of UCN sources. The goals of such an experiment served as a decisive stimulus for the development of a new technology in the production of ultracold neutrons. The UCN sources available at present do not permit us to expect any significant improvement in the result achieved. At present, work is under way at several foreign research centers to construct new ultracold neutron sources: ILL (France), LANL (USA), PSI (Switzerland), and TUM (Germany). Plans to construct high-intensity ultracold

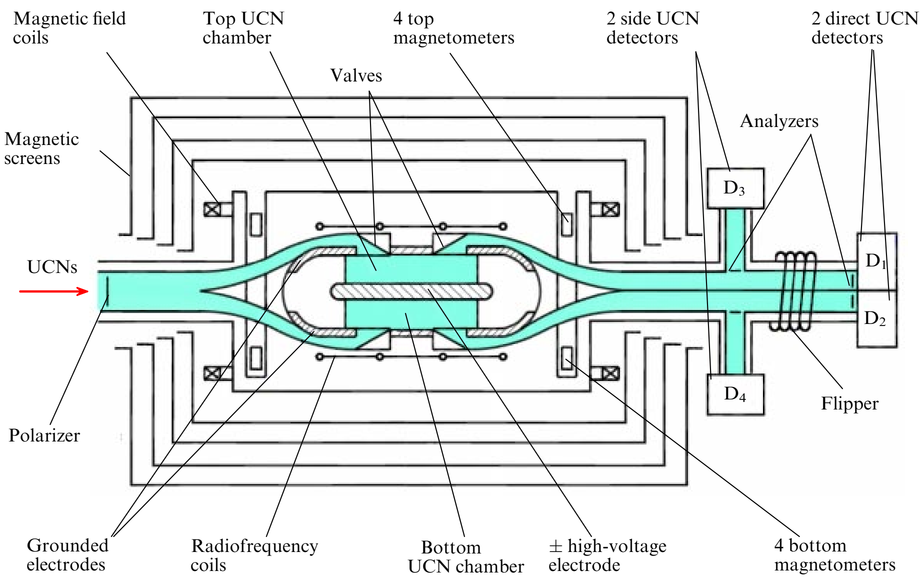


Figure 11. (Color online.) Schematic of a double-chamber EDM spectrometer.

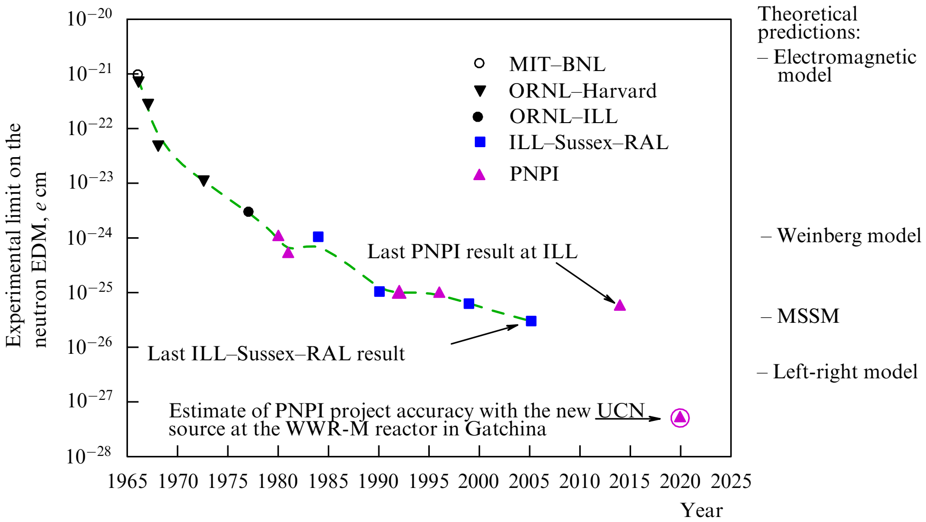


Figure 12. (Color online.) History of the lowering of the experimental limit on the neutron EDM and of prospects for improving the measurement accuracy. MSSM — minimal supersymmetric Standard Model.

neutron sources, based on superfluid helium, at the WWR-M reactor also exist at PNPI (Gatchina, Russia) [20–23]; we have already discussed them in Section 2.4. Moreover, the use of UCN sources is planned at the reactor PIK under construction. The calculated UCN density of these sources is 2–3 orders of magnitude higher than the UCN density of the existing ILL source. The construction of such sources will permit the precision of a neutron EDM measurement to be raised at a level better than 10^{-27} e cm, as shown in Fig. 12.

2.6 Search for the neutron electric dipole moment based on the diffraction of cold neutrons in crystals without a center of symmetry

A new method of searching for the electric dipole moment of the neutron has been proposed in V V Fedorov's laboratory at PNPI. The main idea of the method consists in using enormous electric fields (up to 10^9 V cm^{-1}) acting on a neutron in a crystal without any symmetry center throughout the entire thickness of the crystal, which may reach several dozen centimeters. The possibility was first put forward and realized for singling out neutrons that traversed the crystal in electric fields differing in sign and value, with the aid of a special analyzing crystal with an adjustable interplanar separation. The wavelength and energy of a neutron that traversed the working crystal and was reflected by a second crystal is determined by the interplanar separation of the reflector. This quantity can be adjusted by changing the temperature of the reflecting crystal. In turn, it also influences the value and sign of the electric field acting on the neutron in the crystal. Thus, the possibility has been realized of regulating the sign and value of the electric field acting on the neutron being registered. The layout of the experiment and a photograph of the device are presented in Fig. 13.

A cycle of test experiments was performed at the WWR-M reactors of the PNPI (NRC KI) and the ILL reactors [48]. The following results were obtained. The strength of electric field acting on a neutron in a quartz crystal was measured and found to be $E_{\text{exp}} = (0.7 \pm 0.1) \times 10^8$ V cm^{-1} and to coincide with the calculated value. The sensitivity to the neutron EDM

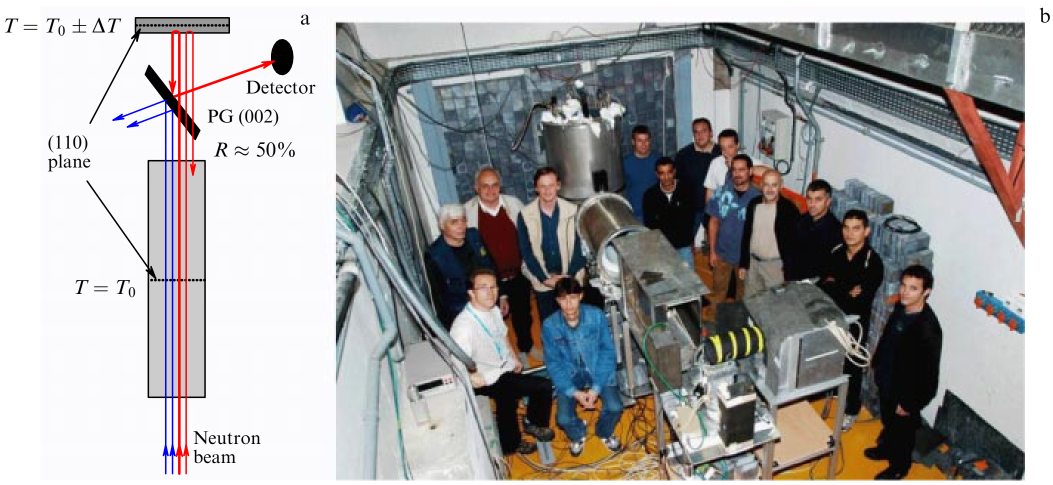


Figure 13. (Color online). Schematic diagram of experiment searching for the neutron EDM (a), and test device at the ILL reactor (b).

in the test experiment amounted to $1.6 \times 10^{-23}\,e$ cm per day and was restricted by the geometry of the experimental equipment utilized. Recalculation of this value to a full-scale experiment yields a sensitivity of $\sim 2 \times 10^{-25}\,e$ cm per day, which confirms preliminary estimates. The value of the neutron EDM measured in the test experiment amounted to $d_n = (4 \pm 6) \times 10^{-24}\,e$ cm. The actual setup of the experiment was shown to exhibit a highly selective capacity relative to the neutron EDM. The possibility exists of excluding false effects due to residual magnetic fields and the Schwinger interaction. The purpose of this activity lies in creating a full-scale facility based on the use of a crystal without central symmetry as a source of the electric field and to achieve a precision of the neutron EDM reaching $10^{-27}\,e$ cm. Although extrapolating the achieved sensitivity by three orders of magnitude seems too optimistic, the crystal-diffraction method of searching for the neutron EDM must be actively developed. It is very important that this be essentially different method of searching for the neutron EDM.

Naturally, apart from our plans of enhancing the measurement accuracy, approaches exist of at least four experimental teams that are developing new EDM spectrometers and new UCN sources with the aim of increasing the UCN density by factors amounting to tens and hundreds. Therefore, studies carried out along this line of research are accompanied by severe competition, which is dictated by the importance of the scientific problem.

2.7 Neutron decay. The Standard Model and cosmology

Like most elementary particles, neutrons are composed of quarks. Various combinations of quarks provide the diversity of elementary particles. Quarks in elementary particles reside in a state of confinement: they cannot leave the elementary particles, but they can mix with each other and give rise to different decay versions of elementary particles. In the Standard Model of elementary particles, quark mixing is described by the Cabbibo–Kobayashi–Maskava (CKM) matrix, which should be unitary, confirming the completeness of our idea on the number of quark and lepton generations. The values of individual matrix elements are determined from the weak decays of elementary particles. Thus, for example, neutron decay is determined by transformation of the d-quark into the u-quark or by the matrix element V_{ud}. Knowledge of the exact value of V_{ud} plays an important role in verifying the unitarity of the CKM matrix, since the element V_{ud} is the largest one. The V_{ud} element can be determined from β-decay of nuclei and β-decay of neutrons. Determination of V_{ud} from the neutron β-decay is preferable from the point of view of the theoretical simplicity of describing the process compared with decays of nuclei. To determine V_{ud} from the neutron β-decay, it is necessary to measure the neutron lifetime and the β-decay asymmetry with a high precision. The accuracy of theoretical calculations covering various sorts of radiative corrections permits determining V_{ud} with a precision of 0.05%; therefore, the measurement accuracy of the neutron lifetime must be at the same high level. Below, it will be shown that a precision of 0.1% in the measurement of the neutron lifetime has been achieved in an experiment with ultracold neutron storage in traps.

Precision measurements of the neutron lifetime also happen to be extremely important for testing the model of the Universe's formation at its early stages. About 100 s after the Big Bang, leptons, hadrons, and photons were in a state of thermodynamic equilibrium at temperature $T > 10^{10}$ K ($E > 1$ MeV). Owing to the weak interaction, reaction rates depend on the same quantities as the neutron decay rate. The temperature at which a neutrino quits the process and the ratio of neutrons to protons is fixed at the initial stage of primary nucleosynthesis depends on the rate of weak reactions. The neutron decay process further alters the ratio between the numbers of neutrons and protons. The abundances of deuterium and ^{4}He serve as observable quantities in the Big Bang model. These quantities depend on the ratio of the number of baryons to the number of photons at the moment of nucleosynthesis and on the neutron lifetime τ_n, as specified above. The baryon asymmetry of the Universe is measured in cosmic studies of the microwave background radiation; therefore, all the quantities turn out to be measurable and related to each other. Thus, for instance, in the model of primary nucleosynthesis, a change in the neutron lifetime by 1% will lead to a change in the abundance of ^{4}He by 1.5% (for a fixed baryon asymmetry value) or to a 17% change in the baryon asymmetry (for a given value of ^{4}He abundance). Regretfully, the relative measurement accuracy of the ^{4}He abundance is still insufficient ($\pm 0.6\%$); however, the accuracy with which the baryon asymmetry is measured is improving very rapidly owing to cosmic studies, and at present it amounts to $\pm 5\%$. Thus, the neutron lifetime must be measured with an accuracy significantly exceeding 1% for it to be applied successfully in the model of primary nucleosynthesis.

Significant progress in the measurement accuracy took place in the 1990s owing to the utilization of ultracold neutrons [49, 50]. But this result was not achieved all of a sudden. Precise measurement of the neutron lifetime was preceded by long searches for conditions appropriate for prolonged storage of UCNs in traps.

2.8 Measurement of the neutron lifetime using an ultracold neutron gravitational trap

The most accurate (0.1%) experiment with UCNs was performed in 2004 by the PNPI–ILL–JINR Collaboration [51, 52]. The loss probability attained in this experiment was 1% of the neutron decay probability, so the collaboration succeeded in observing the nearly direct neutron decay process in a trap.

The facility was created thanks to the joint efforts of the B P Konstantinov Petersburg Nuclear Physics Institute (PNPI) and the Joint Institute for Nuclear Research (JINR). It was first applied as the universal source of cold and ultracold neutrons at the WWR-M reactor in Gatchina. At first, a refrigerator was used to cool the facility to a temperatures of 10–15 K. Subsequently, the facility was modified according to a cryostat setup and became autonomous, which permitted measurements at the high-flux reactor ILL in Grenoble. Figure 14 presents the modified schematic of the facility.

The facility represents a gravitational UCN trap, but at the same time it can also be utilized as a differential gravitational spectrometer. Therefore, a feature distinguishing this experimental installation lies in the possibility of measuring the UCN energy spectrum after storage in a trap. Trap *1* for UCN storage is installed in the vacuum volume of cryostat *2*. The trap has a window and can rotate around the horizontal axis so that the UCNs turn out to be trapped by gravitation in the trap, when the window holds its upper position. The ultracold neutrons arrive at the trap through the

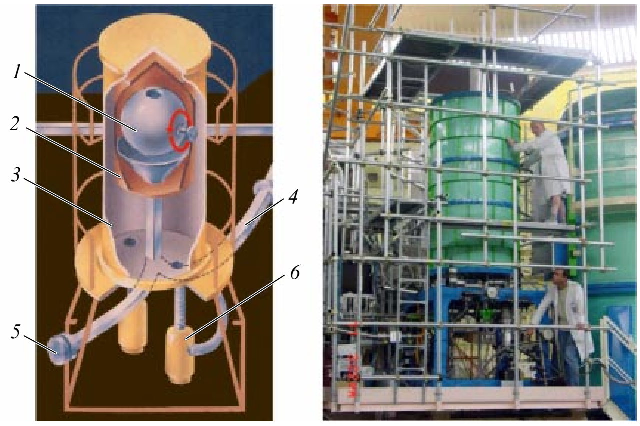


Figure 14. (Color online.) Gravitational trap: *1* — trap for storage of UCNs, *2* — cryostat, *3* — vacuum volume, *4* — guide for ultracold neutrons, *5* — UCN detector, and *6* — sorption pump.

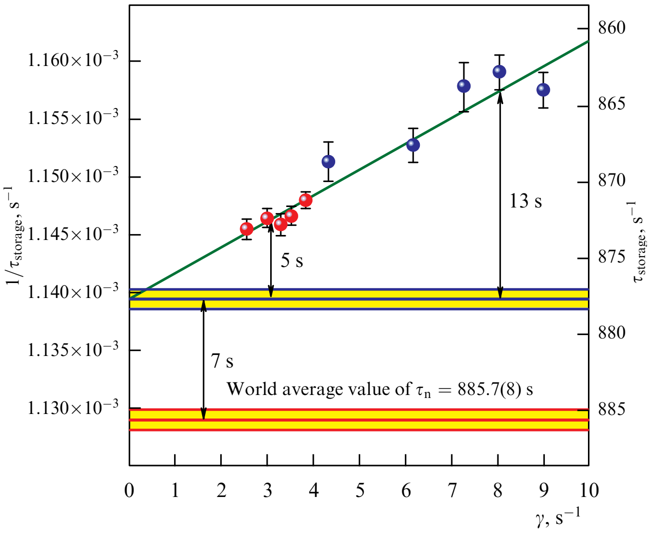


Figure 15. (Color online.) Result of extrapolation to the neutron lifetime making use of the combined energy and dimensional extrapolation. Measurements with a quasispherical trap — light (red) circles, and measurements with a cylindrical trap — dark (blue) circles.

neutron guide *4*, the open entrance valve, and the distributive valve. Filling the trap with ultracold gas takes place when it is in the position of 'window down'. After being filled, the trap rotates to the position of 'window up'. The position (height) of the window relative to the trap bottom determines the maximum energy of UCNs which can be stored in the trap. Different heights of the window correspond to different edge energies limiting the UCN spectrum — such a rotating trap represents a gravitational spectrometer. The spectral dependence of the storage time can be measured by consecutive turns of the trap up to the position of 'window down'. The trap was kept in each intermediate position for 100–150 s to register UCNs in the respective energy region. By applying such a procedure, it is possible to measure the spectrum of UCNs captured in the trap.

The neutron lifetime was measured by the dimensional extrapolation method. To this end, two UCN traps of different dimensions were used. The first was quasispherical and 80 cm in diameter. The second trap was cylindrical, 76 cm in diameter, and 14 cm in width. The neutron collision frequency with the walls of the second trap was approximately 2.5 times greater than in the first trap.

A new type of material was used in the experiment for covering the walls of the trap — low-temperature Fomblin, which can be deposited onto a surface by vacuum evaporation. The composition of this oil only includes C, O, F, so, consequently, it has a small neutron capture cross section. Preliminary investigation of several types of low-temperature Fomblin revealed that quasielastic and inelastic UCN scattering on low-temperature Fomblin for $T < -120\,^{\circ}\mathrm{C}$ is much less than on ordinary Fomblin at room temperature. Quasielastic UCN scattering is totally suppressed for $T < -120\,^{\circ}\mathrm{C}$, and the expected UCN loss coefficient η, owing to inelastic scattering, equals approximately 2×10^{-6}.

The results of measurements of the UCN storage time for different energy intervals and various trap modifications (broad and narrow) are presented in Fig. 15 versus the effective collision frequency γ.

Extrapolation of all data to the neutron lifetime yields the value of 877.60 ± 0.65 s with $\chi^2 = 0.95$. When the systematic correction, related to the vacuum conditions in which the experiment was performed, is taken into account, we obtain the final result for the neutron lifetime: $878.5 \pm 0.7_{\mathrm{stat}} \pm 0.3_{\mathrm{syst}}$ s.

The extrapolation of direct experimental data (the UCN storage time in the trap) to the neutron lifetime in this experiment only contributes 5 s. However, the result of extrapolation differs from the world average value by 7 s, although the extrapolation accuracy amounts to 0.8 s. The difference between the result of the new experiment and the average value of all experiments amounts to 6.5 standard deviations and represents an apparent contradiction. The results of the study were published in 2005 [51].

Subsequently, the situation developed as follows. First, the PNPI result was confirmed by an experiment involving UCN magnetic storage [53]. The results of preceding experiments were further corrected [54, 55]. As a result, the world average neutron lifetime adopted by the Particle Data Group (PDG) in 2013 was 880.0(9) s. To a significant extent, it is determined by the result obtained by the PNPI–ILL–JINR collaboration. Figure 16 illustrates the development of the situation with the distribution of experimental data on the neutron lifetime. As a result, the experimental results for the neutron lifetime obtained with UCNs turned out to be consistent. However, analysis of the data, taking into account beam experiments, revealed a discrepancy of 3.3 standard deviations [56], and after the publication of paper [57] the discrepancy increased to 3.9 standard deviations [58]. The contribution from data obtained in the beam experiment does not affect the world average value of the neutron lifetime significantly. Most likely, the issue is of a methodical character and will be resolved by further experiments.

A new experiment with a big gravitational trap is to be carried out by the PNPI–ILL–JINR collaboration [59]. Figure 17 depicts the layout of the installation that is at the stage of assemblage at the ILL reactor (Fig. 18). In this installation, the gravitational shutter principle is applied for UCN confinement in a material trap. The UCN storage volume in the new trap is about 4 times larger than in the trap of the preceding facility; moreover, an insert that can be lifted up or pushed down in the trap without the device being opened is to be used in the new installation. This allows both

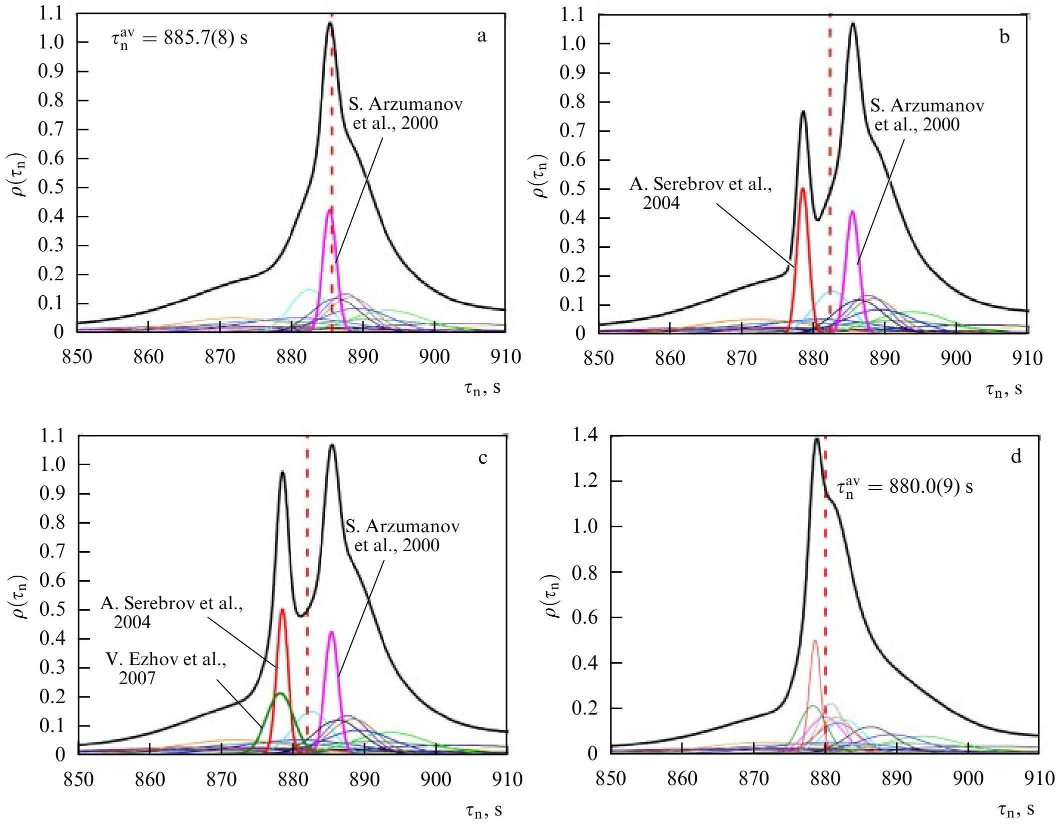


Figure 16. (Color online.) Distributions of results of neutron lifetime measurements: (a) in 2003 (before the result of the PNPI–ILL–JINR experiment with a UCN gravitational trap), (b) in 2004 (after publication of the PNPI–ILL–JINR result with a UCN gravitational trap), (c) in 2007 (after announcement of the result with a magnetic trap), and (d) in 2011 (after corrections and additions resulting in the average value of 880.0 ± 0.9 s accepted by the PDG).

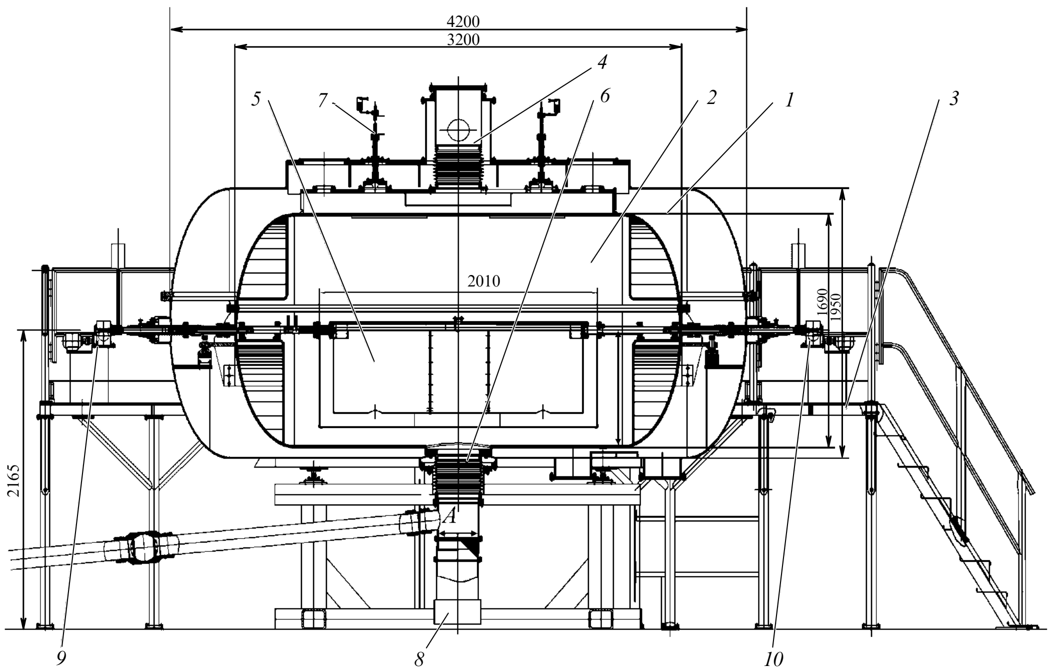


Figure 17. Schematic view of a big gravitational trap: *1* — outer vacuum vessel, *2* — inner vacuum vessel, *3* — platform for service maintenance, *4* — input for evacuation of the inner vessel, *5* — trap with insertion in the lower position, *6* — neutron guide system, *7* — system for vacuum coating of trap and insertion, *8* — detector, *9* — mechanism for rotating trap, and *10* — mechanism for rotating insertion.

excluding systematic uncertainties and significantly enhancing the statistical accuracy of the experiment. The planned measurement accuracy reaches 0.2 s, which is 4 times better than the existing precision level. To achieve such an accuracy, low-absorbing coatings will be employed, which are based on fluoropolymers at the temperature of liquid nitrogen, and,

Figure 18. Completing assembly of the big gravitational trap.

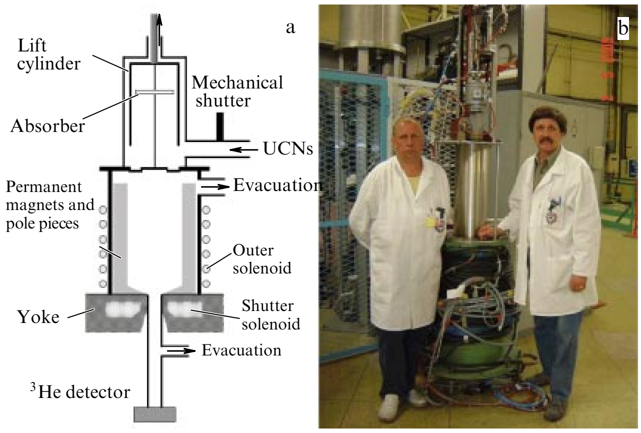


Figure 19. Layout of magnetic trap (a) and the first, preparatory, stage of measurements (b).

subsequently, of liquid helium, in order to lower the loss coefficient to below 10^{-6}.

Improving the experimental accuracy is important for studying the contradiction that is beginning to show itself among different techniques for measuring the neutron lifetime — the beam method and the UCN storage method. Although the most probable explanation seems to be the presence of a systematic error in the beam experiment, one cannot be sure yet that no systematic error is present in the experiment with UCNs, so its accuracy must be enhanced. The difference between these two techniques is that in the beam experiment measurements are made of a sole neutron decay mode involving the emission of a proton, while in the case of UCN storage all possible decay channels resulting in the disappearance of the neutron are dealt with. Finally, the existence of some additional unknown neutron decay mode cannot be ruled out. To formulate (without theoretical grounds) such an issue, it would be necessary to improve the accuracy of the beam experiment and to perform an independent beam experiment. In this connection, we shall note that our plans for measuring the neutron decay asymmetry in a beam of cold neutrons from the PIK reactor by making use of a superconducting solenoid [60] can be supplemented by a measurement of the neutron lifetime in a beam, taking advantage of a similar technique (see Section 2.11).

Finally, measurement of the UCN storage time in a magnetic trap is a third independent and very important experimental technique.

2.9 Measurement of the neutron lifetime by the storage of ultracold neutrons in a magnetic trap

The possibility of storing neutrons in magnetic traps was discussed in detail back at the dawn of their discovery by V V Vladimirskii (ITEP (NRC KI)) [2].

In such systems, UCNs of a certain polarization are reflected from a magnetic barrier and undergo no collisions with the walls. Thus, in principle, it is not possible for anomalous UCN losses related to reflections from the walls to exist in magnetic traps. However, it is necessary to avoid the UCN depolarization effect at a level better than 10^{-6} in a single approach to the magnetic wall, so as to compete successfully with ordinary UCN storage for which a loss level of 2×10^{-6} per collision with the wall has already been achieved [52]. The problem reduces to the creation of magnetostatic systems in which the magnetic field increases in all directions.

Modern technology permits the production of permanent magnets with a saturation induction of 1.4 T or more. A magnetic trap with a magnetic field on the order of 1 T at its wall (Fig. 19) was constructed on the base of such magnets at PNPI (NRC KI) in the V F Ezhov laboratory, together with a team from the Technical University Münich and the Institut Laue–Langevin (Grenoble). In 2004–2005, it was tested on the UCN beam of the Institut Laue–Langevin. The storage time of neutrons in this trap was measured during the period of April–August 2005. The value obtained amounted to 878.3 ± 1.9 s [53]. This value is close to the neutron half-life. No losses due to neutron depolarization during their storage in the trap were revealed. An increase in the trap volume by an order of magnitude will permit a precision of 0.3 s to be achieved. The new trap, like the preceding one, can be created entirely on the basis of Russian technologies.

It must be noted that, although the possibility of storing neutrons in a magnetic trap has been under discussion for over 50 years, a magnetic system that can successfully compete with the best material traps has been realized only now. This is also a purely Russian achievement. However, this line of research is recently being actively developed in the USA at the Los Alamos National Laboratory (LANL), where a large magnetic trap has been constructed and plans are to implement a precision measurement of the neutron lifetime and to compare the result with those of measurements in a cold neutron beam. The result obtained in the experiment at LANL for the UCN storage time in the trap is at present 860 ± 19 s [61].

2.10 The Standard Model and primary nucleosynthesis with the new neutron lifetime

The new result for the neutron lifetime can be utilized in testing the unitarity of the quark mixing matrix. The neutron lifetime relates the matrix element $V_{\rm ud}$ and the ratio of the axial-vector and vector weak interaction constants (λ); therefore, in order to determine $V_{\rm ud}$ from the neutron β-decay, it is also necessary to measure λ from the β-decay asymmetry. Figure 20 plots the dependence of $V_{\rm ud}$ on λ from data on the neutron lifetime obtained with a UCN gravitational trap (the inclined belt), as well as the value of λ from data on decay asymmetry measurements (vertical belt) [62]. Their intersection determines the range of $V_{\rm ud}$ values (upper horizontal belt). In Fig. 20, Particle Data Group data on the neutron lifetime (dashed–dotted inclined belt) as of 2004, i.e., before

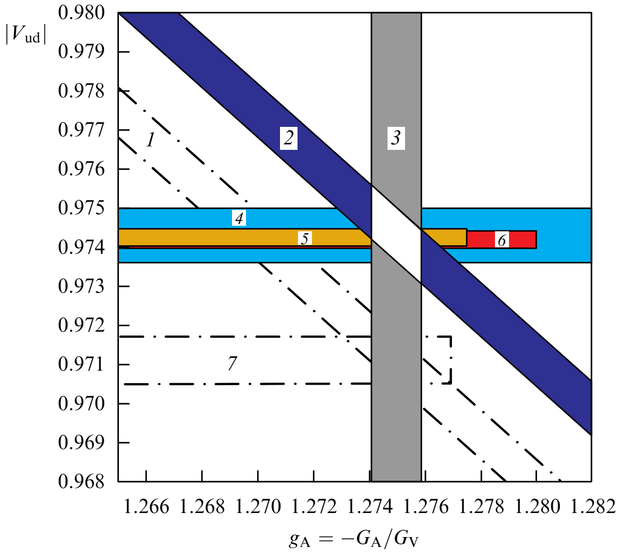


Figure 20. (Color online.) Dependence of quark mixing matrix element $|V_{ud}|$ on the axial coupling constant g_A for different neutron lifetime values: *1* — neutron lifetime, PDG 2006; *2* — neutron lifetime, Ref. [51]; *3* — neutron β-decay asymmetry, Perkeo 2007; *4* — neutron β-decay: 880.0 ± 0.9 s + Perkeo 2007; *5* — unitarity; *6* — nuclear β-decay; *7* — neutron β-decay, PDG 2004 + Perkeo 2007.

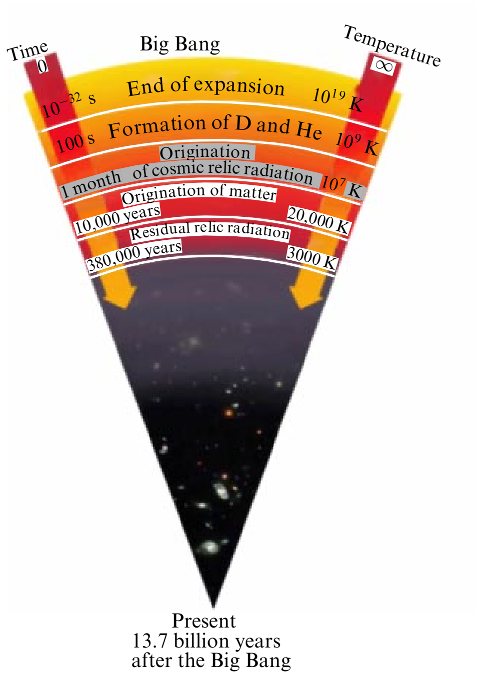
measurements of the neutron lifetime were made with a UCN gravitational trap, are also used. The result of determining V_{ud} from the new data on neutron β-decay (upper horizontal belt) is in reasonable agreement with the analogous result based on unitarity and on V_{ud} determined from the decay of strange mesons (second horizontal belt from the top), as well as the β-decay of nuclei (third horizontal belt from the top). Thus, the three approaches to determine V_{ud} are consistent with each other and confirm the Standard Model. Naturally, using tabular neutron lifetime data of the Particle Data Group 2004 in such an analysis will lead to evident contradictions.

In this analysis, the most precise measurements of the electron asymmetry A in neutron decay were used, which have not yet been confirmed by other experiments. Therefore, new measurements of the neutron decay asymmetry must be performed. In this connection, it may be noted that an installation is under development at PNPI to measure the neutron decay asymmetries, which is to be installed at the PIK reactor [60] (see Section 2.11).

We shall now consider the influence of new data concerning the neutron lifetime on simulation of the primary nucleosynthesis process at the early stage of formation of the Universe (~ 100 s after the Big Bang; Fig. 21). As was noted above, the neutron lifetime relates the observed ^{4}He abundance and the observed baryon asymmetry of the Universe. This relationship is shown in Fig. 21 both for the old tabular lifetime value and for the new value obtained in the experiment with the UCN gravitational trap [63]. The observed values of the ^{4}He abundance and of the Universe's baryon asymmetry are shown by horizontal and vertical belts, respectively. The dependence involving the new lifetime value passes through the intersection point of the observable quantities, which cannot be said about the dependence based on the tabular neutron lifetime of 2004. However, the latest data on helium abundance in the Universe again change the picture of this accord and point to the advisability of introducing an additional neutrino [64].

2.11 Prospects for the continuation of research at the PIK reactor

Although studies carried out at the WWR-M reactor and at the ILL achieved very important results, the interest in the problems formulated has recently only increased. New studies at the PIK reactor open new possibilities for enhancing the accuracy of measurements owing to the increase in neutron intensity and to the development of ever more perfect devices.



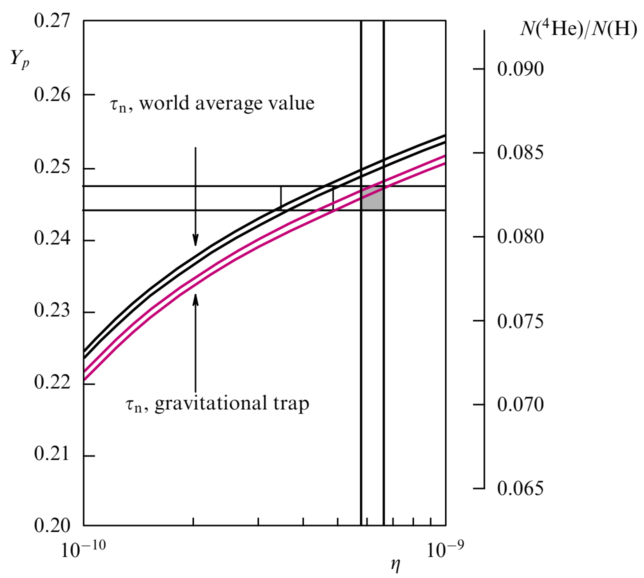


Figure 21. (Color online.) ^{4}He abundance during the Big Bang nucleosynthesis process versus the baryon–photon ratio η in the case of the tabular value of 2004 for the neutron lifetime of 885.7 ± 0.8 s and for the neutron lifetime of 878.5 ± 0.8 s.

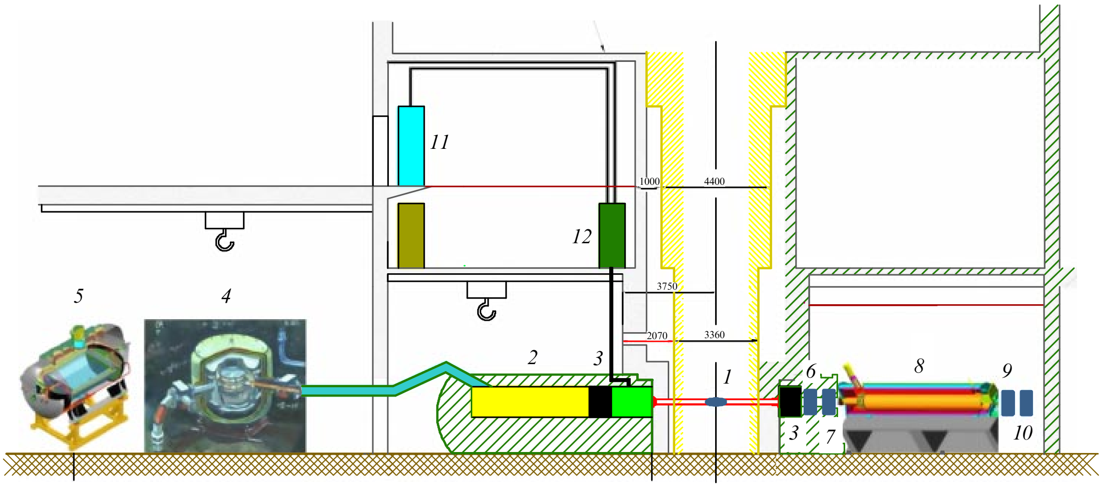


Figure 22. (Color online.) Vertical cut of GEK-4-4′ channel: *1* — source of cold neutrons, *2* — UCN source based on superfluid helium and situated on the extracted beam of cold neutrons, *3* — uncooled bismuth filters that are part of the set of gate valves of the channels, *4* — EDM spectrometer, *5* — gravitational trap for measurement of the neutron lifetime, *6* — cold neutron beam chopper, *7* — neutron beam polarizer based on polarized ^{3}He, *8* — device with a superconducting solenoid for measuring neutron decay asymmetries, *9* — polarization analyzer, *10* — detector, *11* — helium refrigerator for cooling source of cold neutrons, and *12* — liquid-deuterium condenser for the source of cold neutrons.

The GEK-4-4′ channel serves as the basis of the network of experimental devices aimed at investigating fundamental interactions at the PIK reactor. The channel is open-ended; the source of cold neutrons will be situated approximately at the center of the channel (Fig. 22). The UCN source based on superfluid helium will be installed in the extracted beam of cold neutrons from the GEK-4 channel. An experiment is planned to be carried out on the UCN beam to search for the electric dipole moment of the neutron, as is an experiment for measuring the neutron lifetime with a large gravitational trap and a magnetic trap. A polarizer and a neutron beam chopper will be installed in the GEK-4′ channel. Both channels will be equipped with uncooled bismuth filters that are part of the set of gate valves of the channels. A series of studies of neutron decay is planned to be performed with a superconducting solenoid on the beam of cold polarized neutrons in the GEK-4′ channel. The device under development will permit measuring A (electron) and B (neutrino) asymmetries with a relative precision of $(1-2)\times 10^{-3}$ and to measure the neutron lifetime applying the beam method with a proton trap with an accuracy of 1 s. Performing an independent experiment by the beam method is reasonable, permitting the researchers to resolve the contradiction taking shape concerning the method of UCN storage.

At present, several experiments are planned around the world for measuring the neutron lifetime and investigating neutron decay asymmetries, so the PNPI program for the PIK reactor is quite consistent with general developments along this line of inquiry in physics.

2.12 Searching for mirror dark matter in a laboratory experiment with ultracold neutrons

At the beginning of this review, we discussed the symmetry laws of interactions and their relationship to the origination of the Universe. Owing to spatial invariance violation in weak interactions, our world happens to be left-handed. The reason for such inequality of left and right remains unknown. The Standard Model is successful in explaining how weak interaction is arranged, but it gives no explanation as to why the left-handed (V–A) version of the theory was chosen. In theory, if left-handed asymmetry exists, then why can there not also exist right-handed asymmetry, i.e., its mirror image? Such reasoning leads to far-reaching consequences concerning the possible existence of mirror particles, mirror matter, and so on. This reasoning is all the more important in connection with the existence of dark matter in the Universe, which is revealed by the peculiarities of gravitational phenomena and the abundance of which is even 5 times more than that of ordinary matter. For example, a hypothesis has been proposed that dark matter is actually mirror matter, i.e., two worlds (left-handed and right-handed) exist, embedded in each other and interacting with each other only gravitationally, but in no other manner. Thus, global symmetry of left and right is restored. All this reasoning has a long history and was initiated practically at the same time when nonconservation of spatial parity was introduced. The history of this issue is expounded on in detail in the article by L B Okun [65].

The quite high activity in experimental tests of such hypotheses with the aid of neutron studies originated in 2007. The trigger mechanism was the theoretical article by Berezhiani and Bento [66] published in 2006, in which it was pointed out that oscillations between the neutron and the mirror neutron (if it exists) are closed experimentally only down to the level of one second. In 2007, three independent experiments devoted to this issue were performed. The most accurate result was obtained by our PNPI–ILL collaboration [67].

The idea of the experiment is as follows. If the neutron and its mirror partner are exactly degenerate in mass and there are no external fields with which they interact differently, then their energy states are the same and, then, neutron–mirror neutron transitions, or oscillations, are possible. Naturally, it is necessary for these transitions to introduce a certain superweak mixing. So, the conditions for neutron–mirror neutron oscillations consist in the absence of external fields, the existence of a new superweak interaction, and, of course, the existence of a mirror neutron with the same mass.

An ultracold neutron is kept in a trap by reflection from its walls, but, if during its flight from one wall to another, it undergoes a transition to a mirror state, then the mirror neutron will pass through the wall of the trap without interaction and will leave the trap. To provide such transition

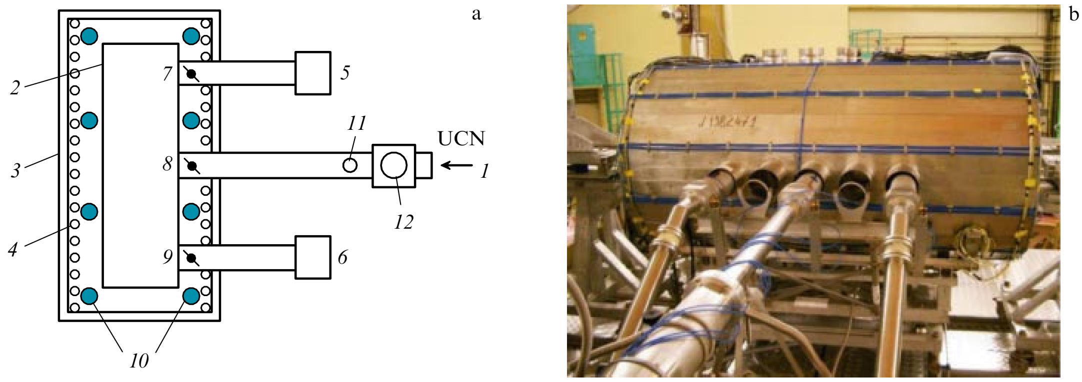


Figure 23. (Color online.) Schematic of a device used in searching for neutron–mirror neutron oscillations (a) and its location on the UCN beam of the ILL reactor (b): *1* — input neutron guide for UCNs; *2* — UCN storage chamber; *3* — magnetic screen; *4* — solenoid; *5*, *6* — UCN detectors; *7–9* — valves; *10* — Cs magnetometers; *11* — monitoring detector, and *12* — input neutron guide.

conditions, the magnetic field must be zero or very small ($< 2 \times 10^{-4}$ Oe), while to suppress transitions it is necessary to switch on a magnetic field of approximately the same value as Earth's magnetic field (0.5 Oe). Thus, the storage time of a neutron in the trap will depend on the magnetic field, if neutron–mirror neutron oscillations exist. By measuring the storage time with an accuracy of 10^{-5} for the cases of 'magnetic field switched on–switched off', one can, for example, set a limit for the oscillation time at a level of 500 s. In our experiment, a magnetic screen and a trap for UCN storage were used (Fig. 23). Measurements were carried out with the UCN beam of ILL, which was prepared by PNPI for the experiment in searching for the neutron EDM. No oscillation effect was revealed, the limit for the oscillation time was 448 s, while the respective limit for the mixing energy was equal to 1.4×10^{-18} eV.

This result partially rejects the hypothesis for the existence of mirror dark matter or of an interaction providing oscillations. But this is the simplest version of the theory with completely degenerate particle masses. If Nature has chosen a more complex version and the particle masses are not degenerate, experimental searches for transitions will be very strongly impeded. In principle, the mass difference can be compensated by the magnetic field. But, since there are no indications of any mass difference, the experimental task reduces to 'searching for a black cat in a dark room with doubts as to whether it is in the room'. Apparently, the problem of nature of dark matter is to be resolved by astrophysical studies.

In conclusion of this section, we would like to mention one more possible use for UCNs in fundamental experiments. It consists in the search for neutron–antineutron oscillations. Transition of a neutron to an antineutron is possible only when there is violation of the law of baryon number conservation. As was already mentioned, baryon number violation is one of the conditions for the formation of the Universe, formulated by A D Sakharov. Investigation of this problem is no less essential than searching for the neutron EDM. At present, there is a limit on the time of neutron–antineutron oscillations equal to 8.6×10^7 s, which was obtained in the experiment with cold neutrons at ILL. Using ultracold neutrons may yield an increase in the experimental sensitivity under the condition of a significant increase (by a factor of $10^2 - 10^3$) in the density of ultracold neutrons. However, the project sensitivity of the new experiment [68] to search for neutron–antineutron oscillations with cold neutrons at the ESS spallation source seems to be the highest possible.

3. Neutrino experiments at the SM-3 reactor

3.1. Creation of a laboratory in search for a sterile neutrino and the first measurements of the reactor antineutrino flux dependence on the distance from the reactor core

At present, the possibility is actively being discussed of the existence of a sterile neutrino, exhibiting a significantly smaller interaction cross section with matter than, for example, electron antineutrinos from a reactor. The assumption made is that, owing to the transition of reactor antineutrinos to a sterile state, the effect of oscillations may be observed at small distances from the reactor and together with the reactor antineutrino deficit at large distances [69, 70]. Moreover, sterile neutrinos are considered to be candidates for dark matter [71].

The ratio between the neutrino flux observed in experiments and the predicted flux is estimated to be 0.927 ± 0.023 [70]. The difference from 1 only amounts to 3 standard deviations. This is not yet sufficient to be confident that a reactor antineutrino anomaly exists. The method for comparing the measured antineutrino flux and the expected flux from the reactor is not satisfactory owing to problems of accurate calculation of the antineutrino flux from the reactor and of the antineutrino detector efficiency.

The idea of oscillations can be tested by direct measurements of the effect of variations in the antineutrino flux and spectrum at short distances from the reactor. The detector must be movable and sensitive to the spectrum. In our experiment, the task to be implemented is to confirm or to reject at a certain level of accuracy the possibility of a sterile neutrino existing. To search for oscillations to sterile neutrinos, it is necessary to register variation of the reactor antineutrino flux. If such a process exists, it can be described by the oscillation equation:

$$P(\tilde{\nu}_e \to \tilde{\nu}_e) = 1 - \sin^2(2\theta_{14})\,\sin^2\left(1.27\,\frac{\Delta m_{14}^2[\mathrm{eV}^2]\,L[\mathrm{m}]}{E_{\tilde{\nu}}[\mathrm{MeV}]}\right), \tag{1}$$

where $E_{\tilde{\nu}}$ is the antineutrino energy, and the unknowns are the oscillation parameters Δm_{14}^2 and $\sin^2(2\theta_{14})$. To perform the experiment, it is necessary to measure the antineutrino flux and spectrum at short distances, for example, 6–12 m, from a practically pointlike source of antineutrinos.

We have examined the possibility of implementing new experiments at Russian research reactors. Precisely research reactors are necessary for these experiments, since they have a compact reactor core and quite a small distance to the possible location of the neutrino detector. Regretfully, the background of neutrons and γ-quanta present in the beam hall of a research reactor is quite high, which significantly complicates the task of carrying out low-background neutrino experiments. The best conditions for performing an experiment in searching for neutrino oscillations at short distances are to be found at the SM-3 reactor owing to certain specific characteristics of its construction. The first preparatory work with the prototype of the neutrino detector was done at the WWR-M reactor and, subsequently, a neutrino laboratory was created at SM-3, the general view of which is shown in Fig. 24 [72–74].

A schematic of the model of the Neutrino-4 detector is presented in Fig. 25. The detector volume of $0.9\times0.9\times0.5\ \mathrm{m}^3$ is filled with a liquid scintillator with admixtures of gadolinium (Gd). Use is made in the detector of 16 PMT-49B photomultiplier tubes located on the upper surface of the detector. The scintillation detector is based on the reaction $\tilde{\nu}_e + p \to e^+ + n$. First, the detector registers the positron, the energy of which depends on the antineutrino energy and two annihilation γ-quanta of energy 511 keV each. The neutron produced in the reaction is absorbed by gadolinium leading to the formation of a shower of γ-quanta with a total energy of about 8 MeV. The detector registers two consecutive signals from the positron and the neutron, respectively — a prompt signal and a delayed one (correlated events). Such a method permits neutrino events to be revealed.

The antineutrino spectrum is retrieved from the positron spectrum, since in the first approximation the relationship between the energies of the positron and the antineutrino is linear: $E_{\tilde{\nu}} = E_{e^+} + 1.8$ MeV. The material of the scintillator is a mineral oil with a Gd admixture of 1 gr l^{-1}. The specific light yield of the BC-525 scintillator amounts to 10^4 photons per MeV. The detector is surrounded by six $0.9 \times 0.9 \times 0.03$-$\mathrm{m}^3$ scintillation plates with PMTs that serve as an active (anticoincidence) shielding against cosmic muons. After test experiments were carried out at the WWR-M reactor, the investigation of the neutrino detector model was transferred to the SM-3 reactor, where the neutrino laboratory hall and the passive shielding of the detector had already been prepared [74].

Figure 24. (Color online.) General views of the passive shielding on the inside and on the outside. The range of shifts of the detector within the neutrino channel amounts to 6–12 m from the reactor core.

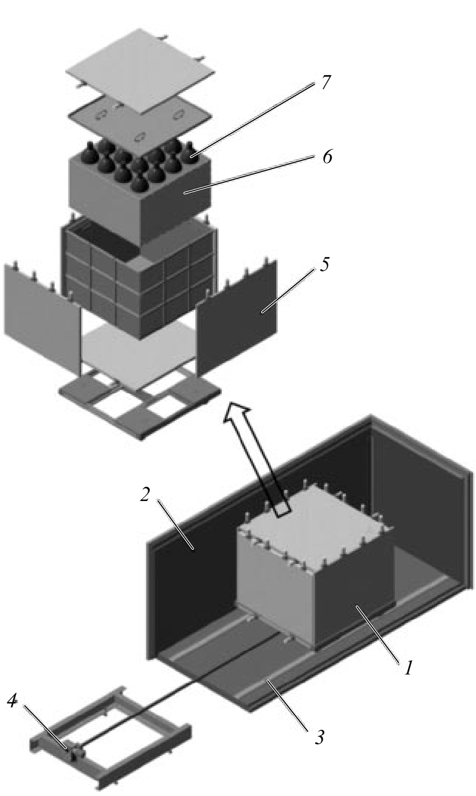


Figure 25. Schematic of a detector: *1* — detector of reactor antineutrinos, *2* — passive shielding from lead (6 cm) and borated polyethylene (16 cm), *3* — rails, *4* — device for shifting the detector, *5* — plates of the active shielding, *6* — liquid scintillator, and *7* — PMT.

The procedure for recording and processing signals was the following. Signals from the neutrino detector and the plates of the active shielding were recorded in a real-time mode. The signal shapes were digitized in steps of 15 ns. In event selection, the current signal from the neutrino detector was chosen to be within a given energy interval (by its amplitude), and a check was made for the absence of restrictions from the active shielding, i.e., for the absence of signals coinciding in a time window of 100 ns. The delayed signals were also chosen to be within their given energy interval. Moreover, restrictions were imposed on all signals from the detector exceeding a given level or arriving after the signal from the active shielding. Such restrictions turned out to be useful for suppression of events related to the cosmic background.

The number of registered neutrino events was determined experimentally as the difference between the numbers of correlated signals, when the reactor was switched on and when it was switched off. The dependences of the reactor antineutrino fluxes on the distance from the reactor core were extracted from the difference between these data and are presented in Fig. 26.

From these test measurements performed with the neutrino detector model, it is possible to draw the following conclusions.

(1) An attempt was made for the first time to measure the flux of reactor antineutrinos at short distances (6–11 m) from the reactor core. Naturally, the measurement accuracy was insufficient for making any conclusions concerning formula-

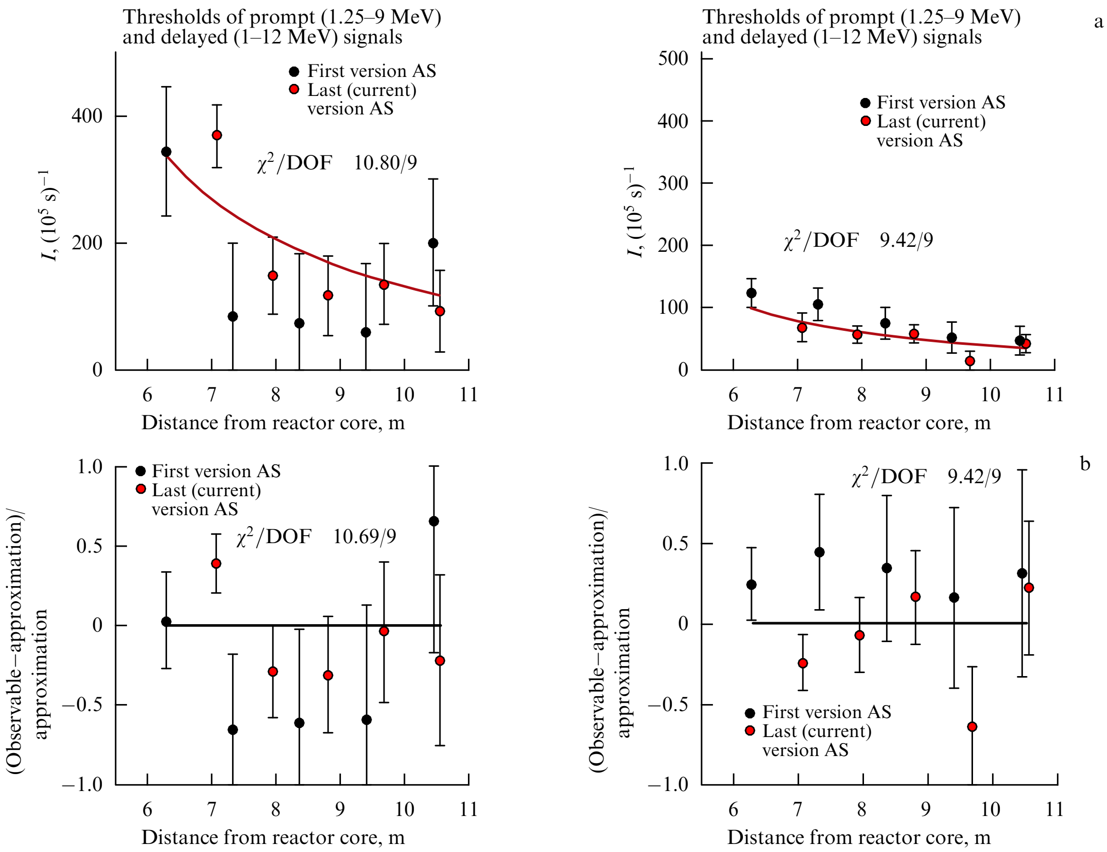


Figure 26. (Color online.) (a) Left panel — dependence of the difference between counting rates of correlated events (reactor switched on — reactor switched off) on the distance from the reactor core for prompt signals in the energy window of 1.25–9 MeV and for delayed signals of 1–12 MeV; right panel — the same for energy intervals of 3–9 MeV and 3–12 MeV. (b) The same data processes for revealing deviations from the $1/R^2$ law.

tion of the problem of searching for a sterile neutrino. The given task was only to examine the possibility of performing such an experiment on Earth's surface given the cosmic background level and the background level related to operation of the reactor. In the experiment, a detector prototype of a small volume was used.

(2) The main problem of this experiment was related to the correlated background due to cosmic radiation. The cosmic ray background depends on the distance from the reactor core owing to the structure in the arrangement of concrete block masses of the building. Moreover, the cosmic background changes with time owing to oscillations in the atmospheric pressure and temperature of the lower layers of the atmosphere. However, the following methods can be proposed for overcoming these difficulties. First, monitoring can be performed of the cosmic ray intensity in the high-energy part of the detector spectrum, starting from 10 MeV. Second, measurements of the distance dependences must be carried out by the method of scanning over the distance. This permits a significant smoothing of the effect of cosmic ray variations in time.

(3) The use of active shielding only permits suppressing the correlated background of cosmic radiation by 66%. Most likely, this is the part of the background related to muons. It can be controlled by the active shielding. The neutron component is not really controlled by the active shielding, so it is necessary to apply the method of identifying signals from recoil protons and from positrons by their pulse shapes.

The work done has provided sufficient information for the development of a full-scale detector. At present, the design of a full-scale detector with a total volume of 3 m^3 has been completed. We believe that realization of the project and the method of identifying signals from recoil protons and positrons by pulse shapes will bring the effect–background ratio closer to unity and will significantly enhance the statistical accuracy of the experiment, allowing studies related to the search for oscillations at short distances to start.

4. Conclusion

In concluding this review, we would like to repeat that methods of precision research and of finding small deviations from the Standard laws of physics allow obtaining information on fundamental interactions and successfully competing with investigations at colliders. Examples of such research are presented in this work. Realization of an experiment in search for the neutron EDM with a precision of 10^{-27} e cm and in search for reactor antineutrino oscillations with a precision of several percent at distances of 6–12 m from the reactor core is quite essential for the physics of fundamental interactions.

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