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Study of Fundamental Interactions with Use of Ultra Cold Neutrons at PNPI and ILL

A.P. SEREBROV[1]

[1]*B. P. Konstantinov Petersburg Nuclear Physics Institute of National Research Centre "Kurchatov Institute," 188300 Gatchina, Leningrad region, Russia*
[2]*Institut Max von Laue – Paul Langevin, BP 156, 38042 Grenoble Cedex 9, France*
[3]*Ioffe Physical Technical Institute RAS, 194021 St. Petersburg, Russia*

serebrov@pnpi,spb.ru

On behalf of the PNPI[1]-IIL[2]-PTI[3] Collaboration

Abstract. Neutrons of very low energy (~10^{-7} eV), which are called ultracold, have a unique property: they can be stored in material and magnetic traps. This phenomenon gives new methodical opportunities for carrying out precision experiments and studying of fundamental questions of physics. One of the most important problems of physics is violation of time invariance which is directly connected with emergence of the Universe. Experiments on search of the electric dipole moment of a neutron, other than zero, are the test for violation of time invariance, and a method of ultracold neutrons provides very high precision of measurements. Precision measurements of neutron lifetime by means of ultracold neutrons are extremely important for test of model of formation of the Universe at its early stage. This article is devoted to experimental investigations with ultracold neutrons at PNPI and ILL. Results and research perspectives are under discussion.

Standard model (SM) in physics of elementary particles is a theory successfully describing their interactions. However, Standard model fails to account for symmetry violation between matter and antimatter. In the Universe, everything is made up of matter and there is almost no antimatter at all. At now the theory of supersymmetry is the most used, within the framework of which the so-called CP-symmetry or time invariance is violated in such a way, that it can interpret baryon asymmetry of the Universe. Experiments on search of the electric dipole moment, other than zero, are the test of time invariance violation, with the ultracold neutron method providing a very high precision of measurements. One and the same mechanism of CP-symmetry violation is responsible for creation of neutron EDM and baryon asymmetry of the Universe, thus, neutron research makes it possible to study, how the asymmetry arose during baryogenesis at the stage of Universe emergence. Moreover, precision measurements of the neutron lifetime with ultracold neutrons (UCN) are extremely important for testing the theory of Universe formation at its early stage.

It is to these two particular tasks that investigations carried out at PNPI are devoted. They were started in the 70-s. Here were elaborated UCN intensive sources with liquid hydrogen moderators in the reactor core [1, 2] with a magnetic resonance spectrometer designed for search of the neutron EDM [3]. In recent years these investigations have been continued at ILL.

Neutron EDM

Ultra cold neutrons can be stored in traps made, for the tens and hundreds of seconds, of substance with a high boundary velocity. In view of this effect, one can sufficiently increase energetic resolution of a magnetic resonance spectrometer for search of the neutron EDM.

The first results of experiments on search of neutron EDM by UCN method were obtained in 1980 at PNPI (Gatchina, Russia) [3, 4], and then at ILL (Grenoble, France) [5, 6]. The first limit on the neutron EDM, obtained with UCN in Gatchina, was $|d_n|<1.6\cdot10^{-24}e\cdot cm$ (90% C.L.). By 1981 the result obtained in Gatchina was improved: $|d_n|<6\cdot10^{-25}e\cdot cm$ (90% C.L.) [4]. In the 1990-s both groups succeeded in reaching the EDM limit of $\sim1\cdot10^{-25}e\cdot cm$ (90% C.L.) [6-9]. At this stage the measurements, which carried out in Gatchina, were stopped, because of exploitation of the UCN source was finished. While in Grenoble the collaboration of RAL/Sussex/ILL continued measurements and after about 10 years the limit on the neutron EDM was been lowered to 3 times [10]. In this work the best constraint on the value of the electric dipole moment of neutron for present time was obtained $|d_n|<2.9\cdot10^{-26}e\cdot cm$ (90% C.L.).

In 2008, the PNPI EDM spectrometer was installed on the beam of UCN PF2 MAM of the reactor of ILL. The work was performed by collaboration of PNPI-ILL-PTI. In 2013 the collaboration could reach limit on neutron EDM $|d_n|<5.5\cdot10^{-26}e\cdot cm$ at 90% confidence level [11, 12]. The result of this work is, to some extent, weaker that achieved in the work [10], however, it was obtained at the methodically different experimental installation. We make use of a magnetic resonance spectrometer with two UCN storage chambers, with a common constant magnetic field and oppositely directed electric fields into the volumes of neutron storage. This experimental scheme provides a principally new possibility to control systematic errors. In the course of conducting measurements at the attained precision level, we did not find any systematic effects.

Accuracy of the result, recently obtained by collaboration of PNPI- ILL- PTI $|d_n|<5.5\cdot10^{-26}e\cdot cm$, is expected to be approximately 3 times higher owing to utilize the more intensive beam of UCN PF2 EDM and a new scheme of the spectrometer. The main opportunity for increasing precision up to the level of $|d_n|<5\cdot10^{-28}e\cdot cm$ is concerned with application of the UCN source elaborated at the WWR-M reactor.

At present, employing UCN for the EDM experiment remains the most promising direction. At considerable enhancement of intensity of the UCN source, sensitivity of the installation will be also increased, thus perspectives of developing EDM experiment are associated with designing a new generation of UCN sources. Tasks solved in the EDM experiment have given a decisive impetus to elaborating a new technology for producing ultracold neutrons. The existing UCN sources do not allow to hope for significant improvement of the already achieved result. Now work on creating new sources of ultracold neutrons is under way in several foreign scientific centers: ILL (France), LANL (USA), PSI (Switzerland), TUM (Germany). The aim of PNPI project is to elaborate UCN sources of high intensity on superfluid helium (Gatchina, Russia) at the operating WWR-M reactor [13]. Moreover, UCN sources are supposed to be built at the reactor PIK under construction [14]. The calculated density of UCN for these sources is by 2-3 orders of magnitude higher than that in the existing ILL source. The creation of such sources will enable to achieve precision of EDM neutron estimations at the level better than $10^{-27}e\cdot cm$, as shown in Fig. 1.

Fig. 1 illustrates chronology of decreasing the upper limit by the neutron EDM value in the experiments carried out in Gatchina and Grenoble and shows further projects for development at the reactor WWR-M in Gatchina.

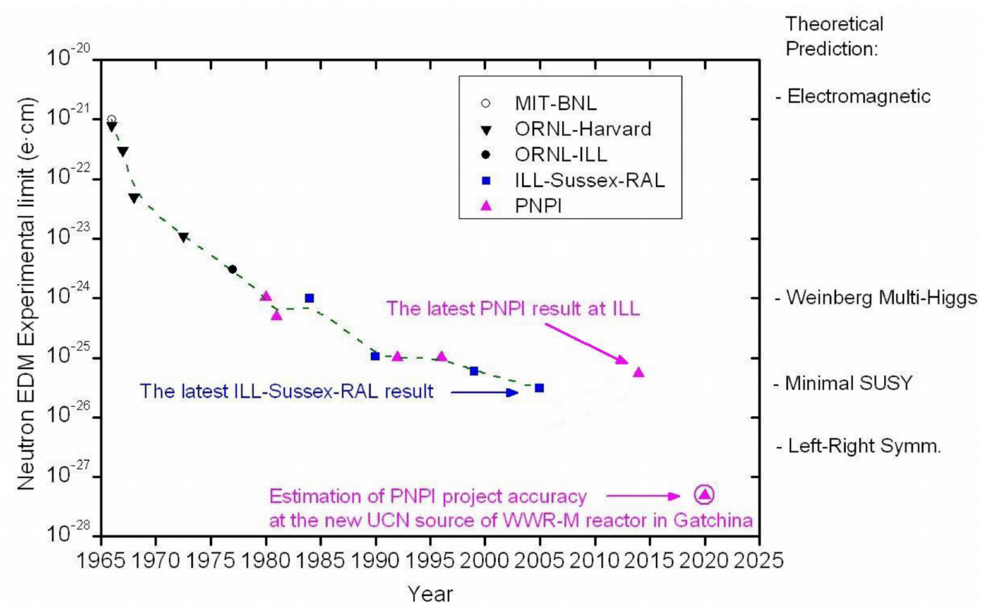

FIGURE 1. History of lowering the experimental limit on the neutron EDM and perspectives of the accuracy increase

Neutron Life Time

In the Standard Model of elementary particles, quark mixing described by the matrix of Cabibbo-Kobayashi-Maskawa (CKM), which should be unitary, indicating completeness of our understanding the number of quark and lepton generations. A module of the matrix element V_{ud} can be derived from the decay of neutron. Precision measurements of the neutron lifetime are also extremely important to test the model of formation of the universe in its early stages, determining the number of neutrino types.

There are two methods of measuring the neutron lifetime: method of UCN storage in the trap and method of products registration of the neutron decay on the beam of cold neutrons.

Analysis of the two techniques has shown discrepancy to be 3.3 standard deviations [15]; after publishing the paper [16] discrepancy increased up to 3.9 standard deviations [17]. The difference between techniques lies in the fact that in a beam experiment, only one neutron decay mode with emitting protons is estimated, while at UCN storage all possible channels resulting in disappearance of a neutron are taken into account. At the present, neutron lifetime measured with the UCN storage is approximately by 4 standard errors less [16] than that estimated in the beam experiment. Though, the most probable interpretation of this fact is systematic error being made in a beam experiment, one cannot guarantee a systematic error to be avoided in an experiment with UCN. Thus, an experiment with UCN storage is supposed to be upgraded.

At present at PNPI a new more precise experiment has been elaborated to measure the neutron lifetime in a material trap. In this setup the principle of gravitational valve is used to hold UCN in a material trap. The UCN storage volume in a new trap is approximately 4 times bigger than that in the previous one. In addition to this, the setup is equipped with an insert which lifted and putted into trap without opening up the installation. This enables not only to eliminate systematic errors but also to raise essentially statistical accuracy of experiment. Accuracy enhancement will make it possible to resolve the discrepancy between different techniques, aimed at measuring the neutron lifetime, i.e. the neutron beam method and the UCN storage one.

Projects of Construction of High Intensity UCN Sources at PNPI

As already mentioned, at PNPI various sources of UCN were developed. In Fig. 2 a general layout of the development of UCN sources, the contribution of PNPI in this process are shown, as well as a new project of the UCN source at the WWR-M reactor based on utilize of superfluid helium as converter of cold neutrons in UCN is presented.

The project of UCN source for the WWR-M reactor was proposed in 2006 [13, 18-20]. The WWR-M reactor at PNPI provides quite suitable conditions for solving a task of compromise between the level of thermal flux and the flux of neutron, as it has a thermal column. The thermal column is a channel of a large diameter (1 m), which abuts to the reactor core. Such diameter of the channel enables to locate a powerful lead shielding protecting from a reactor core γ-radiation and to place a graphite moderator with a liquid deuterium pre-moderator at temperature 20 K for producing cold neutrons, as well as the UCN source itself based on superfluid helium at temperature 1,2 K.

At present PNPI has elaborated a project of UCN source for the WWR-M reactor. There have been made detailed calculations with the MCNP program, which show that the source with a lead shielding will release 15 kW which is easily removed by a circulating flow of water. A liquid deuterium moderator will be cooled by passing gaseous helium at temperature 20 K. Finally, the most essential point is that the source with superfluid helium is to release 19 W. Such a power at the level of 1,2 K can be removed using accessible cryogenic devices. The Monte-Carlo calculations of UCN density show that in an experimental installation (for instance, in the EDM spectrometer trap) UCN density $\sim 1\cdot 10^4 n/cм^3$ [13,18-20] is to be obtained. It means that the gain factor with respect to the UCN density in Grenoble will be 1000 times. In view of this, we will be able to make considerable progress in fundamental research with UCN. Fig. 2 illustrates development of sources of ultracold neutrons in the world.

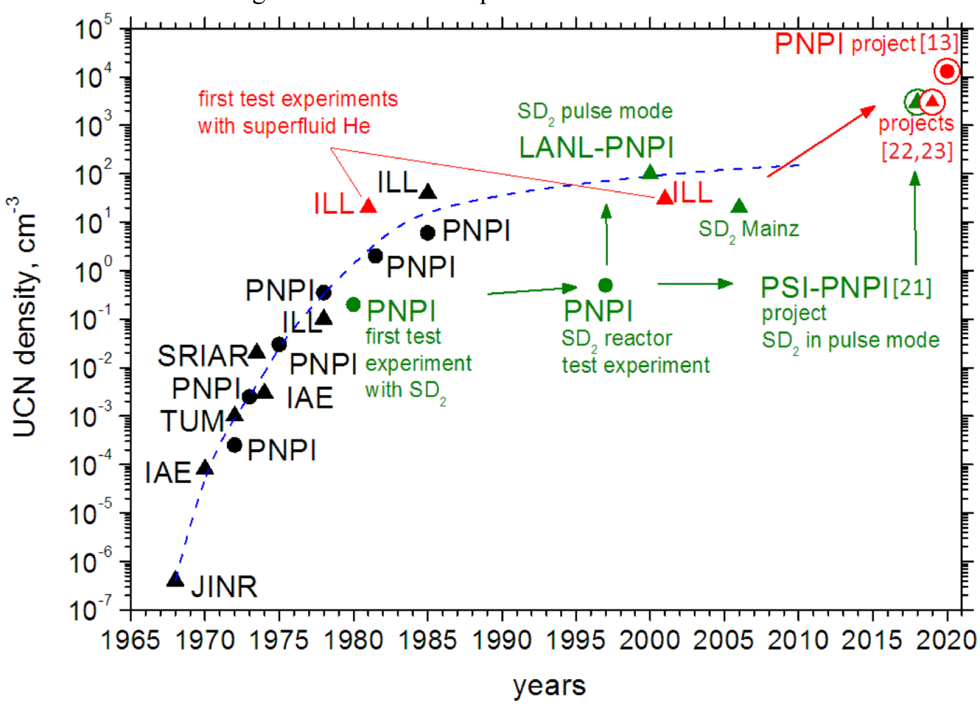

Figure 2. Progress in development of UCN sources is shown. The final point of this diagram is related to the project parameters of a new source, based on use of superfluid helium, at the WWR-M reactor of PNPI, where possible density of UCN in the EDM spectrometer trap is shown

Concluding this article, it is worth emphasizing that methods of precision measurements and those for search of small deviations from the Standard laws of physics make it possible to obtain information on fundamental interactions and successfully compete with investigations performed with the colliders. Examples of such research are given in the present paper. Realization of experiments on search for the neutron EDM with accuracy of $1\cdot 10^{-27}\, e\cdot cm$ is of principle significance for physics of fundamental interactions.

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