Available online at www.sciencedirect.com

ScienceDirect

Physics Procedia 17 (2011) 251–258

Physics Procedia

Physics of fundamental Symmetries and Interactions - PSI2010

SUPERSOURCE OF ULTRACOLD NEUTRONS AT WWR-M REACTOR IN PNPI AND THE RESEARCH PROGRAM ON FUNDAMENTAL PHYSICS

A.P.Serebrov*[1], S.T. Boldarev[2], A.N. Erykalov[1], V.F. Ezhov[1], V.V. Fedorov[1], A.K. Fomin[1],
V.A. Ilatovskiy[1], K.O. Keshyshev[2], K.A. Konoplev[1], A.G. Krivshitch[1], V.I. Marchenko[2],
V.A. Mityuklyaev[1], M.S. Onegin[1], S.P. Orlov[1], V.M. Samsonov[1], A.A. Zakharov[1]

[1] *Petersburg Nuclear Physics Institute, RAS, 188300, Gatchina, Leningrad District, Russia*
[2] *P.L. Kapitza Institute for Physical Problems, ul. Kosygina, 2, Moscow 119334, Russia*

Abstract

On the basis of the working research WWR-M reactor at PNPI there is being built a highly intensive source of ultracold neutrons (UCN) and very cold neutrons (VCN) for scientific research in fundamental physics and investigation of nanoparticles. The source will use superfluid helium that will allow us to obtain the density of ultracold neutrons of 10^4 cm^{-3}, which approximately 1000 times exceeds the available density of ultracold neutron at existing UCN sources.

Selection and/or peer-review under responsibility of the Organising Committee of the 2nd International Workshop on the Physics of fundamental Symmetries and Interactions

Keywords: ultracold neutrons; superfluid helium; deuterium premoderator; reactor; EDM of neutron.

1. Introduction

The creation of a UCN source based on superfluid helium and intensive beams of ultracold and very cold neutrons [1] on its basis will provide a unique possibility of investigating such fundamental interactions as search for the electric dipole moment (EDM) of the neutron with in view of testing the problem of CP-violation, or the high-precision investigation of neutron β-decay in order to test the Standard Model of elementary particles and interactions. Both tasks are of primary importance for the physics of elementary particles and for cosmology. They are aimed at searching for the possibly existing new superparticles in processes right after the Big Bang. To a great extent this research touches upon problems to be studied by physicists using modern high-energy colliders in expensive experiments. In this case, the possibility of solving so significant problems arises by virtue of the high measurement precision possible due to the high density of ultracold neutrons obtained with a new source based on superfluid helium.

Investigation of fundamental interactions in the world of elementary particles is an essential task for our understanding of origin and formation of the Universe. In particular, the task of the experimental search for an electric dipole moment is one of the most important in fundamental physics. It has been investigated for more than fifty years, the latest and most considerable achievement in investigating this problem was the development of the technique using ultracold neutrons.

---

* Corresponding author:Tel.:+781371 46001; fax: +781371 30072.
E-mail address: serebrov@pnpi.spb.ru.

Selection and/or peer-review under responsibility of the Organising Committee of the 2nd International Workshop on the Physics of fundamental Symmetries and Interactions
doi:10.1016/j.phpro.2011.06.044

The current limit on the electric dipole moment (EDM) of the neutron is $3 \cdot 10^{-26} e \cdot cm$ [2], which is the result of the united efforts of many experimental teams. Nevertheless, for the time being, increase of the sensitivity of EDM experiments is more urgent than ever. The Standard Model fails to account for the baryon asymmetry of the Universe that originated during the early stage of its formation due to either a CP violtating mechanism or T-violation. As an alternative, there are supersymmetry theories. Within their framework baryon asymmetry of the Universe can be interpreted. Thus, an experimental finding of an EDM of the neutron could confirm supersymmetry theories with CP-violation. On the other hand, failure in finding an EDM of the neutron will support the idea that the probability of detecting supersymmetric particles with a supercollider LHC in CERN is being reduced.

The increase in intensity of ultracold neutrons will allow to increase 100 times the sensitivity for finding an electrical dipole moment of the neutron and hence might contribute to the major problem of the origin of the Universe.

2. Supersource of ultracold neutrons at WWR-M reactor

The supersource of ultracold neutrons at the WWR-M reactor represents a new generation of techniques as for the first time superfluid helium has been used for obtaining a beam of ultracold neutrons of high intensity within a reactor.

Superfluid helium is a remarkable quantum liquid with amazing properties of superfluidity and thermal conductivity. Not less surprising, however less known, are specific characteristics of interaction of superfluid helium with neutrons. Superfluid helium possesses an enormous transparency for low energy neutrons [3].

The essence of the matter is simple enough. Landau's famous curve, combining energy and momentum of excitations (phonons, rotons) in superfluid helium intersects the curve $E = p^2 / m$ for free neutrons at the same point. This point corresponds to the excitation energy (in temperature units) 12 K. It means that UCN can absorb only a phonon with energy 12 K. In practice there are no such phonons at the temperature of superfluid helium 1 K, as the corresponding Boltzmann factor is an exponent to the power of -12. It provides an explanation for the extremely high transparency of superfluid helium for UCN. Actually, UCN can "live" in superfluid helium until phonon absorption for tens to hundreds of seconds. UCN "are born" in helium by cold neutrons with wavelength of 9 Å, corresponding to a temperature of 12 K, which is equal to the phonon energy, i.e. a cold neutron excites a phonon and practically stops itself, hence becoming an ultracold one. Cold neutrons penetrate through a trap wall while ultracold ones are reflected, resulting in the effect of accumulation of UCN up to the density determined by the storage time in a trap with helium [4].

Experiments on accumulating UCN in traps with superfluid helium have been successfully performed using beams of cold neutrons [5, 6]. The UCN density obtained with superfluid helium on the beam is comparable with that of UCN obtained from the source of the reactor. Divergence of the neutron beam is extremely small with respect to 4π. In collecting UCN emitted in 4π one can gain 3-4 orders of magnitude in intensity. The following questions arise: In what radiation conditions can the UCN source with superfluid helium operate? What power can be removed at a temperature level of about 1K? It is known that one can remove kilowatt power from superconducting magnets at the temperature of 1.8 K. Such installations are bulky and of high cost. We can set ourselves the task of obtaining the cooling power of 20 watts at a temperature of 1.2 K. In this case the task is solved using an available helium liquefier producing 50 liters per hour and the vacuum system of pumping out the helium vapours to get the temperature of 1.2 K. For the problem to be solved successfully one should find some compromise between the level of heat release and neutron flux.

At the WWR-M reactor the conditions for solving this task are quite suitable. There is a thermal reactor column, which represents a channel with a big diameter (1 m), adjacent to an active reactor core. Such a big diameter enables us to arrange an efficient lead protection from γ-radiation of the active reactor core and a liquid deuterium premoderator at 20 K to obtain cold neutrons, and finally, the source of UCN itself on superfluid helium at a temperature of 1.2 K.

At present, the density of UCN used in experiments is 10-40 n/cm^3 [7]. At the same time there is progress on design and construction of new UCN sources based on solid deuterium at the temperature of 4.5 K (LANL, USA; PSI, Switzerland, FRMII TUM, Germany), as well as on the effect of accumulation of UCN in superfluid helium (KEK-RCNP-TRIUMF, Japan-Canada; ILL, France). Obtaining a density of UCN equal to 10^3 n/cm^3 is the goal. Our project aims at obtaining a density of UCN equal to 10^4 n/cm^3, one order of magnitude exceeding that in existing projects and either 100 or 1000 times higher than the present available UCN density.

The world progress as far as the density of UCN is concerned, is shown in Fig. 1. The top right point in the picture is related to the project parameters of the new source project at the WWR-M reactor at PNPI based on using superfluid helium.

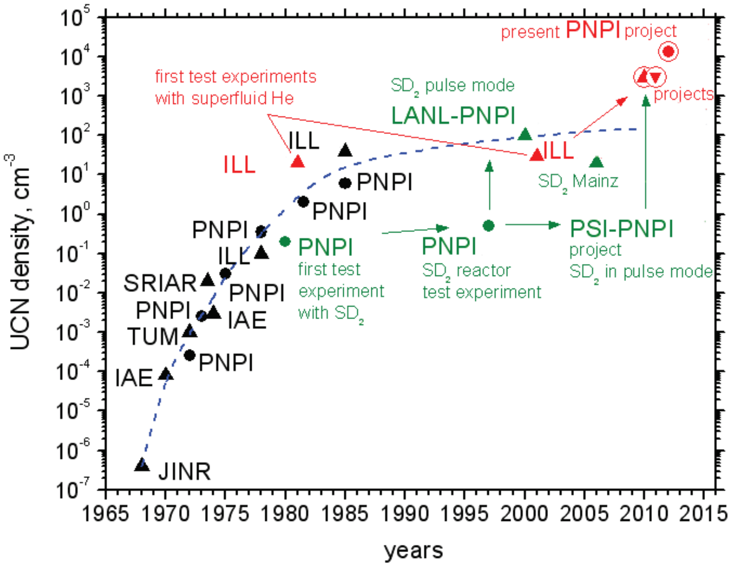

Fig. 1: World progress on achieved UCN densities over the last decades.
▼ - UCN source project based on solid deuterium at PSI,
▲ - UCN source project based on superfluid helium at ILL,
◉ - UCN source project based on superfluid helium at the reactor WWR-M, PNPI.

Fig 2. gives the location scheme of the source in the vicinity of the active reactor core showing the results of estimations on neutron flux and energy release in the material of the source. The heat release in the source with superfluid helium is expected to be equal to 19 watts [8]. Fig. 3 shows the source cooling scheme allowing to solve the problem of heat removal and keeping the temperature at 1.2 K under conditions of radiation heat release [9].

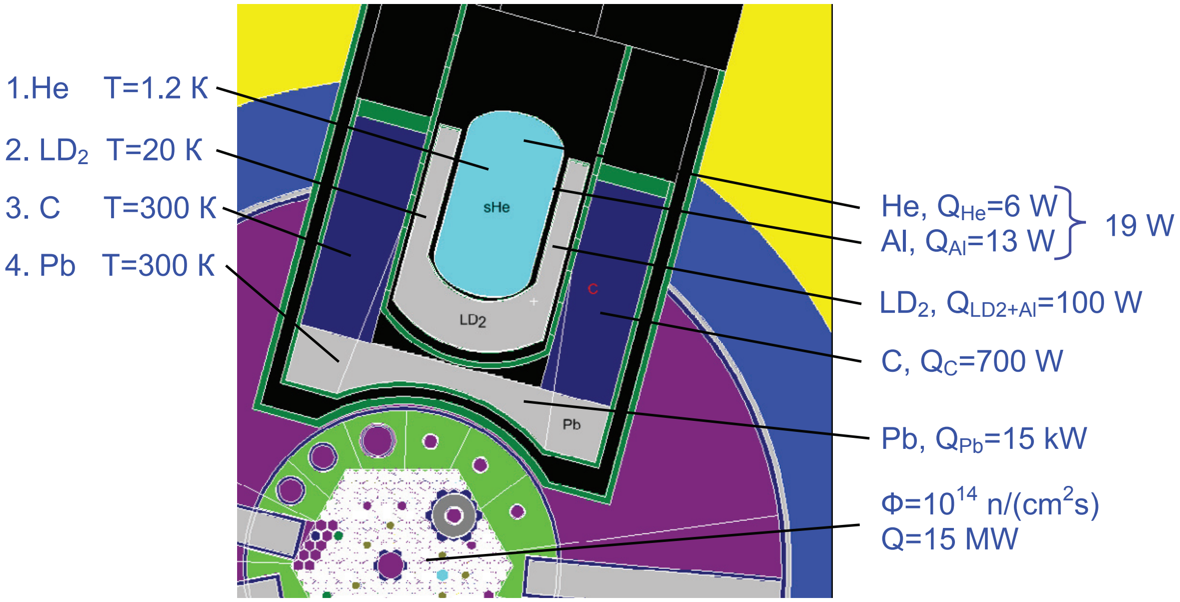

Fig. 2: The main location scheme of the UCN source in the thermal column of the WWR-M reactor.
1 – chamber with superfluid helium @1.2K, 2 – liquid-deuterium premoderator @20K; 3 – graphite reflector @300K, 4 – lead shielding.

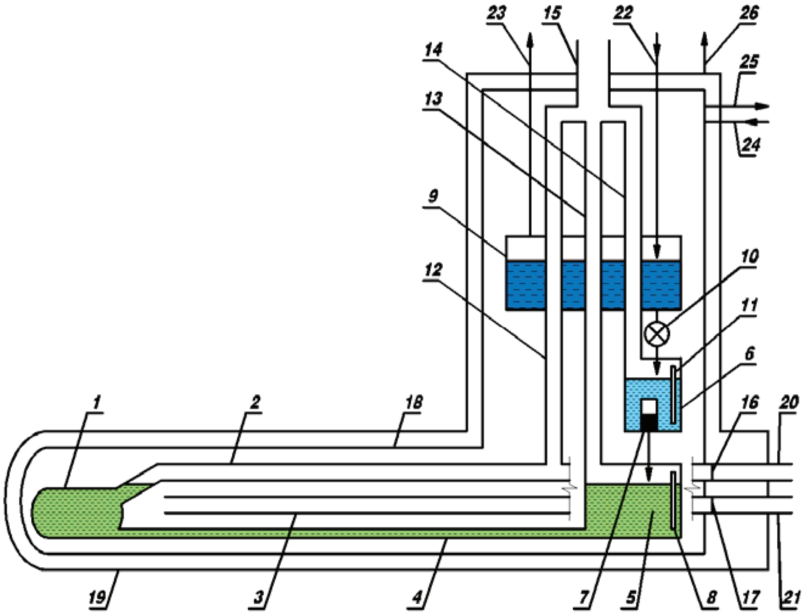

Fig. 3: The main scheme of low temperature unit of the source.
1 – source chamber, 2 – neutron guide UCN, 3 – neutron guide CN, 4 – pipe of filling the chamber, 5 – lower bath @ 1.2 K, 6 – middle bath @ 1.2 K, 7 –filter $_3$He, 8 –detector of liquid level in the lower bath, 9 –upper bath @ 4.2 K, 10 – valve of feeding helium into the middle bath, 11 – detector of liquid level in the middle bath, 12 – pipeline of vacuum pumping out the chamber (gravitational lock of UCN), 13 – pipeline of vacuum pumping out the lower bath, 14 – pipeline of vacuum pumping out the middle bath, 15 – general pipeline of pumping out, 16 – membrane of UCN neutron guide, 17 – membrane of CN neutron guide, 18 – thermal screen @ 20 K, 19 – vacuum enclosure, 20 – external UCN neutron guide, 21 –external CN neutron guide, 22 – filling of an upper bath with liquid helium @ 4.2 K, 23 — removal of helium vapours, 24 – feeding of gaseous helium for cooling the thermal screen 18, 25 – removal of gaseous helium from the thermal screen 18, 26 – pumping out of a vacuum enclosure.

PNPI has designed a few cold neutron sources for reactors in Hungary and in Holland. Recently a liquid- deuterium source for cold neutron production has been installed on a new reactor in Sydney by PNPI. Some work is in progress on the installation of a cold neutron source at a new reactor in China. The Paul Scherrer Institute constructed and presently puts into operation an ultracold neutron source where PNPI contributed in its original proposal.

At present PNPI has done the following:

1. It has elaborated the project of UCN on superfluid helium.
2. It has made measurements in the thermal reactor column showing real possibilities for its up-grading [10].
3. It has made detailed estimations of density of UCN at the outlet of neutron guides [11].
4. It installed low-temperature helium refrigerator of 3 kilowatt power at temperature 20 K.
5. It is assembling a helium liquefier producing 50 liters per hour.
6. It purchased and is assembling the facilities for pumping out helium vapours.
7. It has worked out a project for dismounting the thermal column.
8. It has elaborated a design for storing radioactive elements of thermal column.
9. It has been preparing an experimental equipment for scientific research.

3. Construction of experimental facilities for the investigation of fundamental interactions

Upgraded double chamber neutron EDM spectrometer at PNPI [12].

The main experimental scheme remains the same as [13]: a differential magnetic-resonance spectrometer of accumulating type with the system of dynamic resonance stabilization and double analysis of neutron polarization.

The modification of the installation is directed towards improving the quality of its different joints in order to minimize losses and to increase the time of neutron storage, to decrease magnetic noises and to create more stable resonance conditions, as well as to designing the monitoring system of the average magnetic field in the resonance volume. It will be reasonable to start measurements at the new source using the modernized double chamber EDM spectrometer. It will enable us to make the measurement precision 10 times higher.

Multichamber EDM spectrometer [14].

The new scheme of the spectrometer has a number of advantages over that of the previous EDM spectrometer at PNPI and the PNPI EDM spectrometer at ILL. Estimations show that using UCN at the density to be attained by a new source at PNPI the limit on EDM can be 100 times reduced. Not only does a multichamber scheme of the spectrometer allow to increase the installation sensitivity, but it also gives the possibility of comprehensive control of systematic errors in the course of the experiment. Besides its being a multichamber, a remarkable feature of the new scheme is a new way of creating the polarization of UCN and its analysis. At present, a model of the multichamber spectrometer has been developed and the design of a full-scale spectrometer will be corrected following the results of its testing.

The crystal diffraction technique of neutron EDM search [15].

The method concerned is based on applying interatomic electric fields, acting on diffracting neutrons in a noncentersymmetric crystal in search for a neutron EDM. The magnitude of these fields is 4-5 orders higher than electrical fields created under laboratory conditions and is likely to be as high as 1GV/cm. It is known that the sensitivity of the approach to the EDM of a neutron measurement is determined by the product of the value of the electric field and the time of the neutron staying in this field. In spite of the fact that the time of the neutron flight through crystal is considerably less than the time of UCN storage for really existing quartz crystals, the accuracy of the crystal diffraction approach is likely to exceed the present precision on the neutron EDM and could be as high as ~(4-6)10^{-27} e·cм. Application of other crystals such as PbO or Bi_{12} SiO_{20} , can increase the sensitivity by at least one order of magnitude. This alternative measuring technique is extremely important for the reliability of the scientific results.

The construction of a highly intensive source of cold and ultracold neutrons will enable to conduct neutron experiments within a wide range of wavelengths. In addition to the experimental hall for working with thermal neutrons halls for working with ultracold neutrons, very cold neutrons and cold neutrons will be built at the WWR-M reactor. Fig 4 shows the layout for the experimental halls of cold and very cold neutrons which can be used for this purpose within the reactor building itself.

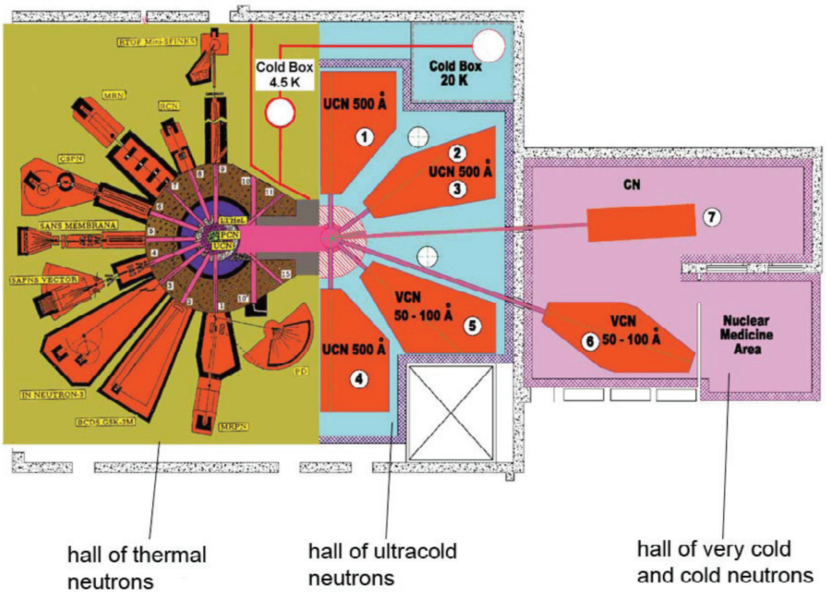

Fig. 4: Experimental halls of the WWR-M reactor.
1,2,3,4 – installations for fundamental research on ultracold neutrons, 5 – diffractometer of very cold neutron, 6 – spectrometer of very cold neutron, 7 – installations for fundamental research with cold neutrons.

Precision experiment for measuring asymmetries of β -decay of neutrons using a superconducting solenoid [16-19].

We suggest applying a polarized beam of cold neutrons and an axial magnetic field in the shape of a bottle created by a superconducting solenoid [16-19]. Such a configuration of the magnetic field permits to isolate the neutron decay electrons and to determine the solid angle with high precision. An electrical static cylinder with 25kV potential determines the area where decays can be detected. Protons escaping from this area are accelerated and then detected by a proton detector. Using coincidences between electron and proton signals enables the background to be considerably suppressed.

The asymmetry of the electron momentum with respect to the neutron spin is measured via the alteration of the sign of the neutron beam polarization. The final accuracy of the decay asymmetry will be determined by the accuracy of the polarization measurements $(1\div2)\cdot10^{-3}$.

An installation for precise measuring the neutron life-time by storing UCN in a gravitational trap.

The construction of a new installation («Big gravitational trap») will enable us to enhance 5 times the statistical precision of measurements and to attain a precision of 0.2 sec. The important fact is that experimental techniques have already been developed and a very small loss factor equal to 1% of the neutron decay probability has already been obtained. Using the new UCN source, the statistical precision of measurements will be enhanced by an order of magnitude.

An installation for precise measuring the neutron life-time by storing UCN in a magnetic trap.

PNPI has designed an experiment for measuring the neutron lifetime by storing UCN in a magnetic trap, in which reflection of UCN from the walls occurs due to the magnetic field gradient. The experiment permits the depolarization process to be controlled because in the case of covering the walls with fomblin the neutrons, which changed their magnetic moment direction with respect to the magnetic field, are not absorbed and after a few collisions with the walls they enter into a neutron guide and are registered with a detector.

Such an alternative technique of making measurements is extremely important for the reliability of scientific results.

4. Long-term investigations

A new generation of high density UCN sources will provide us with the opportunity to make considerable progress in fundamental research. The application of new beam techniques might improve the precision of neutron EDM measurements by two orders of magnitude and will test the predictions of supersymmetric theories which are possible versions of Standard Model extentions. Within the framework of these theories a neutron EDM is predicted on a level accessible for long-term experiments, at the same time assuming the baryon asymmetry of the Universe on the observed level. This could imply the possible correctness of the proposed versions of the theory.

Using the new source of ultracold neutrons at PNPI a precision of $2\cdot10^{-28}$ e · cм is likely to be attained. Fig.5 shows the development over the years of the neutron EDM searches and the possible sensitivities of future installations at new UCN sources. For the time being the limit on the EDM of the neutron is equal to $3\cdot10^{-26}$ e · cm. It was obtained in 2005 by ILL-Sussex-RAL research team [2] and turned out to be 3 times lower than that obtained at PNPI 10 years ago [13]. In the near future we are planning to enhance the sensitivity in searching for a neutron EDM, using the ILL UCN source. It should mention that the level of accuracy a few units of 10^{-28} e · cм is also planned to obtain in other EDM experiments (ILL-cryoEDM, France; SNS-EDM, USA; PSI-nEDM, Switzerland). A few independent measurements are extremely important in this crucial experiment.

The task of a precise measurement of the neutron lifetime is of great importance for elementary particle physics and cosmology. The decay of a free neutron into a proton, an electron and an anti-neutrino is caused by weak interaction, namely the transition of a d quark into a u quark. In the Standard Model of elementary particles the mixing of quarks is described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix, which must be unitary. The matrix element Vud can be derived from the nuclear β-decay and the β-decay of the neutron. The calculation of Vud from the neutron β-decay data is extremely attractive due to the simplicity of the theoretical description. The assumed precision of measuring neutron β-decay will provide the possibility of checking the unitarity of the mixing matrix on a new precision level, i.e. higher than 10^{-3}, which is significant for testing the Standard Model validity and searching for possible deviations.

A precise measurement of the neutron lifetime is extremely important for testing the model of Big-Bang nucleosynthesis. The ratio of light elements depend on the ration of the number of baryons to photons at the stage of the initial nuclear synthesis and the neutron lifetime. Thus precisely measuring the neutron lifetime affects the nuclear synthesis model at the early stage of the Universe. The PNPI project suggests to measure free neutron lifetime with a precision of up to 0.2 s, inside a the gravitational trap of ultracold neutrons.

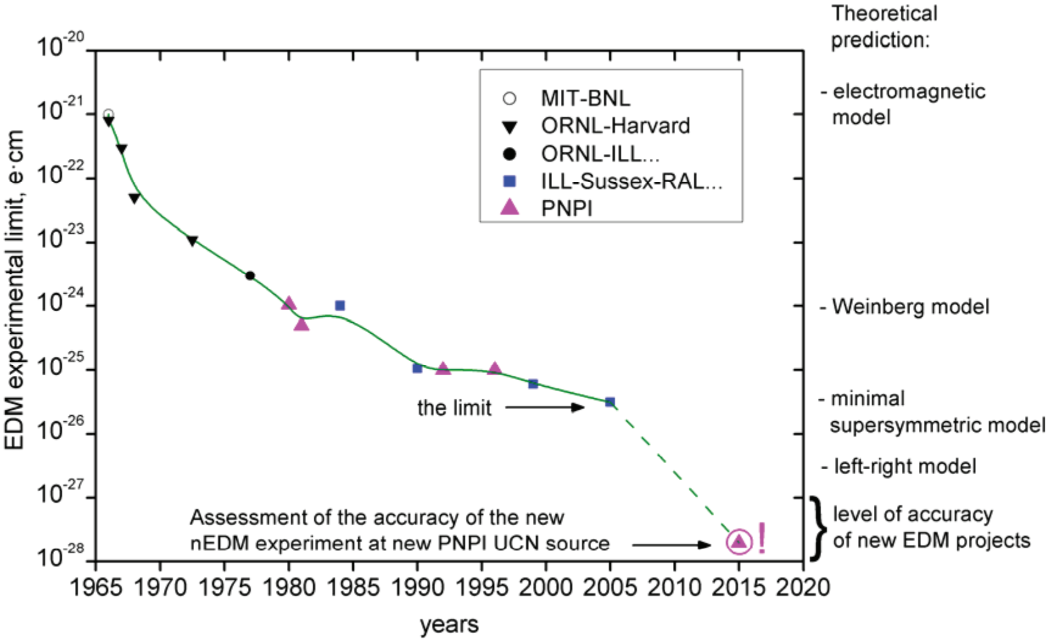

Fig 5. The progress in neutron EDM experiments, assumptions of theoretical models and possibilities of sensitivity improvements.

5. Conclusions

At the operating research WWR-M reactor at PNPI a high intensity source of ultracold neutrons for scientific investigations in fundamental physics and the study of nanostructures will be constructed. The source will use superfluid helium, which will allow to obtain a density of ultracold neutrons of 10^4 cm^{-3}, which approximately 1000 times exceeds the intensity of sources of ultracold neutrons presently available in the world.

Besides, the project suggests installing a new experimental equipment to study fundamental interactions and structure and dynamics of substances using new beams of ultracold neutrons, very cold neutrons and cold neutrons. As a result the number of installations at the reactor will be doubled and the quality of research on high intensity neutron beams with long wavelengths will be considerably improved due to creating better background conditions in the neutron guide halls.

Ultracold neutron beams are expected to have extremely high intensity. The project discussed here will enable us to establish a modern neutron center providing a unique high intensity source of ultracold neutrons for joint investigations. Many institutes and universities of Russia will take part in this center which will also become the center for training of scientific workers. In the field of ultracold neutrons the source is expected to be the most intensive one.

It should be noted that owing to a well-developed infrastructure of the reactor and the institute as well as a highly qualified scientific and engineering staff the project is also highly efficient from economic point of view. The project is based on application of high technologies. It is supposed to be a rather successful contribution to the program of supporting and developing fundamental and applied investigations based on research reactors in Russia.

Acknowledgements

This investigation was supported by the Russian Fund of fundamental research (projects:08-02-01052a, 10-02-00217a, 10-02-00224a) and by Federal Education Agency (contracts: P2427, P2540), as well as by Federal agency of Science and innovations (contract 02.740.11.0532).

References

[1] Serebrov A.P., MityuklyaevV.A., ZakharovA.A. et al., Nucl. Instr. Meth. A. 2009. V. 611.P. 276.
[2] Baker C.A., Doyle D.D., Geltenbort P. et al., Phys. Rev. Lett. 97 (2006) 131801.
[3] Ahiezer A.I., Pomeranchuk I.Ya., JETP. 1946. V. 16. P. 391.
[4] Golub R., Pendlebury J.M., Phys. Lett. A. 1977.V. 62. P. 337.
[5] Golub R., Jewell C., Ageron P. et al., Z. Phys. B – Condensed Matter. 1983.V. 51, P. 187.
[6] Yoshiki H., Sakai K., Ogura M. et al., Phys. Rev. Lett. 1992. V. 68. P. 1323.
[7] Steyerl A., Nagel H., Schreiber F.-X. et al., Phys. Lett. A 116 (1986) 347.
[8] Erykalov A.N., Onegin M.S., Serebrov A.P., The new cold and ultracold neutron source in WWR-M reactor. I. The neutron flux and energy release estimation. Preprint PNPI -2776, Gatchina, 2008. P. 22.
[9] Zakharov A.A., Serebrov A.P., The new cold and ultracold neutron source in WWR-M reactor. II. Low temperature part. Preprint PNPI - 2812, Gatchina, 2009.P. 24.
[10] Antonov A.V., Ilatovsky V.A., Konovalov E.A. et al., Report PNPI № 53.P.08. 2008.
[11] Fomin A.K., Serebrov A.P., The new cold and ultracold neutron source in WWR-M reactor.III. Ultracold neutron yield optimization. Preprint PNPI-2852, Gatchina, 2010. P. 13.
[12] Altarev I.S., Borisov Yu.V., Frei A. et al., Feasibility for accuracy improvement of neutron EDM measuremer magneto-resonance method. Preprint PNPI-2514, Gatchina, 2003. P. 41.
[13] Altarev I.S., Borisov Yu.V., Borovikova N.V. et al., Nuclear Physics. 1996. V. 59. P. 1204.
[14] Fomin A.K. Phd thesis: “Modeling of experiments with ultracold neutrons ”, Gatchina, PNPI, 2006.
[15] Alexeev V.L, Voronin V.V., Lapin E.G. et al., JETP. 1989. V. 96. P. 1921.
[16] O.B. Belomytsev, Yu.P. Rudnev, A.P. Serebrov et al., On measurement of the correlation coefficients in neutr decay with ultracold neutrons. Preprint PNPI – 1391, Gatchina, 1988. P. 10.
[17] Yu.P. Rudnev, A.P. Serebrov, V.E. Varlamov et al., Simulation of experiment for measurement of correlation coefficients in neutron β-decay on ultracold neutrons. Preprint PNPI – 1835, Gatchina, 1992. P. 26.
[18] A. Serebrov, Yu. Rudnev, A. Murashkin et al., Journal of Research of the National Institute of Standards and Technology 110 (2005) 383.
[19] Serebrov A., Rudnev Yu., Murashkin A. et al., Nucl. Instr. Meth. A. 2005. V. 545. P. 344.