

Status of UCN supersource at WWR-M reactor

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Abstract. The WWR-M reactor at NRC «Kurchatov Institute» - PNPI is going to be equipped with high-density ultracold neutron source. Method of UCN production is based on their accumulation in the superfluid helium at 1.2 K temperature. Thus, the source will provide the UCN density at EDM spectrometer equals to $\rho = 1.3 \cdot 10^4 \text{ cm}^{-3}$ which is 2 order magnitude greater than the output density of existing UCN source in the world. An extensive program of fundamental researches such as measuring of neutron lifetime and searching of neutron-antineutron oscillation is planned. In addition, CN and VCN beams are going to be equipped with condensed matter physics experimental setups. The design of the UCN source has been completed, complex tests at full-scale model showed that is possible to maintain superfluid helium under reactor heat load; calculations of an UCN source passive shielding, which ensures source safe operation, is completed. At the moment the process of UCN source manufacturing is taking place.

1. Introduction

The project for creating CN and UCN sources originated in the 70's of the last century. Efficient production of low energy neutrons at WWR-M reactor complex is closely associated with using a cryogenic technique. In this complex high densities of UCN fluxes were obtained by means of passing reactor neutrons through a low temperature converter: beryllium [1], liquid hydrogen [2], liquid deuterium [3], solid deuterium [4]. In the process of thermalizing, the fraction of UCNs in the spectrum can be increased tens or thousands of times. However, UCN fraction fails to be increased by this means, as for this purpose unattainable moderator temperature 10^{-3} K is required.

The modern method of obtaining high density of UCN is the use of superfluid helium. Superfluid helium is a quantum liquid with superfluidity and superconductivity properties [5]. No less surprising, but less known are the features of the interaction of superfluid helium with neutrons. Superfluid helium possesses colossal transparency for low-energy neutrons. The thing is that the famous Landau curve connecting the energy and momentum of excitations (phonons, rotons) in superfluid helium intersects with the curve $E = p^2/2m$ for a neutron at one point. This point corresponds to the excitation energy (in units of temperature) of 12 K. This means that UCN can “absorb” only a phonon with an energy of 12 K. There are practically no such phonons at superfluid helium at 1K temperature. This explains the exceptional transparency of superfluid helium for UCN. Indeed, UCN can “live” in superfluid helium before a phonon is absorbed for tens and hundreds of seconds. Ultracold neutrons are “born” in helium from cold neutrons with a wavelength of 9 Å or energy of 12 K, which is exactly equal to the phonon energy, i.e. the cold neutron excites a phonon and practically stops itself, becoming ultracold. Cold



neutrons penetrate through the wall of the trap, and ultracold ones are reflected, therefore, the effect of accumulation of UCNs up to a density determined by the storage time in a helium trap is possible.

Experiments on the accumulation of UCN in traps with superfluid helium were successfully performed on cold neutron beams [6, 7].

The proposed work is currently under way at the advanced scientific boundaries and is expected to be of a high technical level, as it touches upon a super low temperature 1.2 K in the reactor heating conditions. The devices of such kind, at so low temperatures have not been employed inside the reactor channels anywhere yet.

WWR-M reactor has a unique opportunity of creating conditions for low thermal emission with a sufficiently high neutron flux ($10^{12} \text{ s}^{-1} \cdot \text{cm}^{-2}$). This task can be implemented in the so called thermal column channel, which represents a big diameter channel (1 meter) adjoining to the reactor core [8, 9]. Big diameter of the channel enables to locate the lead shielding of 10 cm thick for reducing a thermal emission level, as well as a liquid deuterium premoderator at temperature 20-22 K for obtaining cold neutrons, and finally, a converter of cold into ultracold neutrons from superfluid He of 35 liters at temperature of 1.2 K. Such a location allows reaching the level of heat-inflows to superfluid He of 35 W. In PNPI, there is a vacuum pumping system with productivity sufficient for heat removal of the given amount. Combined with cryogenic devices made by The Linde, the concerned technological complex is supposed to ensure stable operation of UCN source at WWR-M reactor.

At present, UCN density in experiments is $10\text{-}40 \text{ cm}^{-3}$. Our project is aimed at reaching UCN density equal to 10^4 cm^{-3} , i.e. minimum by two orders of magnitude higher than the currently available level of UCN density (figure 1) [10].

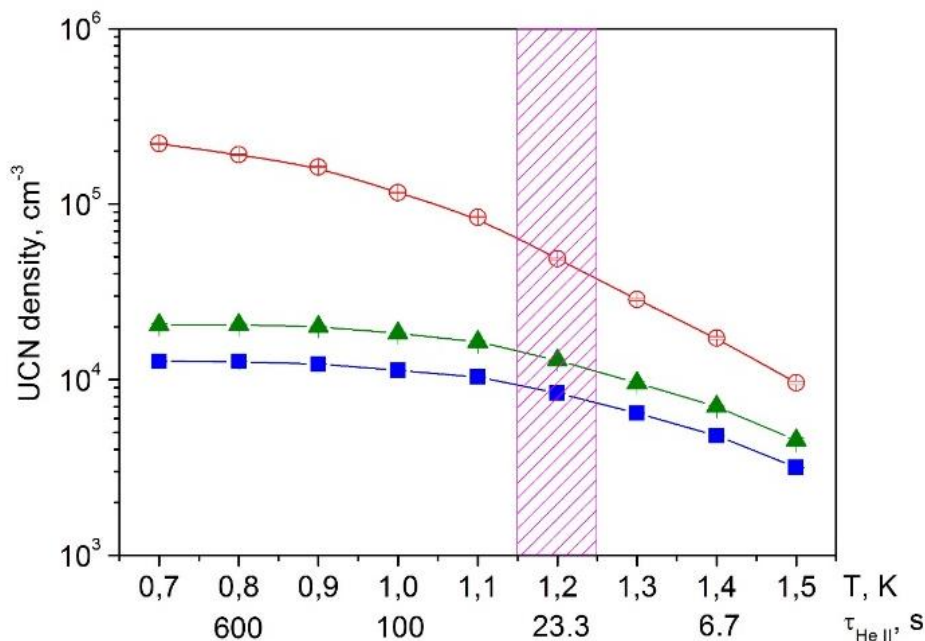


Figure 1. UCN density depending on HeII temperature.

● – in the closed source chamber, ▲ – in the 35 l trap, ■ – in the 350 l trap (l – liters)

The calculations of neutron fluxes of very cold (VCN) and cold (CN) neutrons at the outlets of UCN source neutron guides with super fluid He at WWR-M are presented. As a result of optimized source parameters, the flux density of cold neutrons (2–20 Å) at the outlet of a neutron guide with cross section

of $30 \times 200 \text{ mm}^2$ will be $8.6 \cdot 10^7 \text{ cm}^{-2} \text{ s}$ and the flux density of cold neutrons ($50\text{--}100 \text{ \AA}$) at the outlet of a neutron guide with cross section of $30 \times 200 \text{ mm}^2$ will be equal to $4.6 \cdot 10^5 \text{ cm}^{-2} \text{ s}$.

2. Scientific program

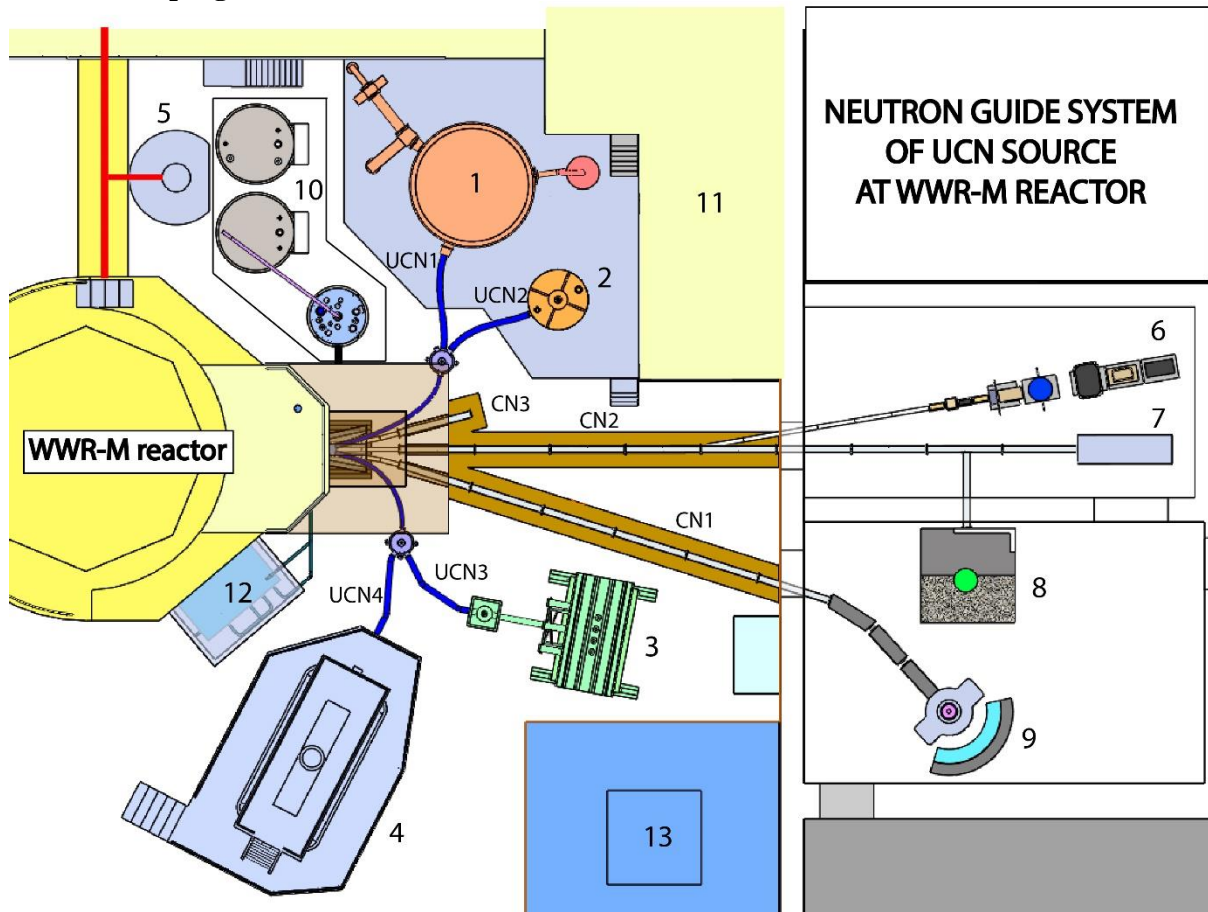


Figure 2. The scheme of an experimental equipment in the main hall of the WWR-M reactor hall.

UCN - beams of ultracold neutrons, CN - cold and very cold neutron beams;

- 1 – EDM spectrometer, 2 – UCN magnetic trap, 3 – n-n' experiment, 4 – UCN gravitational trap, 5 – Diffractometer, 6 – Reflectometer, 7 – Polarizer, 8 – Powder diffractometer, 9 – spin-echo spectrometer, 10 – cryogenic equipment for UCN source, 11 – technological platform for experimental equipment, 12 – the cooling system for the lead screen of UCN source, 13 – transport entering in the main hall of reactor WWR-M.

Using a new source of UCN at the reactor WWR-M (figure 2), it is supposed to improve the estimation precision of an electric dipole moment (EDM) of a neutron (1) by two orders of value and to test predictions on super symmetry theory, one of the versions of extension of Standard Model. Within the framework of these theories, neutron EDM is predicted at the level available for the planned experiments. At the same time, super symmetry theories assume the baryon asymmetry of the Universe at the observed level, which points out possible validity of the proposed variants of the theory.

In addition to a setup for measuring neutron EDM, two installations for measuring neutron lifetime are presented: one with a magnetic trap (2) and the other one with a big gravitational trap (4). Neutron lifetime precise measurements are important for verification of the model of the Universe formation at its primordial stage, as well as for search of deviations from Standard Model. Besides, the installation for search of mirror dark matter (n-n') (3) is presented. All these installations are elaborated and manufactured in PNPI and at present are tested at UCN beams in ILL (Institute Lauer-Langeven,

Grenoble, France). They are supposed to be transferred to PNPI and mounted at a new UCN source. Enhancing the UCN intensity by more than two orders of value will enable to conduct principally new investigations. Finally, as far as a high intensity source of UCN is concerned, we can discuss performance of the experiment on search for neutron-antineutron oscillations ($n-\bar{n}$), aimed at checking the baryon number violation, the second condition for Universe origin according to A.D. Sakharov theorem.

Thus, in addition to one of the most significant experiments on neutron EDM search, there arise new opportunities for carrying out the whole series of experiments on physics of fundamental interactions.

The research program for the condensed state on cold neutron beams is elaborated for five experimental stations. Among them, there are four installations ready for operation: a reflectometer (6), a polarimeter (7), a powder diffractometer (8) and a spin-echo spectrometer (9). The outlet of a reserve beam of very cold neutrons VCN (CN3) for future experiments is also foreseen.

3. Current status of UCN source at WWR-M reactor

The project of the UCN source on superfluid helium has been implemented for 10 years and has been 80% completed by now. For the development of ultracold neutron (UCN) production technology, a full-scale technological model of the source has been created and launched at the WWR-M reactor. As a result of experiments on the full-scale model, real temperatures of superfluid helium were obtained with a heat load up to 60 W [11], while the calculated heat load on the WWR-M reactor is estimated at 35 W. The capacity of the liquefier is sufficient to clean and liquify the necessary amount of helium for the smooth operation of the technological complex during the emptying of the upper bath of the cryostat.

The temperature dependence on the supplied heat load was obtained. The highest helium temperature $T=1.371$ K was recorded at a thermal load of 60 W. At the same time, the power reserve of the vacuum pumping system is more than 200%. Even with such large loads on the model of the UCN source, helium continues to remain in the superfluid phase.

Experimental substantiation of the possibility of retaining helium in a superfluid state under a supplied thermal load makes it possible to proceed to the manufacturing process of the intracanal part of the UCN source.

Constructively, UCN source for the reactor WWR-M is made of three units:

1. Vacuum module;
2. Cryogenic module;
3. Transport trolley.

UCN source is manufactured in the working shop of EOP on the territory of NRC «Kurchatov Institute» - PNPI. At present, a vacuum module and a transport trolley as well as separate units of a cryogenic module have been made (figure 3).



Figure 3. The assembled UCN source

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References

- [1] Altarev I S, Egorov A I, Ezhov V F, Ivanov S N, Lobashev V M, Nazarenko V A, Porsev G D, Serebrov A P, Taldaev R R and Kharitonov A G 1976 *Preprint LNPI/246*
- [2] Altarev I S *et al* 1980 A liquid hydrogen source of ultra-cold neutrons *Phys.Lett. A* **80** 413-416
- [3] Altarev I S *et al* 1986 *JETP Lett.* **44** 269-272
- [4] Serebrov A P, Mityukhlyayev V A, Zakharov A A, Kharitonov A G, Nesvizhevskii V V, Lasakov M S, Tal'daev R R, Aldushchenkov A V, Varlamov V E and Vasil'ev A V 1995 *JETP Lett.* **62** 785-790
- [5] Korobkina E, Golub R, Wehring B W and Young A R 2002 Production of UCN by downscattering in superfluid He4 *Phys. Lett. A* **301** 462-469
- [6] Golub R, Jewell C, Ageron P, Mampe W, Heckel B and Kilvington I 1983 Operation of a superthermal ultra-cold neutron source and the storage of ultra-cold neutrons in superfluid helium⁴ *Zeitschrift für Physik B Condensed Matter* **51** 187-193
- [7] Yoshiki H, Sakai K, Ogura M, Kawai T, Masuda Y, Nakajima T, Takayama T, Tanaka S and Yamaguchi A 1992 Observation of ultracold-neutron production by 9-Å cold neutrons in superfluid helium *Phys. Rev. Lett.* **68** 1323-1326
- [8] Serebrov A P *et al* 2015 *Vestnik of Saint Petersburg University* **60(2)** 27-41
- [9] Serebrov A P 2011 Supersource of ultracold neutrons at the WWR-M reactor and the program of fundamental research in physics *Crystallography Reports* **56** 1230-1237
- [10] Serebrov A P and Fomin A K 2015 Calculation of the ultracold neutron yield from a superfluid helium source in the WWR-M reactor *JTP* **80** 1238-1242
- [11] Serebrov A P, Lyamkin V A, Prudnikov D V, Vasil'ev A V, Keshishev K O and Boldarev S T 2017 Putting in operation a full-scale ultracold-neutron source model with superfluid helium *Technical physics. The Russian journal of applied physics* **62** 329-333