



## Preparation of facilities for fundamental research with ultracold neutrons at PNPI

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### ABSTRACT

The WWR-M reactor of PNPI offers a unique opportunity to prepare a source for ultracold neutrons (UCN) in an environment of high neutron flux (about  $3 \times 10^{12}$  n/cm<sup>2</sup>/s) but still acceptable radiation heat release (about  $4 \times 10^{-3}$  W/g). It can be realized within the thermal column situated close to the reactor core. With its large diameter of 1 m, this channel allows to install a 15-cm-thick bismuth shielding, a graphite premoderator (300 dm<sup>3</sup> at 20 K), and a superfluid helium converter (35 dm<sup>3</sup>). At a temperature of 1.2 K it is possible to remove the heat release power of about 20 W. Using  $4\pi$  flux of cold neutrons within the reactor column can bring more than a factor 100 of cold neutron flux incident on the superfluid helium with respect to the present cold neutron beam conditions at the ILL reactor. The storage lifetime for UCN in superfluid He at 1.2 K is about 30 s, which is sufficient when feeding experiments requiring a similar filling time. The calculated density of UCN with energy between 50 and 230 neV in an experimental volume of 40 l is about  $10^4$  n/cm<sup>3</sup>. Technical solutions for realization of the project are discussed.

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### 1. Introduction: Evolution of UCN sources and prospects for future developments

Ultracold neutrons (UCN) are successfully used in fundamental research: for the search of the neutron electric dipole moment, neutron lifetime measurements, measurements of neutron decay asymmetries, and other studies. The accuracy one may reach in these experiments is severely limited by counting statistics. Therefore, there is a strong activity in the development of more intense UCN sources (Fig. 1).

After the first demonstration of UCN production in Dubna [1] and in Munich [2] the UCN density has been increased by eight orders of magnitude using more powerful reactors and cold neutron sources in Gatchina (PNPI) [3] and in Grenoble (ILL) [4]. These sources were placed in extremely high neutron fluxes and we employ liquid hydrogen (PNPI) or liquid deuterium (ILL). In the 1990s this line of UCN source development came to saturation. Promising developments of alternative UCN sources employ

superfluid He 4 at a temperature of about 1 K or below, and solid deuterium at about 4 K.

A first test experiment with solid deuterium has been carried out in Gatchina (PNPI) in 1980 [5]. More detailed studies of solid deuterium UCN source were realized in Gatchina at the WWR-M reactor in 1994 [6]. The solid deuterium UCN source with volume 6 l was installed in the thermal column of the reactor. It was demonstrated that solid deuterium gives a gain factor of about 10 with respect to liquid deuterium. Unfortunately, it requires an environment of lower heat release density. A pulse mode is suitable when the average heat release is low enough, which can be realized at neutron spallation sources. Therefore, the project of the so-named UCN factory was proposed in Ref. [7] and presented in the first UCN Workshop devoted to this project in Pushkin, Russia, in 1998. The first and simplest realization of this idea was done in LANL [8]. A more detailed project of UCN factory was developed by PNPI and PSI [10], which is now under construction at PSI.

UCN production in superfluid He 4 was proposed in Ref. [11]. After the first demonstration of the method at the ILL in 1980 [12], it has been further investigated in Japan in 1992 [14], and in 2002 again at the ILL [13]. Now there are a few projects, one based on using superfluid He with UCN accumulation in the converter

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(ILL/Munich [15]), or in the regime of steady-state operation (Japan [16], Gatchina [17]).

## 2. Scheme of UCN source implementation in the thermal column of the WWR-M reactor

In this article we discuss the project of an UCN source at the WWR-M reactor of PNPI [14], for which superfluid helium shall be used as a converter for UCN. The thermal column of diameter 1 m, situated close to the reactor core (see Fig. 2), offers a unique opportunity to install a source for UCN in an environment of high neutron flux (about  $3 \times 10^{12}$  n/cm<sup>2</sup>/s) but still acceptable radiation heat release (about  $4 \times 10^{-3}$  W/g). In order to reduce the heat release from  $\gamma$ -rays from the reactor core, a bismuth shielding will be installed. The external diameter of this cylindrical shielding will be 990 mm with a wall thickness of 95 mm. The closing of the cylinder in the direction of the reactor core will have a thickness of 150 mm. The bismuth is enclosed in a water-cooled aluminum shell (5 mm thick). Inside the bismuth shielding a graphite moderator with thickness 150 mm will be installed. It will be cooled down to 20 K by means of a helium refrigerator. This graphite is also enclosed in an aluminum shell and this

construction is placed in a vacuum jacket. Inside the graphite moderator a cylindrical vessel with superfluid helium at a temperature of 1.2 K is placed. Its diameter is 300 mm, and length 500 mm. The thickness of the aluminum walls is 2 mm. The internal surfaces of the Al walls are coated with  $(3-5) \times 10^3$  Å <sup>58</sup>NiMo alloy with critical velocity 7.8 m/s. UCN can be extracted from the source by means of an UCN guide coated by <sup>58</sup>NiMo too. UCN guide and source volume will be separated by a 100- $\mu$ m-thick Al membrane with support grid. The scheme in Fig. 2 is shown in scale. The thicknesses of Bi shielding and graphite premoderator have been chosen to obtain the maximum possible neutron flux with wavelength 9 Å, at the condition that the heat load on the superfluid source will not exceed 20 W.

Calculations of neutron fluxes and heat release were done using the MCNP code. The total heat releases at 16 MW reactor power are: 16 kW in the bismuth shielding, 750 W in the graphite moderator, 13 W in the aluminum shell of the helium source, and 6 W in the superfluid helium. Hence the total heat load at temperature 1.2 K is 19 W.

## 3. Premoderator

The choice of graphite as a cold moderator is a compromise between simplicity and the goal to obtain the maximum possible flux of cold neutrons with wavelength 9 Å. These neutrons can be converted into UCN by means of a one-phonon process. UCN production due to multi-phonon processes can be similarly strong but it depends on the neutron spectrum [18]. Fig. 3 shows the results of calculations of cold neutron spectrum for the following materials: liquid deuterium, graphite, frozen heavy water, and beryllium. For all cases the temperature of the moderator was chosen to be 20 K. From a practical point of view the graphite moderator is the simplest one. However, it is inferior to liquid deuterium in the production of 9 Å neutrons by a factor of two.

## 4. Cryogenic scheme of source

Now we would like to discuss the practical realization of the proposed scheme (Fig. 4). The method of heat removal is based on the huge thermal conductivity of superfluid helium. The superfluid component moves to the source of heat and the normal component moves to the heat exchanger; so it is not necessary to specially arrange the circulation of liquid helium.

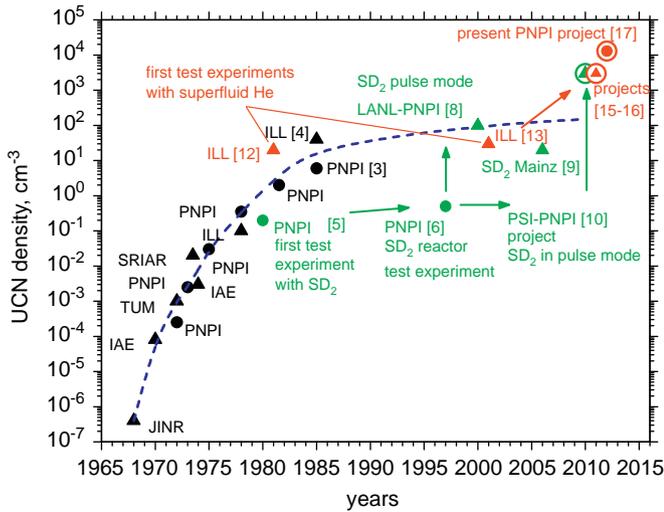


Fig. 1. Development of UCN sources and future prospects. More detailed information can be found in Refs. [3–6,8–10,12,13,15–17].

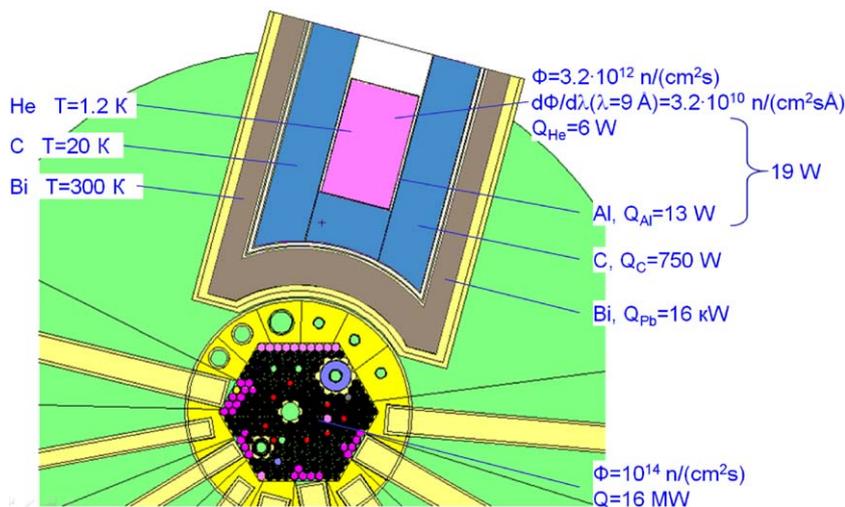


Fig. 2. Implementation scheme of the planned UCN source in the thermal column of the WWR-M reactor (see text for description of the components).

Superfluid helium around the UCN guide is used as a guide of heat release. Its cross-section is  $630\text{ cm}^2$ , and length is about 3 m. The difference of temperature along superfluid helium will be  $1.2 \times 10^{-2}\text{ K}$  at a heat load of 20 W. Taking into account a jump of temperature on the surface of the heat exchanger, we estimate that the temperature difference between the helium in the source and in the pumping bath will be  $2 \times 10^{-2}\text{ K}$ . The temperature in the pumping bath is kept at 1.2 K, corresponding to a pressure of 0.55 mbar. A heat load of 20 W corresponds to a consumption of liquid helium of about 38 l/h. For the pumping of gaseous helium, two vacuum pumps with pumping rate  $8\text{ m}^3/\text{s}$  will be required. It corresponds to pumping 7.5 l/s of helium gas at atmospheric pressure. These estimations show that the proposed project can be realized.

## 5. Estimation of UCN density

MCNP calculations gave the following results for the full reactor power of 16 MW. The neutron flux incident on superfluid helium is  $3.2 \times 10^{12}\text{ n/cm}^2/\text{s}$ , and the differential neutron flux around  $9\text{ \AA}$  is  $3.2 \times 10^{10}\text{ n/cm}^2/\text{s}/\text{\AA}$ . The rate  $R$  of UCN production due to the one-phonon process can be calculated by the theoretical formula [13]  $R = 4.55 \times 10^{-8} d\Phi/d\lambda(9\text{ \AA})/\text{cm}^3/\text{s}$ . Taking into account the multi-phonon processes and neutron spectrum in the source [18], we expect the rate of UCN production will be  $2.9 \times 10^3\text{ n/cm}^3/\text{s}$ . The total number of UCN produced in the source is about  $1.0 \times 10^8\text{ n/s}$ . The UCN

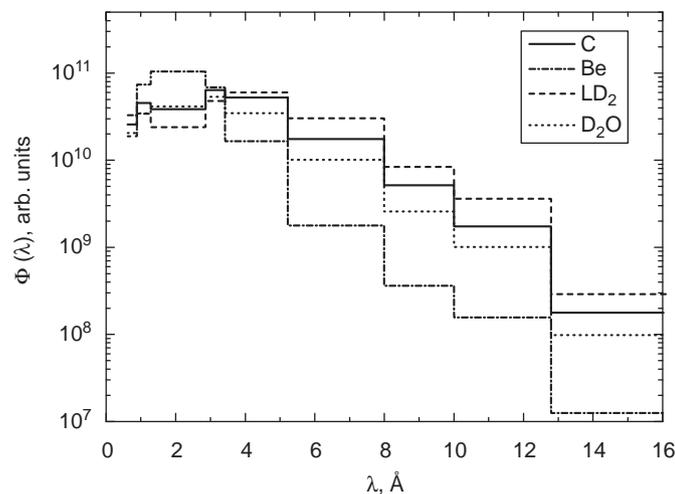


Fig. 3. Neutron spectrum incident on the helium converter, for different premoderators.

lifetime in superfluid helium at a temperature of 1.2 K is about 30 s, but after taking into account UCN losses on the trap walls, it is about 20 s. This estimation was done using a rather pessimistic assumption of  $10^{-3}$  losses per collision. Thus the UCN density in a closed trap with superfluid helium could reach  $5.8 \times 10^4\text{ n/cm}^3$ . However, we are interested in the UCN density in an experimental trap placed in the experimental hall. For this purpose Monte-Carlo calculations have been done for an experimental scheme, that includes a trap with superfluid helium with a volume of 35 l, an UCN guide with diameter 140 mm and length 3 m, and an experimental trap with a volume of 35 l. In addition, a scheme with an experimental trap of 350 l has been calculated too. The volume with superfluid helium is separated from the UCN guide by an aluminum membrane with thickness  $100\text{ }\mu\text{m}$  on a supporting grid. The vacuum of the guide for cold neutrons is also isolated from the warm UCN trap by means of a similar membrane to avoid freezing of residual gas on the cold guide and the source window. The calculations take into account the losses in the walls of the UCN guide and the experimental traps, which were chosen as  $3 \times 10^{-4}$  per collision. A mirror reflectivity of 99.3% for the guides was used, which was obtained from measurements of the transmission factor for replica guides [19]. The critical velocity of the helium trap and the UCN guide was 7.8 m/s ( $^{58}\text{NiMo}$ ), but for the experimental trap it was chosen to be 6.8 m/s (Be, BeO). Losses in the aluminum membranes were taken as defined by the capture cross-section. The coefficient of UCN reflection from the aluminum membranes was calculated taking into account the critical velocity 3.2 m/s and albedo reflection due to the inhomogeneity of density inside the foils [20]. It is well known that reflection plays an important role and can strongly reduce the transmission coefficient. The calculations show that the UCN density in the 35 l experimental trap is less by 4.5 times than the hypothetical UCN density in the closed helium trap, i.e.  $\rho_{\text{trap } 35\text{ l}} = 1.3 \times 10^4\text{ n/cm}^3$ . The time of filling of the trap in this scheme is 22 s. For the experimental trap with a volume of 350 l the UCN density  $\rho_{\text{trap } 350\text{ l}} = 7.7 \times 10^3\text{ n/cm}^3$ . The filling time constant of the big trap is 55 s. In principle, this UCN density can be increased by a factor of 3 by changing the configuration of the reactor active core but the heat load will be increased correspondingly. Certainly, obtaining an UCN density of order  $10^4\text{ n/cm}^3$  is very important for fundamental physics experiments with UCN.

## 6. Plan of realization and conclusion

Presently the first steps for the realization of this project have been done. A refrigerator with a cooling power of 3 kW at 20 K to cool the graphite moderator was put into operation in the cryogenic laboratory. In 2009 we have to put into operation a helium liquefier, which has already arrived at PNPI. The time table of the project strongly depends on the program of the thermal

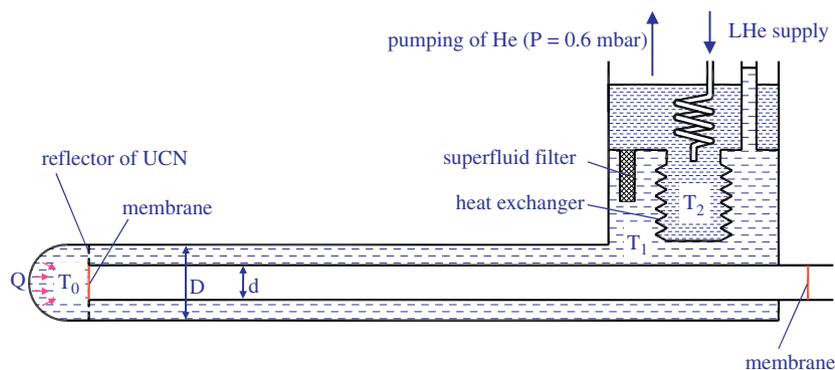


Fig. 4. Cryogenic scheme of the UCN source.

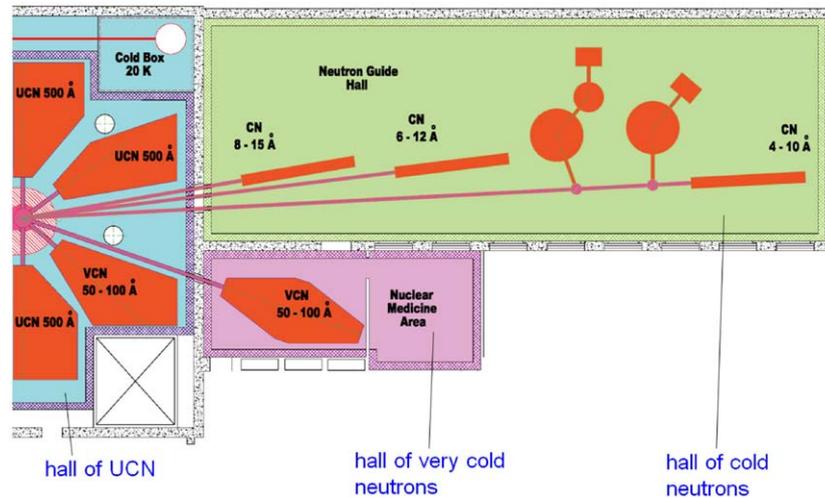


Fig. 5. Neutron guide halls and beam positions around the new source of cold and ultracold neutrons at the WWR-M reactor.

column modernization, which will require 3–5 years. Thus an optimistic time estimate of source launching is 2012.

This neutron source will produce cold and very cold neutrons as well. The general scheme of the neutron guide halls is presented in Fig. 5. The realization of this project will create an UCN source with record UCN density for fundamental studies. In particular the accuracy of the neutron EDM measurement can be increased by more than an order of magnitude. Besides, cold and very cold neutrons can be used for studies of nanostructures and other research in the field of condensed matter.

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