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Ultracold neutrons at the WWR-K: From the first experiments to a high-intensity UCN source

K. Turlybekuly*, A.V. Strelkov

Joint Institute for Nuclear Research, Dubna, Russia

e-mail: turlybekuly@jinr.ru

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Abstract

This article presents the development of ultracold neutron (UCN) research in Kazakhstan and outlines a concept for a new high-intensity UCN source at the WWR-K research reactor of the Institute of Nuclear Physics (INP, Almaty). A brief overview of the emergence of UCN physics and the formation of the INP scientific school is given in the context of early work at WWR-type research reactors equipped with thermal columns, where the first UCN sources were realized.

The results of experiments performed at the WWR-K reactor are summarized, including configurations of UCN production and transport systems, key measurements, and limitations of the existing infrastructure. Based on an analysis of the neutronic characteristics of the WWR-K thermal column, a concept for a modernized UCN source is developed. The proposed approach includes the installation of a dedicated cryogenic module in the thermal column, optimization of the neutron spectrum and spatial distribution, and efficient extraction of UCNs to experimental stations. It is shown that the combination of reactor parameters, thermal column design, and proposed engineering solutions provides favorable conditions for the creation of an internationally competitive high-intensity UCN source and for the implementation of a long-term program of fundamental and applied research in Kazakhstan.

1 Introduction

The increase in the sensitivity of neutron electric dipole moment (nEDM) searches was one of the key motivations for the discovery of ultracold neutrons (UCN). Fyodor L. Shapiro was among the first to point out the distinctive advantages of using UCNs in nEDM measurements and proposed an experimental approach based on a pulsed reactor in Dubna. At his initiative, the first experiment on the detection of UCNs was carried out at the IBR pulsed reactor of the Frank Laboratory of Neutron Physics, Joint Institute for Nuclear Research (FLNP JINR). These experiments demonstrated the feasibility of producing and extracting UCNs from a reactor neutron flux [1].

Independently of the JINR studies, experiments with slow neutrons were carried out in Germany under the leadership of Professor Albert Steyerl. In these experiments, neutrons were observed with energies so low that they were totally reflected from material surfaces at any angle of incidence and could be stored for extended periods in a closed volume [2]. Thus, the existence of ultracold neutrons was effectively established experimentally. The combination of Shapiro's ideas on the use of UCNs for precision measurements and the independent observation of UCNs in Steyerl's experiments marked the beginning of a new field in neutron physics.

Ultracold neutrons are conventionally defined as neutrons with kinetic energies on the order of several hundred nanoelectronvolts and below, corresponding to velocities of a few meters per second. For such neutrons, total reflection from material surfaces at any angle of incidence is a characteristic property [3, 4]. This enables their confinement in closed storage vessels for hundreds of seconds or longer. The unique capability of UCNs for long-term storage in a finite volume, together with the available methods for their "manipulation," opens broad opportunities for studying the fundamental properties of the neutron [5–9].

At the same time, the first experiments at the IBR pulsed reactor demonstrated that, under the prevailing conditions, achieving a sufficient UCN density was extremely difficult. On average, these studies recorded only one ultracold neutron approximately every 200 s, corresponding to a UCN density of the order of $10^{-5}\,\mathrm{cm}^{-3}$ [1]. This limitation was largely determined by the relatively low reactor power of IBR, about 6 kW. Under such conditions, a full-scale experimental program with UCNs was hardly feasible, and the team led by Fyodor L. Shapiro was thus faced with the task of identifying a more powerful and experimentally suitable facility for UCN studies.

In Dubna and other research centers, a focused search began for the most suitable facilities to advance this new field. Potential converter materials were investigated, along with the conditions for UCN moderation and extraction, as well as methods for their transport and storage. A natural step was to turn to pool-type research reactors, which provide a steady neutron flux and a flexible experimental infrastructure. Accordingly, at the IRT-M reactor of the I. V. Kurchatov Institute of Atomic Energy, the first experiments with ultracold neutrons were carried out. These experiments yielded data confirming the feasibility of producing UCNs directly from the reactor flux, extracting them via neutron guides, and storing them for extended periods in closed vessels.

In this context, the main body of UCN experiments was transferred to the institute's more powerful IRT research reactor. During the period 1969–1974, researchers from FLNP JINR, together with the group led by L. V. Groshev, investigated various aspects of UCN physics at this facility, including converter–moderator materials, the propagation of UCNs through neutron guides, gravitational spectroscopy of ultracold neutrons, and processes of their storage and detection [10–12]. Already in the first experiments, the feasibility of long-term UCN confinement in storage vessels was convincingly demonstrated. However, the measured storage time was significantly shorter than expected, indicating the presence of additional losses associated with UCN interactions with the vessel walls.

To elucidate the origin of these losses and to develop sufficiently intense UCN sources, the studies were continued at more powerful research reactors. Beginning in 1973, the staff of the Neutron Physics Laboratory, together with a group from the Research Institute of Atomic Reactors (RIAR), with the support of Yu. S. Zamyatnin, initiated joint work at the 110 MW SM-2 reactor in Dimitrovgrad [13–16]. In these experiments, the "heating" of UCNs into the thermal-energy range was observed for the first time as one of the principal causes of the anomalously short storage time of UCNs in closed vessels. The spectrum of the heated neutrons was measured.

At the same reactor, experiments were performed with a so-called dynamically clean vessel, in which the walls were continuously renewed during UCN storage by deposition of aluminum atoms. Similar measurements were carried out with coatings of copper, zinc, lead, and beryllium. A storage time of about 650 s was achieved in a vessel with a beryllium coating. In degassed beryllium vessels, a UCN "leakage" was observed that depended only weakly on temperature over a broad range of (20–800) K and remained practically unchanged upon deuteration of the walls and deposition of condensed CO_2 and D_2O films.

Using a flow-through technique, the partial survival time of UCNs with respect to heating and capture at the beryllium surface was measured. The spectra of heated neutrons were also studied as a function of the degree of wall degassing. The development of this large-scale program naturally required the involvement of additional research reactors. With the aim of establishing sufficiently intense UCN sources, methodological, as well as scientific and engineering, studies were carried out at the WWR-K reactor of the Institute of Nuclear Physics in Almaty [17–22]. It is with these works that the development of UCN physics in Kazakhstan begins. At the WWR-K reactor, the first experiments on UCN production, transport, and storage were performed. Dedicated research teams were formed, and the foundations for further studies in this field were established.

It should be noted, however, that the profound governmental and economic transformations that took place in the country led to a significant weakening of the experimental infrastructure and to a prolonged interruption of systematic UCN studies at the WWR-K reactor. As a result, a noticeable gap emerged in the development of UCN research in Kazakhstan.

Nevertheless, owing to the combination of suitable reactor power, specific features of the core and biological shielding, the availability of neutron channels for beam extraction, and the possibility of installing cooled moderators and converters, the WWR-K reactor remains one of the most suitable facilities for the development of a high-intensity UCN source. In terms of its inherent design potential, it is capable of providing UCN densities among the highest achievable worldwide.

The present work provides a systematic account of the historical development of UCN physics in Kazakhstan, with particular emphasis on experiments performed at the WWR-K research reactor. The main stages in the establishment of this field are outlined, including studies of UCN production, transport, and storage. The specific features of the WWR-K reactor are analyzed in comparison with other WWR-type research reactors constructed during the Soviet period.

Special attention is given to the current concept of developing a high-intensity UCN source at WWR-K. This concept is aimed at restoring and advancing the scientific traditions established earlier and at positioning UCN research in Kazakhstan at the forefront of the field.

2 UCN Production Facilities at the WWR-K Reactor

Following the work of Fyodor L. Shapiro and his school, a scheme was implemented in which UCNs were extracted directly from a moderator located in the reactor core into horizontal or vertical neutron guides with reflecting walls. In this approach, a thin near-surface layer of the moderator, with a thickness on the order of the UCN mean free path, adjoins the bulk moderator volume. It is within this layer that neutrons with energies up to several hundred neV are produced. This layer is treated as the UCN converter and is structurally separated from the main moderator volume by placing it at the entrance of the neutron guide, in the region of maximum thermal neutron flux. The converter is the key element of the facility, as it largely determines the source intensity, spectral characteristics, and overall UCN extraction efficiency.

2.1 The Facility at the Tangential Channel of the WWR-K Reactor

A baseline facility for UCN production and transport was constructed on the 193 mm diameter tangential channel [17]. An aluminum tube with an outer diameter of 187 mm was routed through the water, cast-iron, concrete, and lead shielding. All elements of the facility are accommodated inside this tube (Figure 1). At the center of the reactor core, in the region of maximum thermal neutron flux density, a UCN converter with a diameter of 175 mm is installed. Around it, a circulating cooling water flow is arranged, serving both as a heat-removal medium and as an additional moderator.

At the exit of the biological shielding, a copper neutron guide is connected to this tube, a straight section that transports UCNs from the converter to the detector. The inner surface of the neutron guide is carefully polished, thereby minimizing UCN losses during multiple reflections from the walls. The guide diameter is comparable to that of the tangential channel, ensuring efficient "capture" of the UCN flux. The external part of the neutron guide is enclosed in an aluminum jacket connected to a pumping system. Low pressure is maintained along the entire transport line, so that UCN losses due to collisions with residual gas become negligible.

UCNs were detected using scintillation and proportional counters. In the scintillation detectors, ZnS(Ag) plates were employed, coated with a thin layer of $LiOH \cdot H_2O$ with an areal density on the order of a few hundredths of a milligram per square centimeter. The entrance-window area was 14 or 28 cm^2. The proportional counters registered UCNs via ionization signals arising from neutron capture on lithium nuclei. In all experimental series, the counting rates were normalized to an area of 28 cm^2.

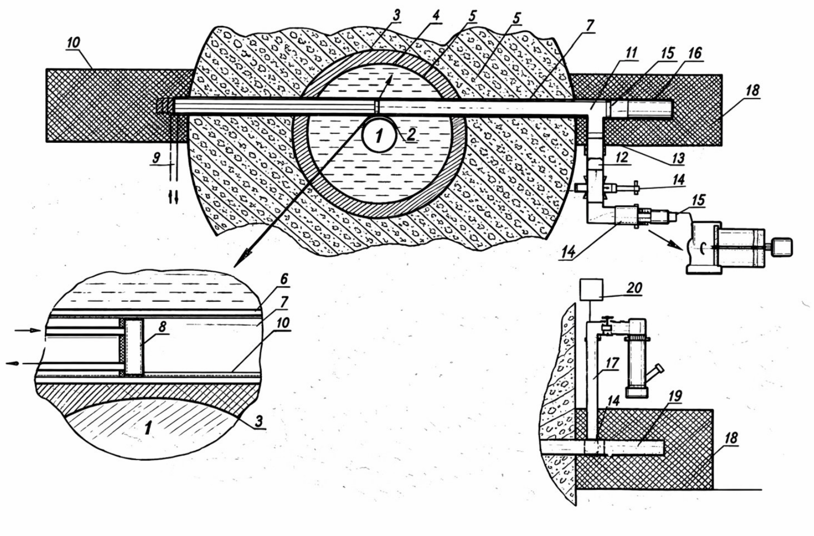

Figure 1: Schematic of the experimental setup: 1 – reactor core; 2 – 50 mm thick lead shielding; 3, 4, 5 – water, cast-iron, and concrete reactor shielding, respectively; 6 – through-going tangential reactor channel; 7 – aluminum tube; 8 – UCN converter; 9 – converter cooling system; 10 – copper cylinders; 11, 12, 13, 14 – copper sections of the neutron guide; 15 – copper foil; 16 – aluminum tube; 17 – vertical neutron guide section for vacuum pumping; 18 – direct beam shielding; 19 – UCN detector; 20 – helium filling and pressure-monitoring system. Note: Compiled from Ref. [17], p. 713.

The background was determined from measurements with the neutron guide entrance closed or with the converter filled with a gas yielding a negligible UCN output, and was subtracted from the total signal.

The spatial distribution of the thermal neutron flux density along the axis of the tangential channel was measured by the activation method using gold and copper foils. The profile shown in Figure 2 indicates that the flux maximum corresponds to the central region of the reactor core. The UCN converter was installed precisely at this location, thereby providing the maximum UCN yield for a given reactor power.

The dependence of the UCN count rate on reactor power for different converters (Figure 3) was found to be linear over the entire investigated power range. This indicates the absence of saturation and other nonlinear effects and confirms the proper operation of the facility. The differences in the slopes of the straight lines reflect the differing efficiencies of the converters employed.

A dedicated series of measurements was aimed at estimating the diffusion-transport time of UCNs along the neutron guide. To this end, helium was introduced into the guide at various pressures, and the UCN count rate was measured (Figure 4). Fitting the measured dependence $J(p)$ within a diffusion model that includes absorption showed that the characteristic UCN propagation time from the converter to the detector is on the order of a few seconds (about 4 s). The pronounced attenuation of the signal already at pressures of several tens of torr indicates a large number of reflections from the guide walls.

The dependence of the count rate on the detector entrance window area (Figure 5) showed that, for small areas, increasing the window size leads to a steep rise in

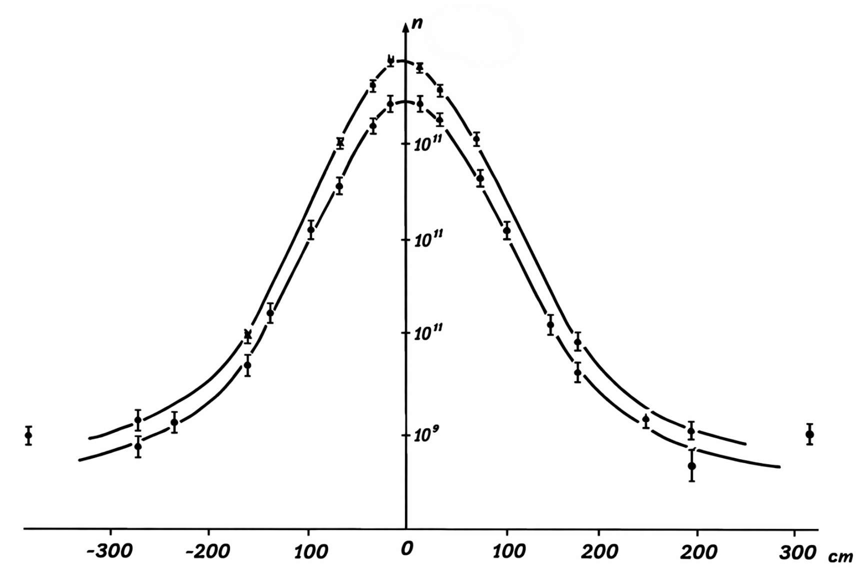

Figure 2: Thermal neutron flux distribution along the through-going tangential reactor channel for two reactor-core configurations. Note: Compiled from Ref. [17], p. 714.

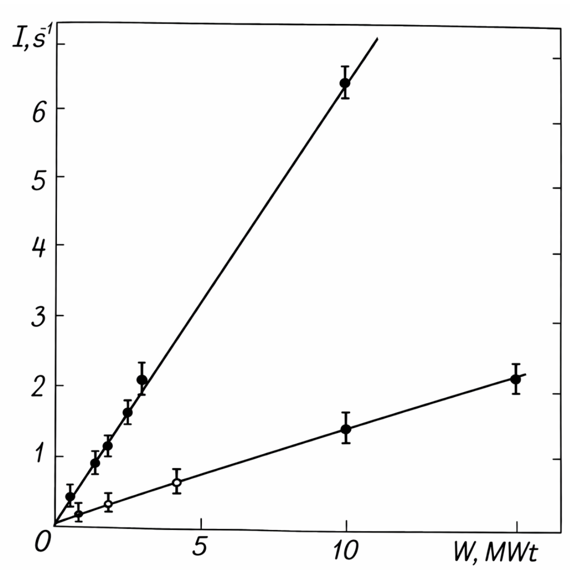

Figure 3: UCN count rate J as a function of reactor power W for the converters. Filled circles correspond to the aluminum converter; open circles correspond to the water converter in an aluminum ampoule. Note: Compiled from Ref. [46], p. 49.

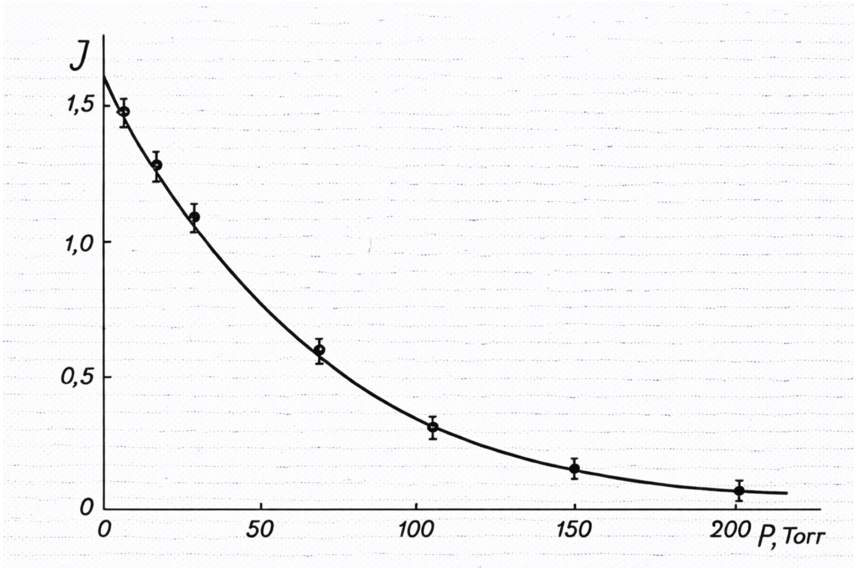

Figure 4: Dependence of the UCN count rate J on the pressure P. The theoretical curve is normalized to the experimental value of J at $P = 0$. Note: Compiled from Ref. [17], p. 714.

the signal. However, as the area approaches that of the cross section of a 200 mm diameter tube, the curve saturates. This implies that, for complete interception of the UCN flux, detectors with an entrance window area comparable to the neutron guide cross section must be used.

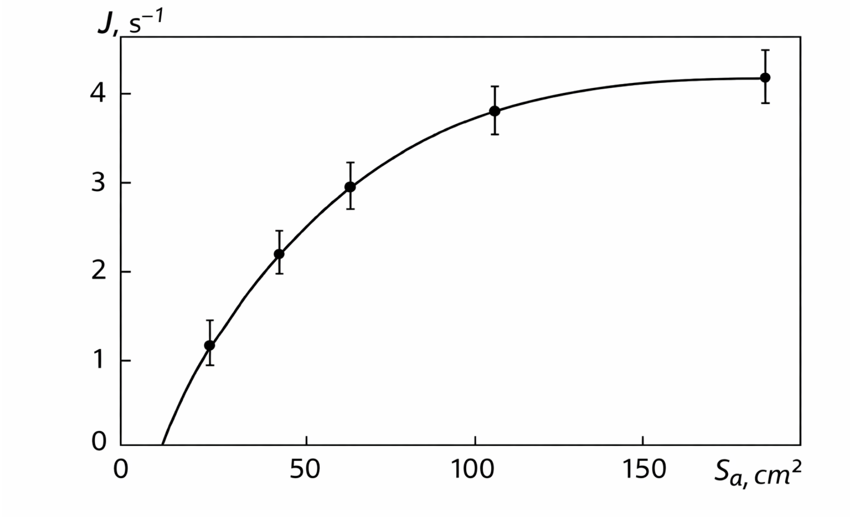

Figure 5: Dependence of the UCN count rate J on the detector area S_a in the neutron guide. Note: Compiled from Ref. [46], p. 52.

The next stage was the development of a universal converter assembly that, while preserving the same geometry, enabled a comparative evaluation of the efficiency of various moderator–converter materials. In the work of the INP team, several basic configurations were implemented:

- a solid converter (a stack of metallic or hydride blocks);

- a water converter (a thin-walled aluminum ampoule filled with water);
- a gas converter (a gas-filled volume with a thin exit window).

Using this facility, the relative UCN yields were measured experimentally for aluminum and magnesium converters, a zirconium-hydride-based converter, a water converter, a gas converter with an aluminum window, as well as for frozen layers of hydrogen-containing liquids [17–19].

A special role was played by the gas converter (Figure 6). It consisted of a sealed cylindrical aluminum vessel with a thin front wall acting as an exit window through which UCNs entered the neutron guide. The internal volume was filled, via nozzles and valve assemblies, with various gases (H_2, para-H_2, D_2, He, Ne, Ar, air, etc.). The converter was water-cooled. When required, the inner surface of the window was additionally cooled down to liquid-nitrogen temperature, which made it possible to freeze thin layers of hydrogen containing liquids onto it. As a result, the same assembly could operate both as a gas converter and as a frozen-layer converter.

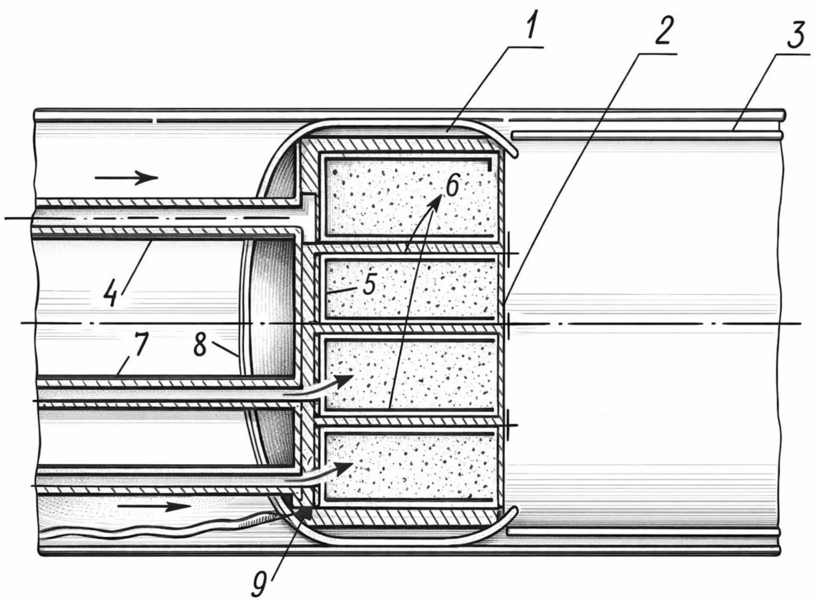

Figure 6: Design schematic of the gas converter: 1 – aluminum converter; 2 – window for UCN from the gas into the neutron guide; 3 – UCN neutron guide; 4 – cooling system tubing; 5 – copper foil; 6 – support rods; 7 – gas inlet tube; 8 – spring; 9 – thermocouple. Note: Compiled from Ref. [24], p. 11.

2.2 The Facility at Radial Channel No. 1 of the WWR-K Reactor

To extend the research program on UCN matter interactions at the WWR-K reactor, a second UCN production facility was commissioned in September 1975 on the horizontal radial channel No. 1 [20]. Its layout is shown in Figure 7. A 5 mm thick disk of zirconium hydride, ZrH_x, installed in a thermal neutron flux of about $2 \times 10^{13}\,\mathrm{cm^{-2}\,s^{-1}}$, was used as the moderator–converter. UCNs were transported from the converter through a cylindrical neutron guide made of electropolished stainless steel, 4 m in length and 9 cm in diameter.

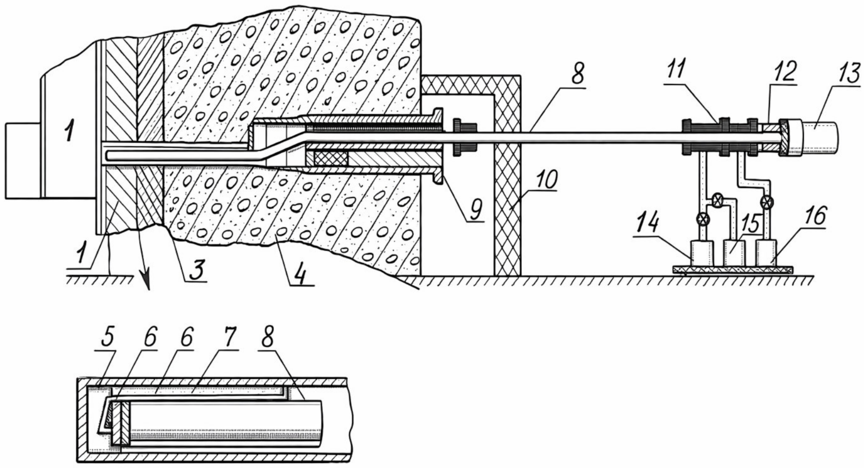

Figure 7: Schematic of the experimental setup at radial channel No. 1 of the WWR-K reactor: 1 – core; 2, 3, 4 – water, cast-iron, and concrete shielding, respectively; 5 – horizontal radial channel; 6 – water-cooling tubes for the converter; 7 – zirconium-hydride converter; 8 – UCN neutron guide; 9 – shielding plug; 10 – additional shielding; 11 – 60 μm-thick aluminum foil; 12 – copper shutter; 13 – UCN detector; 14, 15, 16 – vacuum pumps: magneto-electrical-discharge, zeolite, and diffusion, respectively. Note: Compiled from Ref. [20], p. 179.

To reduce the dimensions of the external biological shielding for the direct beam and to shorten the neutron-guide length, an equivalent shielding plug was fabricated in place of the standard shutter channel. Inside this plug, the neutron guide included two 30° bends and was raised by 24 cm with respect to the axis of the radial channel. The converter was cooled by flowing water at a temperature of $\sim 50\,^\circ\mathrm{C}$. The neutron guide, connected to the experimental apparatus, was separated from it by a 60 μm-thick aluminum foil in order to maintain the required vacuum. Evacuation was provided by an NEM-100 pump with magnetron-discharge, zeolite, and diffusion stages down to a pressure of $\sim 10^{-6}$ torr. UCN detection was performed with a ^{3}He proportional counter equipped with an aluminum entrance window of 60 cm^2. At a reactor power of 10 MW, the UCN count rate was $(139 \pm 2)\,\mathrm{s}^{-1}$ with a background of about 50%, and after six months of operation the intensity decreased by approximately 20%.

The key element of this facility is the gas target chamber (Figure 8), i.e., a section of the neutron guide converted into a hermetic vessel equipped with ports for gas inlet and pumping, as well as pressure gauges and temperature sensors [21]. The chamber is designed to operate both at room temperature and under cooling down to ~ 80 K (liquid-nitrogen jacket, thermal shields). It was filled with H_2, para-H_2, D_2, ^{4}He, Ne, Ar, N_2, O_2, air, Xe, and other gases; for each of them, the UCN transmission was subsequently measured as a function of pressure.

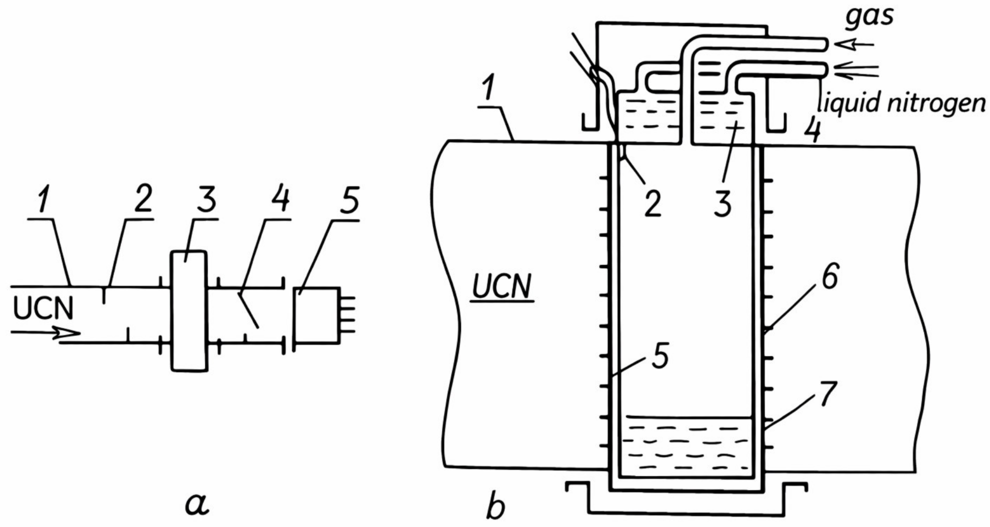

Figure 8: Schematic of the experimental assembly (a) and the gas chamber (b). (a) 1 – neutron guide; 2 – filter; 3 – gas chamber; 4 – shutter; 5 – detector. (b) 1 – neutron guide; 2 – thermocouple; 3 – chamber side wall; 4 – filling and cooling tubes; 5 – windows; 6 – grids; 7 – cooling cavity. Note: Compiled from Ref. [46], p. 63.

A unique two-leg gravitational spectrometer was used for spectrometric measurements [22]. It consisted of a vertical section of the neutron guide equipped with a UCN detector movable in height. At a height z, the detector registered neutrons with energies $E > mgz$. The dependence of the count rate on height made it possible to reconstruct the integral UCN spectrum. Coupling the spectrometer to the setup for measuring UCN transmission through gases enabled studies of the energy dependence of interaction cross sections.

The integral UCN spectrum measured with the gravitational spectrometer exhibited an upper energy cutoff of about 162 neV, which is lower than the wall critical energy (172–187 neV). This was attributed to a ~ 25 neV downward shift of the spectrum resulting from the elevation of the neutron guide by 24 cm with respect to the channel axis. The corresponding curve is shown in Figure 9.

Thus, a suite of facilities for the production and investigation of ultracold neutrons was established and progressively developed at the WWR-K reactor: (i) the tangential-channel setup, optimized for systematic studies of various converters (solid, gaseous, and frozen-layer, including para-hydrogen and frozen water) and for measurements of the UCN energy spectrum using a gravitational spectrometer; and (ii) the facility at radial channel No. 1, dedicated to investigating UCN transmission through materials and gases.

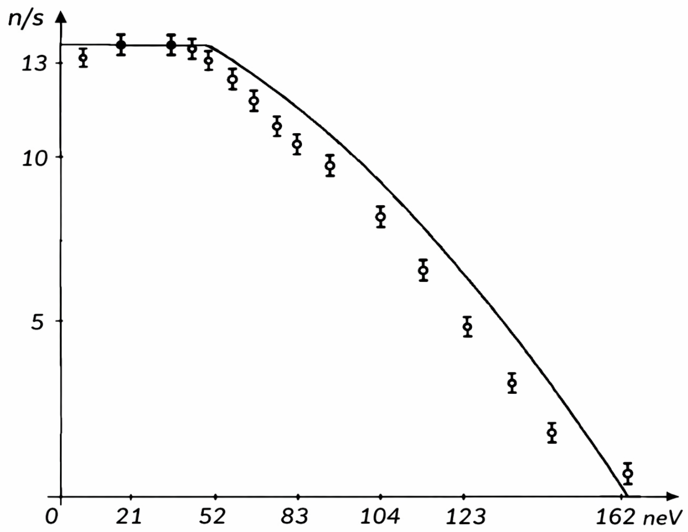

Figure 9: Integral UCN spectrum in radial channel No. 1 of the WWR-K reactor. Note: Compiled from Ref. [46], p. 61.

3 Experiments Performed at the Facilities

Based on the facilities described above, systematic studies were carried out of UCN production in various converter assemblies. The converters were placed at the center of the tangential channel, in a region where the thermal neutron flux density was on the order of $5 \times 10^{12}\,\mathrm{n/(cm^2{\cdot}s)}$ at a reactor power of 10 MW. Aluminum and magnesium converters of different thicknesses, a zirconium hydride based converter, a thin walled ampoule with flowing water, a water converter, and a gas converter were investigated.

The measured UCN count rates for these converter systems at different temperatures are summarized in Table 1.

Table 1: UCN yields from water and solid converter systems.

Converter	Thickness (mm)	Temperature (K)	UCN count rate (s^{-1})
Aluminum	5	400	4.8 ± 0.2
	12	400	5.0 ± 0.2
	5	100	4.2 ± 0.2
Magnesium	10	320	12.7 ± 0.4
	10	100	17.8 ± 0.5
Zirconium hydride	5	300	25.5 ± 0.3
	5	100	40.7 ± 0.5
Water in an aluminum ampoule	10	290	11.9 ± 0.3
Water ampoule	0.25	300	5.0 ± 0.2

The values are recalculated to a detector area of 28 cm^2 and normalized to the UCN yield from the aluminum converter at room temperature. To verify the normalization, activation measurements were performed on aluminum, magnesium, and zirconium-hydride samples using gold and copper indicators. A comparison with calculations based on the theory of Ref. [23] showed agreement within the experimental uncertainty.

Figure 10 shows the temperature dependence of the UCN count rate for the magnesium converter. As the temperature increases, the signal decreases. The theoretical curve, calculated according to the procedure of Ref. [23] and normalized to the room-temperature data point, reproduces the experiment qualitatively, although the measured values are somewhat lower than the calculated ones. Similar behavior was also observed for the aluminum converters.

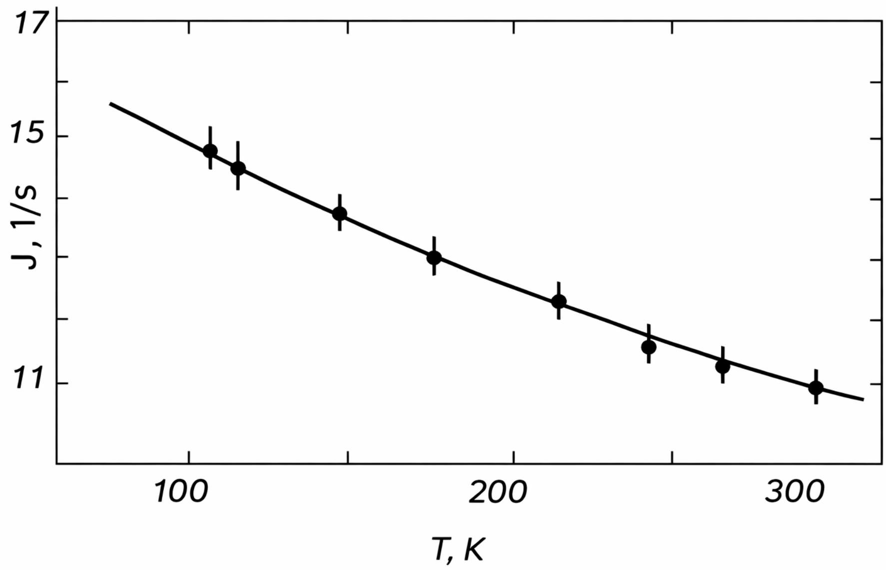

Figure 10: UCN count rate as a function of the magnesium-converter temperature. The theoretical curve is normalized to the experimental value of J at room temperature. Note: Compiled from Ref. [46], p. 70.

Of particular interest was a thin walled water ampoule filled with flowing distilled water at $T \approx 290$ K. According to Table 1, the UCN yield for this system is, within uncertainties, comparable to that of the magnesium converter at higher temperature, although, taking into account reflection losses at the ampoule walls, the effective yield is somewhat lower. This result demonstrates the potential of water as a room temperature UCN converter, which is important from the standpoint of practical implementation.

A broad range of experimental problems was addressed using the gas converter at the radial channel facility [24, 25]. The converter was filled with H_2, para-H_2, D_2, noble gases, and air. In separate series of measurements, thin layers of hydrogen-containing liquids were frozen onto the converter walls and onto the entrance section of the neutron guide.

Figure 11 shows the dependences of the UCN count rate J on the gas pressure p for a number of gases at different temperatures. The highest values of J are obtained for para-H_2 at $T \approx 80$ K, with somewhat lower values for normal H_2. For D_2 and the noble gases, the yield is substantially smaller, whereas for ^{4}He the UCN yield is essentially absent over the pressure range considered. When the converter is filled with air, the signal is small; upon replacing air with ^{4}He, it vanishes. Altogether, these results clearly demonstrate the dominant role of hydrogen and its isotopes in UCN production and the weak contribution from light noble gases [24, 25].

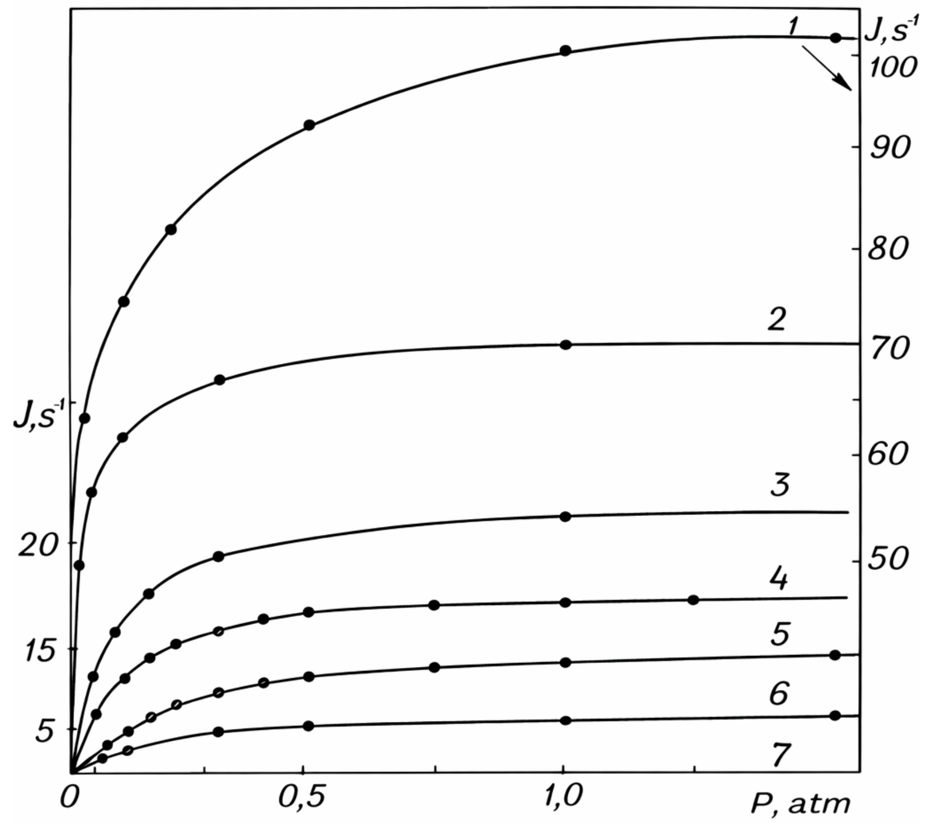

Figure 11: UCN intensity J (s^{-1}) as a function of gas pressure P and temperature for gases filling the converter: 1 – para-hydrogen, 80 K; 2 – hydrogen, 80 K; 3 – deuterium, 80 K; 4 – hydrogen and para-hydrogen, 300 K; 5 – deuterium, 300 K; 6 – air, 300 K; 7 – ^{4}He, 300 K. Note: Compiled from Ref. [24], p. 13.

When the gas converter was filled with water, the UCN yield proved to be lower than for filling with H_2, which was attributed to substantial UCN losses upon reflection from the ampoule walls. To reduce these losses, a technique was implemented in which thin layers of hydrogen-containing liquids were frozen onto the inner surface of the aluminum neutron guide. A metered amount of water, alcohols, and other liquids was introduced into the internal volume with the pumps switched off. After achieving a uniform distribution and restoring the vacuum, the neutron guide was cooled down to liquid-nitrogen temperature, and a layer of thickness d formed on the wall.

Figure 12 presents the averaged dependences $J(d)$ for water and alcohols at $T \approx 80$ K: as d increases, the count rate first rises rapidly and then reaches saturation. A similar saturating behavior was also observed for heavy water frozen onto a zirconium-hydride surface. These results indicate that a relatively thin layer already provides a UCN yield close to the maximum, whereas a further increase in thickness has little effect on the outcome [24, 25].

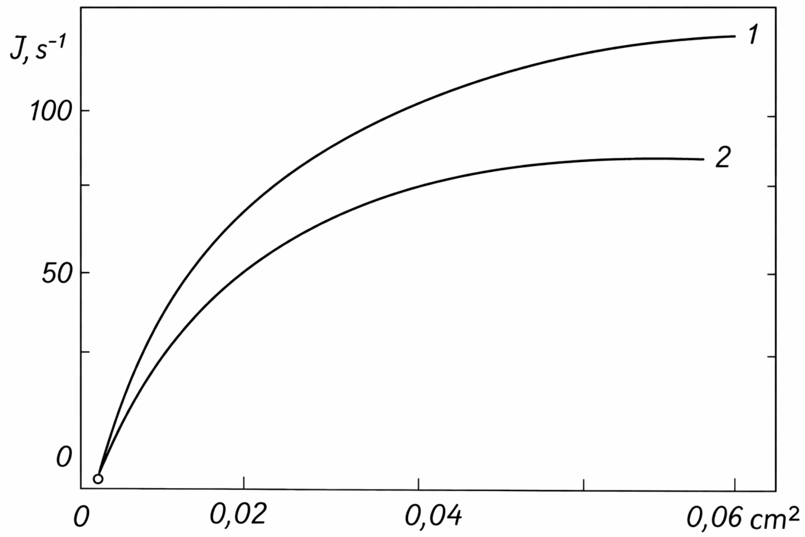

Figure 12: Averaged (over several measurement series) dependences of the UCN intensity J on the thickness d of liquids frozen onto an aluminum substrate.

According to calculations [24], gaseous para-H_2 at $T \approx 80$ K should provide a substantially higher UCN yield than equilibrium hydrogen. Para-H_2 was produced using a paramagnetic converter through which H_2 was passed before being fed into the converter volume. Under real operating conditions, the para component can partially convert back to the ortho component under intense reactor radiation and due to possible catalytic effects of the materials used in the gas converter assembly. Therefore, an important task was to track the temporal evolution of the UCN yield.

A gradual decrease in the yield over the first hours of operation is observed, which is interpreted as a consequence of para-to-ortho conversion upon contact with the walls and the influence of temperature inhomogeneities [25]. This result highlights the need to minimize the length of the gas line and to carefully prepare the surfaces when using para-H_2.

4 WWR-type Research Reactors with a Thermal Column

Research reactors of the WWR type equipped with a thermal column, constructed in the USSR and in the countries of the socialist bloc in the late 1950s–1960s, constituted a standardized family of pool-type, water-moderated and water-cooled facilities intended simultaneously for fundamental research and for applied tasks in nuclear science and technology. The WWR-S reactor design, implemented in Măgurele (Romania) [33,34], was originally regarded as a reference ("typical") project for a series of analogous installations intended for operation both within the USSR and abroad. One of the key elements of this series was the thermal column, coupled to the reactor core via a horizontal channel and accommodated in a dedicated recess of the biological shielding.

Using the WWR-S reactor as an example, the thermal-column design clearly illustrates the essential capabilities of such a unit. According to the description by V. F. Kozlov [35], a horizontal channel of 100 mm diameter is brought to the periphery of the core and mated to a movable (trolley-mounted) thermal column consisting of graphite blocks with a system of vertical experimental channels. The entire column, together with its cast-iron biological shielding, can be rolled out of the shielding recess along rails and returned with high positioning accuracy relative to the core channels. This design enables, within the graphite volume, the formation of an intense, well-thermalized thermal-neutron field with a reduced gamma background and with convenient access for installing large-scale experimental equipment.

It is precisely these features that make thermal columns natural candidates for hosting cold- and ultracold-neutron (UCN) sources. In contrast to small-diameter horizontal experimental channels, a thermal column provides a substantial volume – both in transverse dimensions and depth – with a high thermal-neutron flux, where it is feasible to accommodate a low-temperature cryogenic module (premoderator and UCN converter) based on liquid or superfluid helium, as well as UCN-transport components. At the same time, the distance to the core and the intervening layers of graphite and heavy shielding can markedly reduce the gamma load and heat deposition in cryogenic assemblies, which is a critical prerequisite for stable operation of UCN sources.

The six WWR-type reactors considered in the present work are structurally close to one another: WWR-S (Măgurele) [33, 34], WWR-SM (Tashkent) [36], two WWR-M reactors (Gatchina and Kyiv) [37–39], WWR-c (Obninsk) [40], and WWR-K (Almaty) [41]. The principal technical parameters of these reactors are listed in Table 2. All of them are pool-type, heterogeneous, water-moderated and water-cooled reactors with downward coolant flow through the core, surrounded by a beryllium or water reflector, and they feature an extensive system of horizontal and vertical experimental channels as well as a thermal column integrated into the biological shielding.

The WWR-S reactor in Măgurele (IFIN-HH, Romania) was the first representative of this family built outside the USSR (Figure 13). It was a 2 MW pool-type thermal-neutron research reactor with nine horizontal and sixteen vertical experimental channels, one movable thermal column, and three biological channels. The reactor operated from 1957 to 1997, providing a high thermal-neutron flux and a broad range of experimental capabilities. In 2002, the Romanian government adopted a decision on its final shutdown for decommissioning, after which a staged dismantling program was implemented, culminating in the complete release of the site from regulatory control and the repurposing of the building for non-nuclear radiation technologies. As a consequence, WWR-S no longer exists as a potential platform for a UCN source.

The WWR-SM reactor (Figure 14) at the Institute of Nuclear Physics of the Academy of Sciences of Uzbekistan (Tashkent), which is of a similar type, was originally commissioned as a multipurpose research facility. In accordance with the institute's profile, its experimental infrastructure was oriented toward fundamental studies and applied developments in nuclear and relativistic nuclear physics, radiation physics and materials science, neutron activation analysis, radiochemistry, instrumentation, as well as the production and application of radionuclide products. In recent years, reactor operation has in practice been concentrated on radionuclide production, and the infrastructure around the core has been transformed accordingly. In this configuration, the use of the thermal column for deploying a large-scale UCN

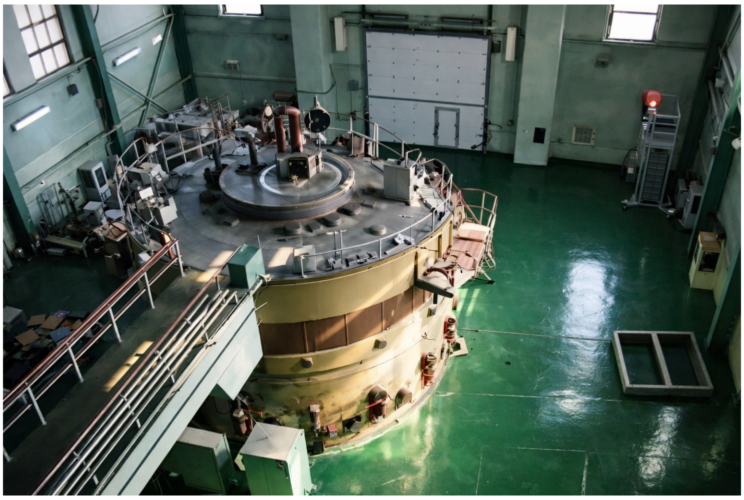

Figure 13: The WWR-S Reactor in Măgurele (IFIN-HH, Romania).

source based on liquid helium becomes technically and organizationally challenging.

Figure 14: The WWR-SM Reactor at the Institute of Nuclear Physics of the Academy of Sciences of Uzbekistan (Tashkent).

The WWR-M reactors in Gatchina (Figure 15; PNPI, formerly LNPI of the USSR Academy of Sciences) and in Kyiv (Figure 16; Institute for Nuclear Research, NAS of Ukraine) are also pool-type facilities and employ broadly similar design solutions. In the Ukrainian WWR-M variant, the reactor vessel is an aluminum tank with a volume of about 22 m^3, a diameter of 2300 mm, and a height of 5705 mm. Nine "cups" (nozzles) for horizontal experimental channels are welded into the vessel wall, and a thermal-column recess with a diameter of 1150 mm is provided, directly coupled to the core and the beryllium reflector. The experimental infrastructure comprises nine horizontal channels, one thermal column, and thirteen vertical isotope channels. Historically, this reactor has been used for a broad range of studies in radiation materials science, nuclear-power engineering, neutron activation analysis, as well as for the production of radioisotopes and radiopharmaceuticals.

At the same time, a decommissioning concept has already been developed for the Kyiv WWR-M, and a decontamination program has been approved. The program

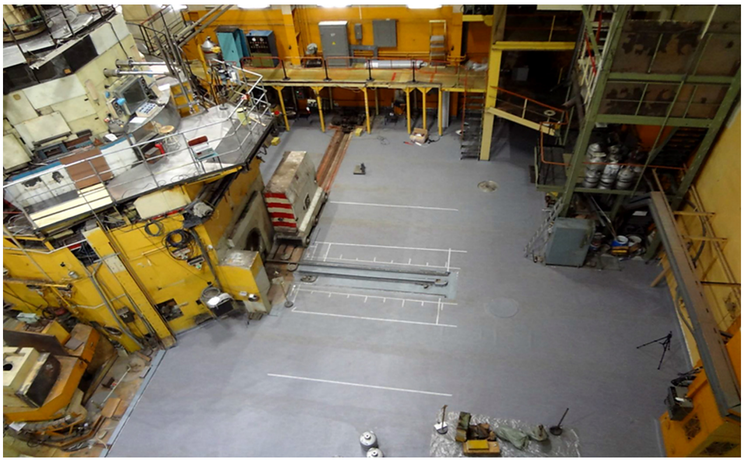

Figure 15: The WWR-M reactor in Gatchina (PNPI, formerly LNPI of the USSR Academy of Sciences).

Figure 16: The WWR-M reactor in Kyiv (Institute for Nuclear Research, NAS of Ukraine).

adopts an immediate dismantling strategy, providing for the stepwise removal of major assemblies and the final "release" of the site for non-nuclear radiation technologies. This implies that the long-term development horizon required for the deployment and sustained operation of a UCN source is substantially limited for this reactor.

The WWR-c reactor (Figure 17) at the L. Ya. Karpov Research Institute of Physical Chemistry in Obninsk is, to the greatest extent, oriented toward radionuclide production (primarily for medical applications) and toward the development of the associated technological and diagnostic infrastructure. In particular, it is used to optimize the production of ^{99}Mo and other high-demand isotopes. From the design standpoint, WWR-c is also a pool-type reactor with a cylindrical aluminum tank, a core located in the central region, vertical and horizontal experimental channels, and a thermal column that is identified in the design documentation as a separate unit (item 3 in the vertical cross section). The tank accommodates 28 vertical experimental channels, and five horizontal channels, as well as a recess for moving a mobile experimental device, are brought to the core separator. This emphasizes the high degree of utilization of the core periphery by the existing experimental equipment.

Figure 17: The WWR-c reactor at the L. Ya. Karpov Research Institute of Physical Chemistry in Obninsk.

Finally, the WWR-K research reactor (Figure 18) at the Institute of Nuclear Physics (INP) in Almaty belongs, in terms of its design, to the same family of pool-type, water-moderated and water-cooled reactors with a thermal column as the facilities listed above. The key distinction of its present status is that WWR-K remains an operating installation with a long-term outlook for continued operation and modernization, and the Institute's strategic plans include the development of very-cold- and ultracold-neutron sources on its basis, together with the advancement of the corresponding areas of fundamental and applied neutron physics.

Figure 18: The WWR-K research reactor at the Institute of Nuclear Physics (INP) in Almaty.

Moreover, the WWR-K thermal column is structurally accessible for the installation of a dedicated liquid-helium-based cryogenic module, which makes it possible to implement a UCN source directly in the region of the maximum attainable thermal-neutron flux without interfering with the existing experimental channels.

Thus, despite their common origin and the close similarity of the WWR-S, WWR-SM, WWR-M, and WWR-c reactor designs, their present-day status and institutional priorities differ in a fundamental way (see Table 2). WWR-S has been permanently shut down and is being dismantled. WWR-SM operates de facto as a radionuclide-production reactor. The WWR-M reactor in Gatchina has been placed in long-term shutdown. For the WWR-M reactor in Kyiv, a decommissioning program is underway. WWR-c is deeply integrated into isotope-production and medical infrastructure. Against this background, WWR-K remains the only reactor of this family for which the combination of design features and the long-term development strategy of the Institute of Nuclear Physics makes the creation of a liquid-helium-based UCN source in the thermal column a realistic objective.

Table 2: Key characteristics of research reactors with a thermal column.

No.	Parameter	WWR-S	WWR-SM	WWR-M	WWR-M	WWR-c	WWR-K
1	Country (site)	Romania, Magurele	Uzbekistan, Tashkent	Russia, Gatchina	Ukraine, Kyiv	Russia, Obninsk	Kazakhstan, Almaty
2	Year of first criticality	1957	1959	1959	1960	1964	1967
3	Thermal power, MW	2	10	18	10	15	6
4	Coolant	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O
5	Moderator	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O + Be
6	Reflector	H_2O	Be	Be	Be	H_2O	H_2O + Be
7	Thermal neutron flux density, n/(cm^2·s)	2×10^{13}	1.2×10^{14}	4×10^{14}	1.2×10^{14}	1×10^{14}	2×10^{14}
8	Status	Shut down	Operational	Shut down	Shut down	Operational	Operational

5 Concept of a UCN Source for the WWR-K Reactor

After the decision had been taken to preserve the WWR-K research reactor as an operating facility with a long-term modernization program, a dedicated concept of the AlSUN ultracold-neutron source (Almaty Source of Ultracold Neutrons) was developed at the Institute of Nuclear Physics (INP), specifically tailored to the geometry and neutronic characteristics of this reactor [42]. The concept is based on the use of superfluid ^{4}He(SF ^{4}He) [43] in the WWR-K thermal column, employing an accumulation regime in the production region and subsequent high-efficiency transport of UCNs to experimental setups, with the converter temperature below ~ 1 K.

At present, there are two "in-reactor" (in-source) projects employing superfluid helium may be highlighted. One of them is being pursued at TRIUMF (Canada), where the source is installed at a tungsten target irradiated by 483 MeV protons [47]. The expected total UCN production rate in the source is $(1.4\text{–}1.6) \times 10^7$ UCN/s, and the expected volumetric UCN density in a 70 L experimental apparatus for neutron EDM measurements is about 220 UCN/cm^3. The other UCN-source project was developed at the WWR-M reactor of the Petersburg Nuclear Physics Institute (PNPI, Russia), with an expected UCN production rate of $(6\text{–}8) \times 10^7$ UCN/s and an expected volumetric density of $\sim 10^4$ UCN/cm^3 in the experimental apparatus [48]. These two broadly similar projects differ not only in the type of primary neutron source, but also in the superfluid-helium cooling schemes. In the first project, cooling the superfluid helium to $T \sim 0.8\text{–}1$ K is envisaged using a ^{3}He-based refrigeration system, whereas in the second project a direct pumping of ^{4}He vapor through a cooling circuit is employed to reach $T \sim 1.2$ K.

At the 6 MW WWR-K research reactor (Water–Water Reactor Kazakhstan), it is possible to implement a UCN-source concept similar to those proposed at TRIUMF (Canada) and at the WWR-M reactor (PNPI, Russia). For this purpose, as in the case of WWR-M, the WWR-K reactor is equipped with a thermal column – a large-diameter (1 m) channel directly adjacent to the reactor core. The WWR-K thermal column (Figure 19), as in the WWR-M reactor, is a cylindrical channel of 1 m diameter directly adjacent to the core. Between the core and the front wall of the thermal column, there is a water layer of variable thickness; its minimum thickness in the central part is about 5 mm, which provides the extraction of the maximum thermal-neutron flux into the column. According to MCNP6.2 calculations [44], the maximum thermal-neutron flux at the front wall of the thermal column at a reactor power of 6 MW reaches $(1.21 \pm 0.06) \times 10^{12}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ [45]. With a comparatively modest reactor thermal power, this configuration provides favorable conditions for accommodating several sequential source components: a γ-shield, a moderator, a premoderator, and a cold UCN converter, as well as the required cryogenic and experimental equipment.

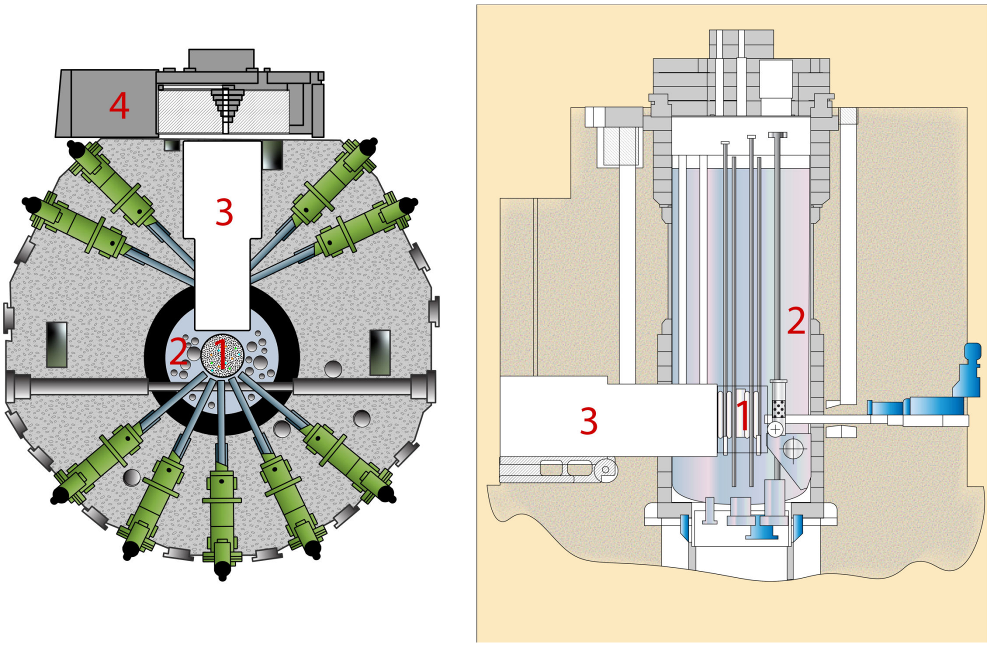

Figure 19: Scheme of the WWR-K reactor: top view (**left**) and side view (**right**). 1 – reactor core; 2 – moderator H_2O; 3 – thermal column; 4 – rollback protection.

Structurally, the proposed source is a cylindrical trap containing a superfluid ^{4}He volume of about 35 L (diameter ~ 30 cm, height ~ 50 cm), placed in the frontal part of the thermal column and irradiated over an almost full solid angle, close to 4π (Figure 20). The trap is surrounded by a liquid-deuterium volume of ~ 90 L at $T \approx 20$ K, which acts as an efficient premoderator for cold neutrons; outside it are a graphite moderator at room temperature and a lead γ shield with a thickness of about 10 cm, to be optimized with respect to the trade-off between reducing the heat load and attenuating the neutron flux. On the side facing the core, the LD_2 layer is thickened (up to ~ 20 cm), which further suppresses the fast-neutron flux into the superfluid-helium volume. To mitigate radiation heating, the lead shield is placed as close as possible to the front wall of the thermal column, while the irradiation geometry of the converter is retained with high efficiency.

A key feature of the AlSUN concept is the separation of the heat-removal path from the UCN transport path. Heat is removed through the thermally conducting

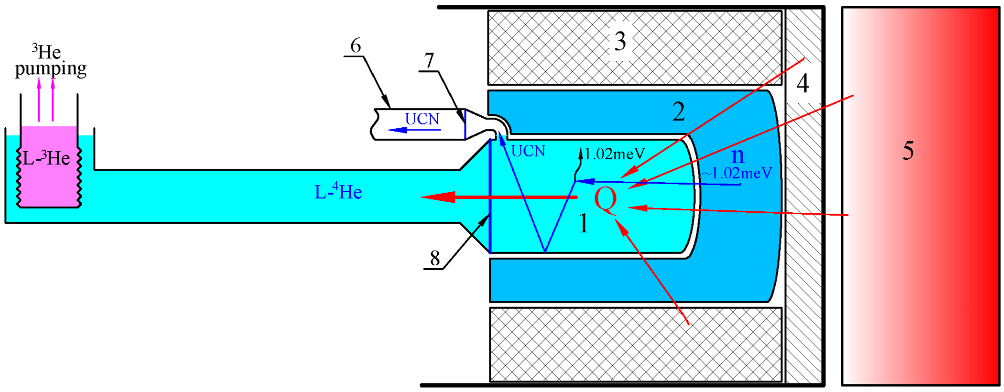

Figure 20: Scheme of the UCN source at the WWR-K reactor. 1 – trap with SF ^{4}He at a temperature $T < 1$ K; 2 – LD_2, $T \approx$ 20 K; 3 – graphite, $T \approx$ 300 K; 4 – Pb; 5 – reactor active zone; 6 – neutron guide; 7 – separating foil; 8 – heat-conducting wall.

rear wall of the trap to a remote cryogenic unit based on pumped ^{3}He vapor, enabling the ^{4}He in the converter to be maintained below 1 K. For an expected total heat load of about 10 W on the SF ^{4}He volume at a reactor power of 6 MW (with roughly two thirds associated with energy deposition in the wall material), the heat flux through a rear wall of 30 cm diameter is ~ 140 W/m^2. Estimates show that, under these conditions, the temperature jump of ^{4}He across the thermally conducting wall (the Kapitza resistance) does not exceed ~ 0.2 K at an operating temperature near 1 K. At the same time, UCNs are extracted from the trap through a comparatively small upper exit window of about 3–4 cm^2, covered by an aluminum separation foil that reflects thermal radiation from the neutron guide and separates the vacuum of the source from that of the transport line.

Neutronic calculations indicate that the differential cold-neutron flux at a wavelength of 8.9 Å in the converter volume is $(1.62 \pm 0.08) \times 10^{10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\text{Å}^{-1}$, which, for a 35 L trap, corresponds to an expected integral UCN production rate of about 2.6×10^7 s^{-1} for beryllium-coated walls ($E \approx 252$ neV). At an SF ^{4}He temperature of ≈ 0.9 K, the calculated UCN storage time in a closed trap reaches ~ 80 s, corresponding to a maximum achievable accumulation density of $\sim 6 \times 10^4$ UCN/cm^3. Taking into account the optimal exit-window size, gravitational spectral selection, transmission through the separation foil, and losses in a transport line equipped with a focusing neutron guide of about 5 m length, the expected UCN density in an experimental chamber of comparable volume is $\sim 5 \times 10^3$ UCN/cm^3, close to the performance of the best currently operating sources of this class. A comparison of the proposed AlSUN project with selected current and planned high-intensity UCN sources is given in Table 3. For each external facility or project, the quoted parameters are taken from the corresponding published sources.

The implementation of the concept requires a set of technical solutions and preliminary studies [42]. First, it is necessary to experimentally confirm that the cryogenic system can effectively remove a heat load of order 10 W through the thermally conducting wall at temperatures of ~ 1 K, taking the Kapitza resistance into account. Second, the selection and qualification of wall-coating materials with high critical energy and low UCN loss coefficient is crucial: calculations indicate that increasing the wall critical energy by approximately a factor of two (e.g., by

Table 3: Comparison of the proposed AlSUN project with representative current and planned high-intensity UCN sources.

Parameter	**TRIUMF**	**PNPI WWR-M**	**AlSUN (WWR-K)**
Status	operational / upgraded source	project	proposed project
Primary neutron source	spallation target	reactor	reactor
Power	19.3 kW [47]	16 MW [48]	6 MW [42, 45]
Expected / achieved UCN production rate	$(1.4–1.6) \times 10^7$ UCN/s [47]	$(6–8) \times 10^7$ UCN/s [48]	2.6×10^7 UCN/s [42]
UCN density in experimental volume	220 UCN/cm^3 [47]	$\sim 10^4$ UCN/cm^3 [48]	$\sim 5 \times 10^3$ UCN/cm^3 [42]
Converter	SF ^{4}He	SF ^{4}He	SF ^{4}He

moving from Be to coatings based on ^{58}NiP, diamond-like carbon, etc.) can increase the UCN output through the source window by a factor of $\sim 7–8$, i.e., significantly more than would follow from a simple $E^{3/2}$ scaling. Finally, focusing UCN neutron guides must be developed and optimized; in such guides, the average number of neutron–wall collisions and the associated losses are reduced by about an order of magnitude compared to straight cylindrical channels, thereby providing a multiple increase in the UCN density at the entrance to experimental apparatus. Taken together, these measures make the AlSUN concept physically and technically viable and define a concrete program for further R&D and modernization of the WWR-K thermal column.

6 Conclusion

The present work provides a coherent overview of the emergence and development of ultracold-neutron (UCN) research in Kazakhstan and at the Institute of Nuclear Physics (INP) in Almaty. It analyzes the key prerequisites and presents a concept for a new UCN source at the WWR-K research reactor. The historical evolution of UCN experiments, the operational experience with UCN sources at WWR-type research reactors equipped with thermal columns, and the results obtained at the WWR-K facilities form a continuous line of development leading to the current stage – the design of an upgradable UCN source based on the WWR-K thermal column.

A comparative analysis of six WWR-type research reactors with thermal columns, at which UCN sources were realized during the Soviet period, shows that WWR-K is the only facility that remains in operation with a long-term perspective for modernization. Combined with the favorable neutronic characteristics of its thermal column and the successful UCN production and utilization experiments, this makes WWR-K a natural platform for the development of a modern high-intensity UCN source.

On the basis of calculated and experimental data for the WWR-K thermal column, a UCN-source concept is formulated that includes the installation of a dedicated cryogenic module in the region of maximum thermal-neutron flux density, optimization of the neutron spectrum and spatial distribution, and efficient extraction of UCNs to experimental stations. The proposed technical solutions can be implemented while meeting nuclear and radiation safety requirements, ensuring adequate heat removal, and providing sufficient radiation resistance of the source components.

The implementation of the proposed UCN-source concept at WWR-K will enable the establishment of a long-term, internationally competitive program of fundamental and applied UCN research in Kazakhstan, including precision experiments on fundamental symmetries and searches for new physics, as well as a broad range of neutron-physics and materials-science studies. In this way, WWR-K and INP can occupy a sustainable position within the global infrastructure of slow- and ultracold-neutron research and contribute to the development of future reactor-based neutron science projects in the country.

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