=== **REVIEWS** ===

Instrument Base of the Reactor PIK

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Received June 5, 2020; revised June 5, 2020; accepted June 13, 2020

Abstract—The program of developing the instrument base of reactor complex PIK is reviewed. This program is carried out in correspondence with the Decree of the President of the Russian Federation No. 356 on July 25, 2019 and the Federal Scientific and Technical Program for the Development of Synchrotron and Neutron Research and Research Infrastructure on the 2019–2027s. The general concept and plans of formation of the instrument base are reported in the four-volume manuscript *PIK Reactor Complex* (editors V.L. Aksenov and M.V. Kovalchuk), published in 2015.

CONTENTS

INTRODUCTION

Neutrons as a tool for studying matter and laws of nature are known to have a number of significant advantages over other analytical tools. These advantages are as follows: first, a wide range of distances and times; second, ideal functioning as a probe for studying magnetism; third, high sensitivity and selectivity with respect to chemical elements and isotopes; and fourth, deep penetration into material studied. In addition, the neutron is a very convenient object for studying fundamental interactions, because it is involved in all interaction types that are known to date (strong, weak, electromagnetic, and gravitational).

The potential of neutron methods for analyzing different objects is demonstrated in Fig. 1.

In the second half of the XX century, a particular attention was paid to the creation of neutron research centers in the Soviet Union. A number of remarkable scientists were involved in the development of neutron scattering technique. The experience of using neutron scattering technique was consolidated and inherited by scientific schools of the Russian Federation. In the XXI century, the fields where neutrons are used cover, as well as previously, most of up-to-date problems of fundamental physics and the questions concerning technical applications of neutrons; however, the mainstream of neutron studies is gradually transferred to biological sciences, physics and chemistry of nanostructured and so-called soft materials (polymers, colloids, etc.) and the analysis of materials and methods of target drug delivery.

The National Research Centre "Kurchatov Institute" (NRC KI) in Moscow is the most advanced research centre in Russia, where modern large physical research systems (primarily, synchrotron radiation and neutron sources) are used in life sciences. An interdisciplinary world-level center (Center of Converging Nano-, Bio-, Information, and Cognitive Sciences (NBICS Center)) has been organized at the NRC KI in the last years. The Department of Molecular and Radiation Biology at the Konstantinov Petersburg Nuclear Physics Institute of the NRC KI (Gatchina) has been successfully functioning since the 1960s.

A neutron source can be used most efficiently when high-efficiency neutron beams extracted from a high-flux reactor are supplied without loss to ultramodern
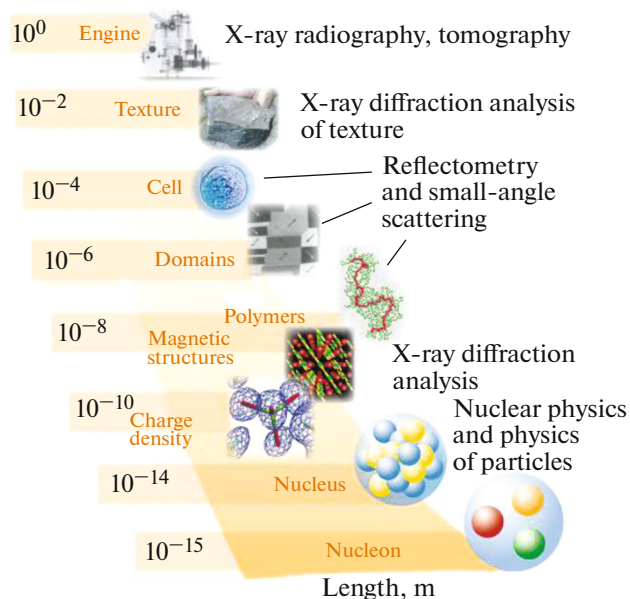
Fig. 1. Comparison of objects studied by different neutron scattering methods and their scales.

1. INSTRUMENTAL PROGRAM IN CONDENSED-MATTER PHYSICS AND BIOPHYSICS

1.1. Neutron Diffraction Complex

Exact knowledge of the atomic structure of materials, being a basis for correct understanding of their properties, allows one to change deliberately these properties. Traditionally, the fields of study of condensed matter in which the use of neutron diffraction is most efficient are considered to be as follows: structural analysis of compounds consisting of light and heavy atoms (hydrides, oxides), compounds with elements having close numbers (alloys, intermetallic compounds), and biological compounds with application of isotopic contrasting (basically replacement of hydrogen with deuterium) of their individual fragments, as well as analysis of the magnetic structure of crystals (i.e., determination of the magnitude and direction of atomic magnetic moments (MMs)). In all aforementioned cases, X-rays fail to distinguish details that are necessary for solving structure. An important factor is the low (in comparison with X-rays) neutron absorption in a medium. As a consequence, the neutron penetration depth in a material may be fairly large (up to several centimeters), due to which one can obtain more adequate structural information and study the microstructure of bulk materials and engineering products.

The range of application of neutron diffraction, as well as the experimental possibilities of this method, have dramatically expanded for the last time. The conventional lines of research (physics, chemistry, materials science) were supplemented with molecular biology, pharmacology, geology, and engineering sciences. The general technical progress and new concepts in the diffractometer design, formation of neutron beams, and development of detector systems have provided possibilities in neutron-diffraction studies that seemed to be impossible only 15−20 years ago. Currently, one can determine ab initio the crystal structure, refine the complex structure of both conventional materials and nanomaterials, analyze local structural distortions with an error of ∼0.1 Å, investigate transient process with characteristic times at a level of 10 s, and operate with samples having a volume of ∼1 mm^3.

A unique range of application of neutron diffraction is the study of the magnetic structure of crystals at the atomic level, i.e., the spatial distribution of MM density (in the simplest case, determination of the magnitude and direction of atomic MMs). The magnetic scattering of neutrons is determined by the magnitude of effective MM (the sum of orbital and spin moments of shell electrons), i.e., depends on the scattering angle. Using polarized neutrons, one can measure very small (several hundredths of Bohr magneton) atomic MMs.

experimental setups, which make it possible to perform most advanced studies in all the aforementioned fields. Therefore, both components (the high neutron source efficiency and modern level of instrument base) are of equal importance for successful implementation of scientific programs of the International Center of Neutron Research based on the PIK (Russian abbreviation for the "vessel beam research") reactor. Thus, one of the main principles of the general concept of the design of experimental stations—upgrade of the instrument base—should be performed hand-in-hand with the improvement of the source.

The work on equipping the PIK reactor complex with modern systems and devices is performed within two projects: "Reconstruction of the Laboratory Complex for the PIK Research Reactor Complex" (completion period 2017−2020) and "Formation of the Instrument Base for the PIK Reactor Complex" (completion period 2019−2024). These projects should result in a research complex equipped with 25 neutron stations, two cold-neutron sources, a hot-neutron source, and an ultracold-neutron (UCN) source (Figs. 2, 3), due to which the requests for neutron studies both from the side of the scientific and technological complex of Russia and from the side of many European partners will be satisfied for a long time. Ten neutron-guide systems (Fig. 2) make it possible to transport neutrons to 17 experimental setups, which are located in the neutron-guide hall under low-background conditions. In total, it is planned to provide up to 50 positions on beams in three experimental halls of the complex, on which different research groups can perform experiments simultaneously.
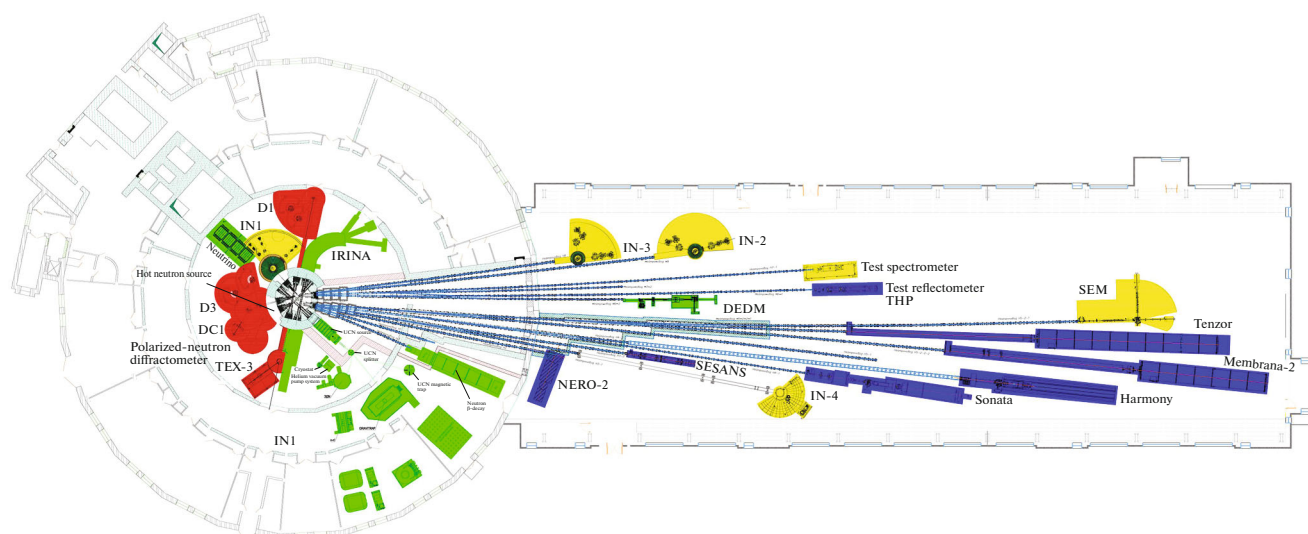
Fig. 2. Schematic arrangement of experimental setups in the hall of horizontal channels and neutron-guide hall.

Among the most important achievements obtained using neutron diffraction, we should note the direct proof of the existence of different types of magnetic ordering; the proof of the fundamental importance of hydrogen bonds in polymers and organic macromolecules; the determination of fine details of high-temperature superconductor structure; the detection of different types of magnetic, charge, and orbital ordering in complex oxides of transition metals; and many others. Examples of studies performed with the use of powder and single-crystal neutron diffraction can be found in [1, 2].

High-resolution powder neutron diffractometer D1 is intended for structural studies using elastic neutron scattering at a constant wavelength with subsequent full-profile analysis of measured neutron diffraction patterns. On the one hand, diffractometer D1, being most conventional with regard to solved problems, is intended for studying (using soft monochromatic neutron radiation) crystalline (organic, inorganic, and complex) compounds, magnetic structures, and the temperature evolution of crystal and magnetic structures of objects with a unit-cell parameter of several or several tens of angstrom, i.e., the overwhelming majority of inorganic materials (including nano- and multilayer materials). At the same time, due to the high resolution and high intensity of neutron flux, one can use diffractometer D1 to solve such fundamental problems of crystallography as ab initio structure solution using powders [3, 4].

D1 is convenient for Rietveld analysis of relatively large structures, such as zeolites with adsorbed molecules, fullerenes, and fullerene-like compounds, as well as for solving structures of some new "quasicrystalline" materials.

Diffractometer D1 is located on the thermal neutron beam emerging from the horizontal experimental channel GEK-6' (Fig. 4). The principle of operation of D1 implies the use of the widest range of neutron radiation spectrum, implementation of variable wavelength, maximal focusing and concentration of neutron beam on samples of different sizes, provision of maximally possible resolution at a sufficiently high aperture ratio, and high data collection rate due to the use of a complex wide-aperture and high-efficiency detector system.

The parameters of diffractometer D1 are as follows: monochromator exit angle ($2\theta_m$) not smaller than 125°; neutron wavelength after monochromator $\lambda = 1.2-2.5$ Å; working scan step $2\theta_i$ is 0.05°; diffracto-
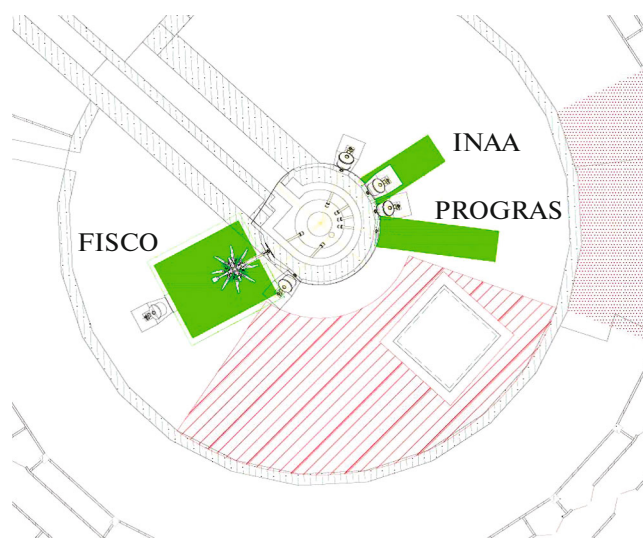

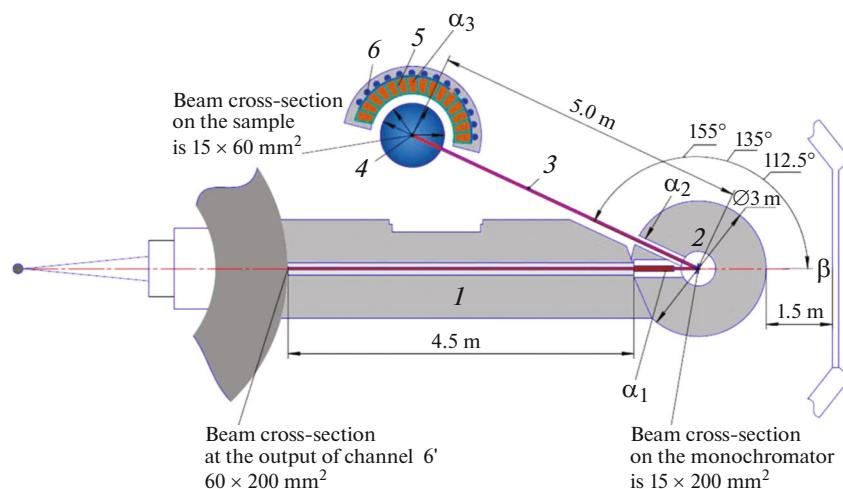**Fig. 3.** Hall of inclined channels.

Fig. 4. Schematics of high-resolution powder diffractometer D1 on the channel GEK-6': (*1*) neutron guide, (*2*) monochromator, (*3*) optical collimator, (*4*) sample table, (*5*) detector collimation system, and (*6*) detector.

meter resolution $\Delta d/d < 3 \times 10^{-3}$ (can be improved several times during exploitation); angular scan range $2\theta = 4°-168°$; maximum momentum transfer $Q_{max} = 12.5$ Å^{-1}; available interplanar spacing range $d = 0.5-15$ Å; and neutron beam cross section in the sample plane is $(10 \times 10)-(10 \times 50)$ mm^2.

High-intensity powder diffractometer of D3. Thermal-neutron powder diffractometer D3, which is characterized by a high flux at the sample position, is intended for studying the atomic and magnetic structure of various compounds [3, 4]. The experiments that call for high intensity can be separated into two groups. The first includes experiments requiring a high measurement rate: investigations with a high temporal resolution, i.e., with a short measurement time. In particular, these are studies in situ and in operando, in which the data collection rate is an important factor for detecting rapidly disappearing precursors or reaction mediators. Fast data collection is necessary for studying phase transitions (PTs) or observing the structure evolution with a change in temperature, pressure, and magnetic and/or electric fields. The second group includes experiments where the sample amount is very small (sometimes no more than 10 mg). Other examples of experiments for which high intensity is important are structural studies of hydrogen-containing samples, weak effects in the fundamental physics of magnets and functional materials, and many others.

The main parameters of diffractometer D3 are as follows: monochromator crystal angles are 44.22° and 90°; neutron wavelengths (for neutrons incident on a sample) $\lambda = 2.52, 1.54, 1.36$, and 1.28 Å; working scan step is 0.05°; interplanar spacing resolution $\Delta d/d \sim 2 \times 10^{-3}$; angular scan range $2\theta = 4°-132°$; and neutron beam cross section in the sample plane is 8×30 mm^2. Linear position-sensitive helium counters (for exam-

ple, Reuter-Stokes 975×8.4 mm) are proposed as detectors.

Four-circle thermal-neutron diffractometer DC1 is intended for studying the atomic and magnetic structure [3, 4]. Diffraction from a single crystal makes it possible to observe finer structural reactions that are inaccessible for the diffraction from a powder or polycrystal. For example, very weak Bragg reflections or weak diffuse scattering can be measured. Diffractometer DC1 is located on the thermal neutron beam outgoing from the horizontal experimental channel GEK-9 (Fig. 5).

The parameters of diffractometer DC1 are as follows: working wavelengths 0.9, 1.2, and 2.4 Å (Cu, Si, and PG focusing monochromators); monochromatization $\Delta\lambda/\lambda \leq 3\%$; angular range of detection around the vertical axis 2θ from −20° to 120°; angular range of detection around the vertical horizontal axis 2θ from −12.5° to 25° (or vice versa, from −25° to 12.5°, depending on the design of detector lift device); proposed sample size no more than 10×10 mm; ranges of sample rotation angles: ω from −34° to 48°, χ from −80° to 200°, and Φ from −179° to 179°, the operating range depends on the sizes of χ ring, sample table, and cryorefrigerator; the error in setting the system to a specified angle no worse than 0.001°.

Four-circle thermal-neutron diffractometer for texture analysis TeX-3. TeX-3 is a four-circle thermal-neutron diffractometer, optimized for studying the texture (orientational distribution of crystallites) in polycrystalline materials. The anisotropy of polycrystalline materials affects significantly their behavior under different thermomechanical treatments, which is highly important for optimizing such processes. Note that crystallites have a preferred orientation in more than 90% of all crystalline materials. Thus, an analysis of crystal texture gives very rich information for many various investigations: from establishing the
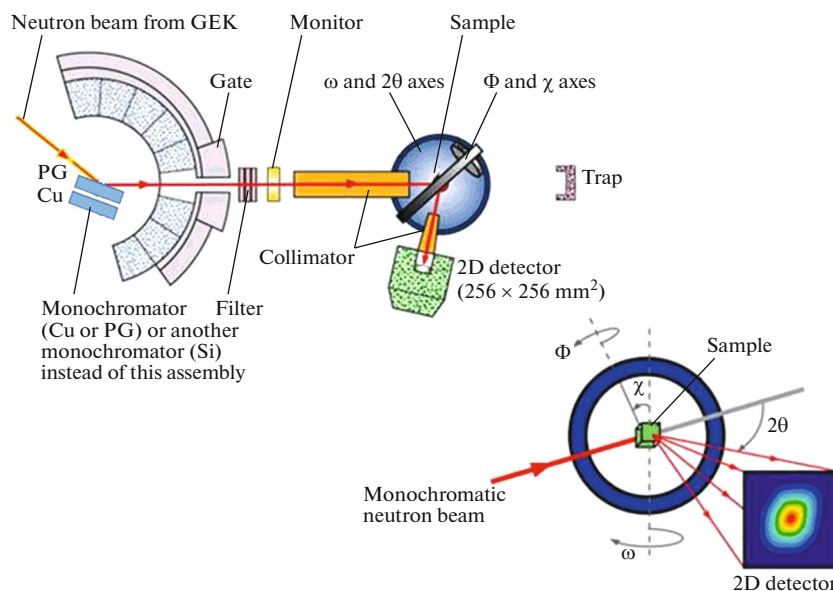
Fig. 5. Schematic arrangement of diffractometer DC1 on GEK 9.

relationship between the structure and properties of latest functional materials to understanding the occurrence of geological processes in rocks. The materials under study vary from pure metals and their alloys, intermetallic compounds, and composites to minerals.

Different approaches are used to determine texture. Currently, diffraction techniques are applied most widely to measure the parameters of preferred crystallographic orientation. X-ray diffraction with a pole-figure goniometer is a generally accepted standard for such measurements. Nevertheless, neutron diffraction has some significant advantages, especially in the case of bulk samples. For most of materials, the attenuation of incident neutron beam due to absorption and scattering is an order of magnitude lower than in the case of X-rays. Therefore, the neutron penetration depth is on the order of centimeters instead of several millimeters for X-rays. A necessary condition for unambiguous interpretation of intensity variations in X-ray techniques (in both Bragg and Laue geometries) is to retain the narrow incident beam within the region under study during sample rotation. In contrast, when using neutrons, it is preferred to place a bulk (1−10 cm in diameter) sample in a wide beam, due to which the same volume can be investigated at any stage. Since the diffracted signal is averaged over volume rather than over surface in this case, the grain statistics is significantly improved in comparison with conventional X-ray studies. Thus, neutron diffraction has undoubted advantages for determining complete pole figures in coarse-grained aggregates.

The X-ray scattering intensity depends strongly on the Bragg angle, whereas in the case of neutrons this dependence is practically absent. Therefore, the peaks obtained at large angles can be estimated more exactly

applying neutron diffraction. Note also that the angular resolution of texture neutron diffractometers generally exceeds that of X-ray diffractometers with pole-figure goniometers, due to which deconvolution of complex diffraction spectra with closely spaced peaks (as, for example, in multiphase systems or low-symmetry materials) can be performed. The diffractometer TeX-3 is placed on the thermal neutron beam emerging from the horizontal experimental channel GEK-6.

The parameters of diffractometer TeX-3 are as follows: diffractometer working wavelength is 1.24 Å; monochromatization $\Delta\lambda/\lambda \leq 3\%$; ranges of sample rotation angles: φ from $-360°$ to $360°$; χ from $-360°$ to $360°$; ω from $-46°$ to $46°$; suggested samples: cube with an edge up to 10 mm, sphere with a diameter up to 20 mm, cylinder with a diameter up to 15 mm and a height up to 15 mm; position-sensitive detector with area of 200×200 mm.

Polarized-neutron diffractometer DIPOL is proposed for a wide range of magnetic studies, such as determination of magnetic structures and specific features of magnetic ordering in crystalline objects, analysis of magnetic phase diagrams, detailed study of complex magnetic structures and magnetic domains, investigation of magnetization density distribution, specific features of magnetic form factor, and local susceptibility. To implement these possibilities, the diffractometer scheme provides operation in two different modes: classical polarized-neutron diffraction and *XYZ*-polarization analysis.

In a classical experiment, a polarized-neutron flux falls on a sample, and the polarization of scattered neutrons is not analyzed. The sample is magnetized by a magnetic field applied along the vertical axis *Z*, the
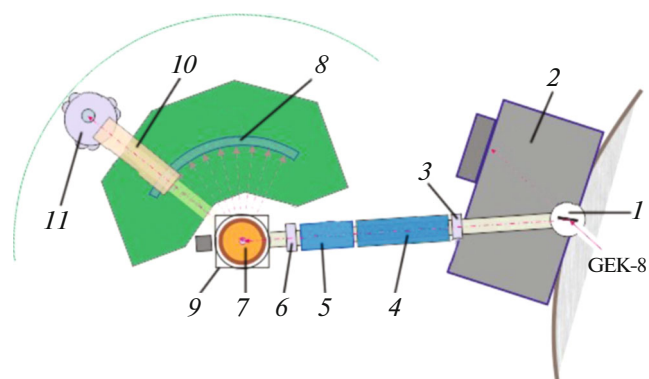
Fig. 6. Schematic arrangement of the main units and functional components of diffractometer DIPOL: (*1*) monochromator unit, (*2*) monochromator protection, (*3*) monitor counter, (*4*) polarizer, (*5*) flipper, (*6*) diaphragm, (*7*) sample unit. Half-polarization mode: (*8*) position-sensitive detector. Polarization-analysis mode: (*9*) guide-field coil on sample, (*10*) polarization analyzer, (*11*) detector unit.

intensities of scattered neutrons are measured for two possible polarization states, and then their ratio R (the so-called flip ratio) is calculated. This mode is also referred to as "half-polarized experiment." It demonstrates a giant increase in sensitivity to weak magnetic signals and is used mainly to study the spin density distribution and specific features of the form factor of magnetic ions in the unit cell.

In the *XYZ*-polarization method, the polarization is oriented along the *X*, *Y*, and *Z* axes, and the spin state of scattered neutrons is analyzed along the same directions. This method is extremely efficient for separating the nuclear and magnetic contributions to neutron scattering and highly demanded when studying systems with interacting order parameters. Polarization analysis also makes it possible to investigate the spin chirality in complex magnetic systems.

The diffractometer equipment for the sample unit is as follows: cryorefrigerator operating in the temperature range $T = 10-340$ K with a vacuum post; cryostat ($T = 1.5-340$ K); temperature controller LakeShore 340; superconducting magnet with a vertical field (up to 7 T); a system for 3D analysis of diffracted neutron beam; and a 2D position-sensitive detector. The diffractometer DIPOL is located on the hot-neutron beam emerging from the horizontal experimental channel GEK-8 (Fig. 6).

The parameters of polarized-neutron diffractometer are as follows: operating wavelengths 0.7 and 1.0 Å; polarized-neutron flux on the sample ($\lambda = 0.7$ Å) $\sim$ 1×10^7 n/(cm^2 s); polarization 95% or more; measurement temperature range 1.5–300 K; and resolution in momentum transfer is 0.01 Å^{-1}.

1.2. Spectrometry Complex

Inelastic neutron scattering (INS), a technique also referred to as neutron spectroscopy, is one of the cornerstones for any neutron research center based on a high-flux neutron source. Dynamic properties play a very important role in condensed-matter physics, chemistry, biophysics, biology, and materials science; hence, the development of the INS method should to be one of the priority works carried out on the PIK reactor. Proceeding from the critical situation with neutron spectroscopy in the Russian Federation, all researchers interested in the revival of this technique in our country may lay their hopes specifically on PIK [3].

INS is used to study the dynamic properties of materials [5–8]. The importance of neutron spectroscopy for condensed-matter physics can be compared with such a highly informative method as neutron diffraction. Neutron spectroscopy and diffraction are complementary techniques, they cannot be counterposed. Diffraction (both nuclear and magnetic neutron scattering) makes it possible to determine the crystal and magnetic structures of materials, i.e., to answer the question where atoms are located (or how their MMs are oriented). Using diffraction, one can also reveal PTs in materials. However, diffraction methods generally do not make it possible to understand the mechanisms of the phenomena occurring in condensed matter, the nature of PTs, and the factors causing formation of a particular ground state of the system. INS may help to answer these deeper questions, because this method yields spectra of elementary excitations, both lattice excitations (phonons), i.e., answers the question how atoms move, and electron and magnetic excitations (magnons, excitons, etc.).

The concept of quasiparticles [9–13]—elementary excitations of different nature—is the most fruitful concept in the condensed matter physics of the XX century and one of the main tools of scientific cognition in this field of fundamental science. It is not a mere chance that, when awarding the Nobel prize for the development of the technique of neutron studies of condensed matter, one half of the prize was awarded for the development of neutron diffraction and the second for the development of INS. Indeed, exact knowledge of the total energy and symmetry of a system of bound atoms (crystal) and the difference between the energies of different crystalline phases does not make it possible to say anything about the physical properties of crystal: specific heat, magnetization, susceptibility, thermal expansion, thermal conductivity, and resistance. At the same time, elementary-excitation spectra (dispersion relations and density of excitation states) allow one to calculate correctly all main physical properties and determine the PT mechanism [8, 14]. In other words, the diffraction in condensed matter physics is to a great extent a method of diagnostics and searching for effects, while spectroscopy is a method for determining the essence

of phenomena and their driving forces and explaining the physical properties of materials. These two techniques, being reasonably combined, supplement each other quite well. A significant deviation in favor of one of them reduces the scientific efficiency of a neutron source.

The excitations available to INS reflect many degrees of freedom of systems studied. Examples of quasiparticles are phonons, magnons (spin waves in terms of the classical theory of magnetism), spin density waves, paramagnons, spinons, excitons, rotons, phasons, etc. [15]. Neutron spectroscopy is a tool for studying excitations (vibrational and rotational) in molecules. There are many types of one-site (single-ion) excitations: local oscillation modes of impurity atoms in crystals, transitions between levels of ground multiplets split in the crystal electric field, intermultiplet transitions. INS is applied to study the critical dynamics and physics of PTs. Neutron spectroscopy plays an important role in studies of diffusion and relaxation phenomena in both solids and soft materials (polymers, biological objects, organic and inorganic compounds). Fluids (including quantum ones), emulsions, suspensions, amorphous materials and other disordered media, quasicrystals—all these objects are characterized by peculiar forms of excitations, which manifest themselves in neutron spectra.

INS is very important for studying the lattice dynamics [16]. Direct measurements of the dispersion relations and density of phonon states (including partial ones) made it possible to study the ion—ion interaction potentials, understand the nature of formation of many materials, and explain the anomalies of their physical properties. In particular, an excellent quantitative description for superconductors with the phonon mechanism of superconductivity was obtained based on INS spectra.

Neutron spectrometers turned out to be irreplaceable for studying PTs (both structural and magnetic) and revealing the modes to which the structural or magnetic instability of system is related [16]. The critical dynamics in the PT physics is another important niche for INS. Neutron spectroscopy plays a key role in the study of magnets of different classes: ferro- and ferrimagnets, antiferromagnets, zone magnets and systems with spin density waves, spin glasses, molecular magnets, and metalorganic magnets. Neutron spectra contain information about effective exchange constants and other important parameters of magnetic systems [17].

INS is considered to be one of the most promising and highly informative methods for solving the problem of high-temperature superconductivity (HTSC) and studying superconductors of different types (in particular, cuprates). Although the HTSC problem has not yet been solved, a very large amount of information on both the lattice subsystem and magnetic excitations has been accumulated to date, which may

play a decisive role in determining the mechanism of HTSC. Currently, the magnetic and lattice excitations in new-generation superconductors based on iron are being studied.

The role played by INS in the study of systems with strong electron correlations can hardly be overestimated. Measurements of magnetic excitation spectra made it possible to reveal the nature of unusual ground states and reveal excitations characteristic of Kondo systems, heavy fermion modes, and intermediate valence. Numerous anomalies of lattice dynamics were found. Low-dimensional systems, including those with quasi-one-dimensional spin chains and quasi-two-dimensional planes of quantum spins, have been investigated by the INS method. Some fundamental results were obtained, and magnetic excitations of new nature were found.

Backscattering spectrometers and spin-echo devices turned out to be irreplaceable for studying the dynamic processes at low energy transfers, which called for extremely high energy resolution (10^{-3} and 10^{-5} meV, respectively) [17, 18]. Low-energy dynamics is characteristic of relaxation processes and physical phenomena characterized by long characteristic times and low frequencies. The class of objects requiring for studies of low-energy dynamics is very wide. Both structural phenomena and phenomena occurring in magnetic and electronic subsystems are investigated.

Triple-axis thermal-neutron spectrometer IN1. Triple-axis spectroscopy makes it possible to tune a spectrometer to measurements at any point of the energy—momentum or reciprocal space. Due to this feature, triple-axis spectrometers are considered to be one of the main tools for comprehensive studies of the inelastic processes in solids and enter the set of experimental setups necessary for a high-flux neutron source. Spectrometric measurements involve the following processes: diffraction of the primary neutron beam from a monochromator (formation of a monochromatic neutron beam, rotation axis *1*), scattering of the monochromatic neutron beam from the sample (rotation axis *2*), and diffraction of the neutron beam from the analyzer (rotation axis *3*). To increase the efficiency of neutron scattering in the spectrometer, the Rowland focusing geometry is applied, in which the source, monochromator, and sample are located on one circumference. The proposed scheme is in correspondence with the modern concepts of designing triple-axis spectrometers. Neutron studies on the spectrometer IN1 will be performed with a variable wavelength at neutron scattering in the horizontal plane. The spectrometer is proposed to be installed in the main hall of the PIK reactor (channel GEK-10, see Fig. 7).

The parameters of spectrometer IN1 are as follows: neutron energy range $E_i = 15-100$ meV, wavelength range $\lambda_i = 0.9-2.36$ Å; monochromatization $\Delta\lambda/\lambda \leq 3\%$; energy resolution $\Delta E \leq 3$ meV (FWHM); suggested sample size no more than 30×30 mm.
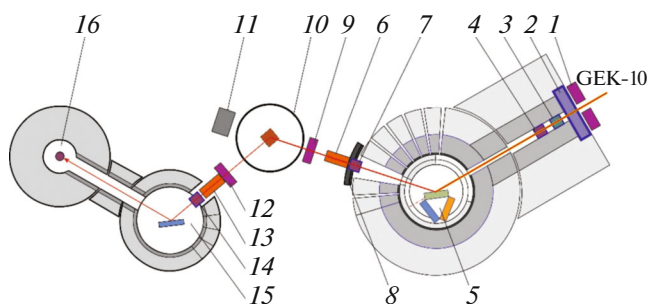
Fig. 7. Schematic arrangement of the main units and functional components of spectrometer IN1: (*1*) input slit (VS), (*2*) shutter, (*3*) filter, (*4*) monitor 1, (*5*) monochromator unit, (*6*, *13*) collimator, (*7*) monitor 2, (*8*) mask, (*9*, *12*) diaphragm, (*10*) sample unit, (*11*) trap, (*14*) monitor 3, (*15*) analyzer unit, (*16*) detector unit. Protection elements are colored gray.

Triple-axis cold-neutron spectrometer IN2 is intended for high-resolution studies of low-energy collective excitations in solids [3]. This spectrometer is expected to provide high resolution in momentum and/or energy transfers and be efficient in solving elastic scattering problems, where an important factor is a large signal/noise ratio. Neutron studies on the spectrometer IN2 will be performed with a variable wavelength at neutron scattering in the horizontal plane. To use efficiently neutron scattering in the spectrometer, Rowland focusing geometry is also applied. The spectrometer is proposed to be mounted in the neutron-guide hall of the PIK reactor (neutron-guide system of channel GEK-2, see Fig. 8).

The parameters of spectrometer IN2 are as follows: energy range 2.3–36 meV; wavelengths 1.5–6.0 Å; monochromatization: $\Delta\lambda/\lambda \leq 3\%$; energy resolution $\Delta E \leq 25, 80, 120$ μeV (FWHM) for incident neutron energies of 2.3, 4, and 5 meV, respectively; and proposed sample sizes (10×10)–(30×30) mm.

Polarized-thermal-neutron triple-axis spectrometer IN3. Along with the energy analysis in the main operating mode of spectrometer, the spin states of the neutrons scattered from the sample are also analyzed. The operation of the spectrometer in this mode should provide efficient solution of problems for complex situations with magnetic and lattice excitations having close energies or momenta. Neutron studies on the spectrometer IN3 will be performed with a variable wavelength at neutron scattering in the horizontal plane [3]. Rowland focusing geometry is also applied in the spectrometer in order to use efficiently neutron scattering. To implement the possibility of polarization analysis, the spectrometer is equipped with a polarizer (installed before the monochromator), two flippers (installed before sample and after it), a system of guiding fields on the sample, and an analyzer of the polarization of neutrons scattered by the sample. The spectrometer is proposed to be mounted in the neu-

tron-guide hall of the PIK reactor (neutron-guide system of channel GEK-2, neutron guide NG-1; see Fig. 9).

The parameters of spectrometer IN3 are as follows: range of neutron energies 15–100 meV, wavelength range 0.9–2.36 Å; monochromatization $\Delta\lambda/\lambda \leq 3\%$; energy resolution $\Delta E \leq 3$ meV (FWHM); suggested sample size no more than 30×30 mm; neutron polarization $P \geq 95\%$.

Time-of-flight neutron spectrometer IN4 is intended for measuring spectra of inelastic neutron scattering in different materials, both in solids (crystals and disordered media) and in liquids, polymers, and other systems of soft-material type in the interests of physics, chemistry, biology, and materials science [3]. A modern time-of-flight (TOF) spectrometer is an efficient scanner of excitations, due to which collective and local excitation modes can be studied in a wide range of energy and momentum transfers. The energy resolution and resolution in the momentum space can be varied by choosing the energy of neutrons incident on the sample and the spectrometer operation mode. The most flexible scheme, which allows one to study both magnetic and structural (lattice) excitations is the direct-geometry spectrometer. The volume of the region available for scanning in the $Q–E$ space for a TOF spectrometer with direct geometry exceeds that for the inverse-geometry spectrometer (Fig. 10). In particular, the range of momentum transfers for the first-type spectrometers is much wider.

To solve various problems of condensed-matter physics, chemistry, biology, and materials science, one must use different measurement modes: both the mode with a high energy resolution (~2%) and the mode with a moderate resolution (~4%) but high intensity. The spectrometer IN4 is a flexible system, which provides a particular operation mode necessary for user.

The parameters of IN4 spectrometer are as follows: the range of neutron energy transfers is 0.5–20 meV; the relative energy resolution in the position of elastic peak not worse than 5%; and the sample size no more than 30×30 mm.

Neutron spin-echo (NSE) setup SEM. The spin-echo spectroscopy setup SEM is intended for studying the dynamics of supra-atomic, molecular, and supramolecular structures: synthetic and biological polymers, macromolecules, and fullerenes. Methods of spin-echo spectrometry are applied to investigate slow relaxation processes. These processes are observed when studying "soft matter" and glass formation: for example, thermal vibrations of membrane surface in a microemulsion; dynamics of polymer chains in a melt; and the motion of thermally activated domains in proteins, which is an important key for understanding protein functions.

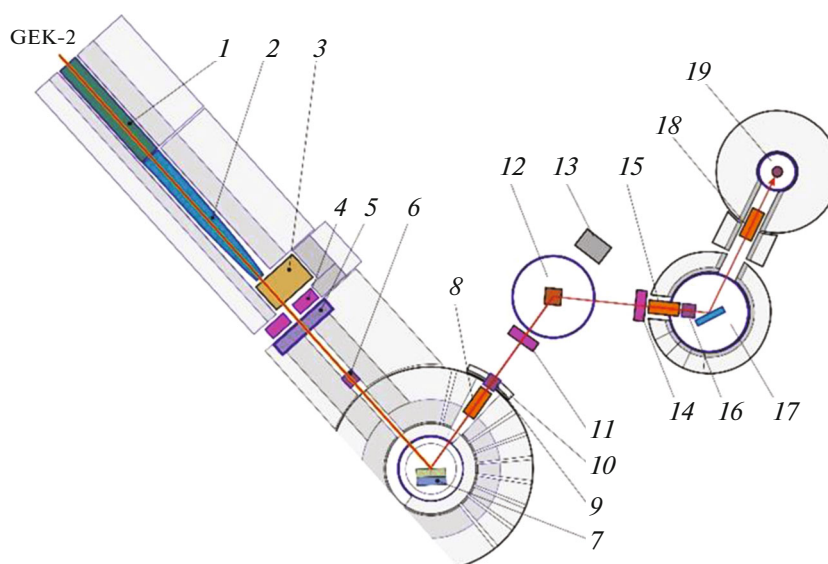NSE spectrometry has the highest energy resolution that can be attained for neutron spectrometers.

Fig. 8. Schematic arrangement of the main units and functional components of spectrometer IN2: (*1*) neutron-guide insert/polarizer, (*2*) elliptical neutron guide, (*3*) velocity selector, (*4*) input slit (VS), (*5*) shutter, (*6*) monitor 1, (*7*) monochromator unit, (*8, 15, 18*) collimator, (*9*) monitor 2, (*10*) mask, (*11, 14*) diaphragm, (*12*) sample unit, (*13*) trap, (*16*) monitor 3, (*17*) analyzer unit, (*19*) detector unit. Protection elements are colored gray.
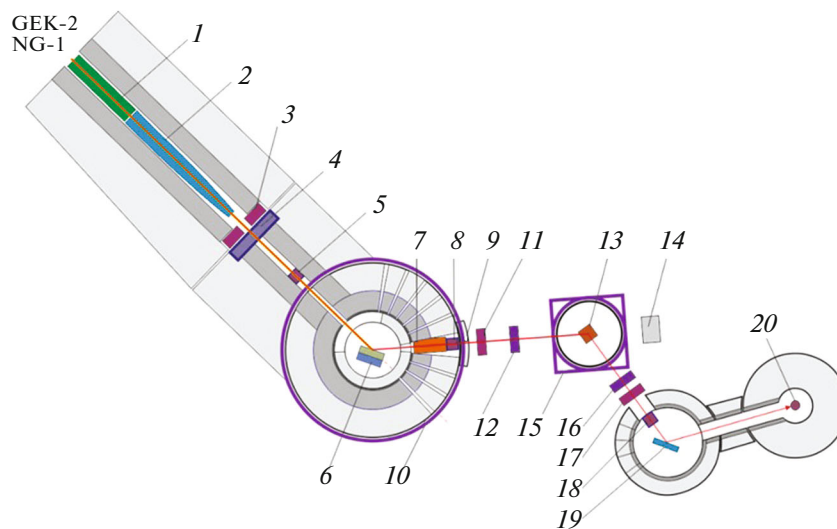

Fig. 9. Schematic arrangement of the main units and functional components of spectrometer IN3: (*1*) insert, (*2*) elliptical neutron guide, (*3*) input slit (VS), (*4*) shutter, (*5*) monitor 1, (*6*) monochromator unit, (*7*) collimator, (*8*) monitor 2, (*9*) mask, (*10*) guide-field coil on monochromator, (*11, 17*) diaphragm, (*12*) flipper 1, (*13*) sample unit, (*14*) trap, (*15*) guide-field coil on sample, (*16*) flipper 2, (*18*) monitor 3, (*19*) analyzer unit, (*20*) detector unit. Protection elements are colored gray.

This method is applied mainly in experiments on quasi-elastic scattering to study the relaxation processes located on the energy scale near zero energy transfer. In contrast to other methods based on inelastic neutron scattering, the NSE technique implies measurement of the intermediate scattering function $S(Q, t)$ at the reciprocal space point Q in dependence of the relaxation time t of the process under study. The range of measured relaxation times, from 10^{-12} to 10^{-7} s,

covers the dynamic scale from microscopic times of atomic collisions and spin exchange to macroscopic times of slow relaxation processes involving large molecules and atomic conglomerates. Unlike other experimental methods providing dynamic information, such as muon spin spectroscopy, NMR, Mossbauer spectroscopy, or measurements of magnetometric susceptibility, NSE yields simultaneously access to microscopic information through the value of momentum
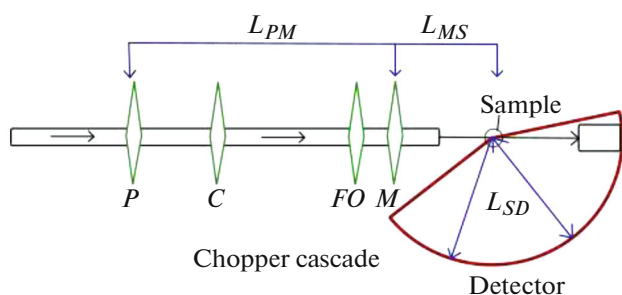
Fig. 10. Block diagram of direct-geometry spectrometer IN4. L_{PM}, L_{MS}, and L_{SD} are, respectively, the distances between the choppers P and M, chopper M and sample S, and sample S and detector D. The C and FO choppers are auxiliary; they absorb neutrons with energy unfit for the experiment (multiply transmitted by the main choppers).

transfer Q in reciprocal space. Thus, NSE can be considered as a link between the aforementioned integral methods and microscopic methods (i.e., conventional techniques of triaxial and TOF neutron spectrometry).

The operation of spin-echo spectroscopy setup SEM is based on the principle of modulation of neutron spectrum over phase wavelengths of Larmor precession of neutron spin in a magnetic field [19]. Two different principles of spin echo are implemented in this instrument: the resonance spin-echo and the Mieze principle (or principle of sinusoidal modulation of neutron flux intensity incident on the sample). Using the neutron spin precession in a magnetic field to measure the dynamic scattering function of objects studied, $S(Q, t) \sim \int S(Q, \omega)\cos(\omega t)d\omega$, the spectrometer makes it possible to separate the processes of changes in the momentum and spin state of neutron in the scattering processes in objects with participation of nuclear and magnetic subsystems. The Mieze option [20] allows one not to restrict oneself to the study of objects with a spin dependence of scattering cross section (magnets, superconductors, hydrogen-containing media) but analyze additionally quasi-elastic processes occurring in practically any systems and under any conditions, including the processes in an external magnetic field.

The spectrometer parameters are as follows: neutron wavelength range 4.0–12 Å; monochromatization $\Delta\lambda/\lambda \leq 20\%$; range of momentum transfers q is 0.01–1.5 Å^{-1}; beam polarization on the sample $P_0 = 0.95$; suggested sample size no more than 20 × 20 mm; range of measured times 0.01–10 ns (at $\lambda_i = 12$ Å) and 0.001–2 ns (at $\lambda_i = 4.0$ Å).

Test neutron spectrometer TNR is intended for measurements of real neutron spectrum on the channel GEK-3. Despite the auxiliary character of the spectrometer, it is demanded for tracking the construction of the neutron-guide system and the entire instrument base in the nearest years. The TNR spectrometer is used to measure the spectra of neutron beams in dif-

ferent portions of neutron-guide channels with subsequent interpolation of experimental data in order to determine the neutron flux at the designed power.

The spectrometer parameters are as follows: measurement range 0.5–20 Å; instrumental resolution 5%; characteristic statistics collection time 1 h (depends on the beam intensity and reactor power); mobile system, which can be installed in any beam.

1.3. Complex of Small-Angle Diffractometers

Small-angle neutron scattering (SANS) is one of the most informative methods for studying the structure of material on the supra-atomic scale: from several nanometers to several tens of micrometers. Therefore, SANS investigations cover an extremely wide class of objects: from the structure of proteins and viruses in biology, medicine, and pharmacology to polymer nanocomposite materials, emulsions, and microemulsions in chemistry, from incommensurate magnetic structures and critical fluctuations at phase transformations in the condensed matter physics to the fractal structures of granular materials in materials science and metallurgy and minerals in geology [21–34].

Small-angle neutron scattering set-up Membrana-2. The small-angle diffractometer Membrana-2 is intended for studying supra-atomic, molecular, and supramolecular structures of different objects: synthetic and biological polymers, macromolecules, and fullerenes [3]. A peculiar class of objects of study includes nanoparticles: nanotubes; catalysts; and nanophase inclusions in metals, alloys, and composites. Agglomerates of nanoparticles are formed in periodic structures, fractals, and systems with short-range order; they all require studies in a wide spatial range. Therefore, the small-angle diffractometer Membrana-2 is designed as an SANS system with a maximally wide range of momentum transfers in one-shot measurement. Neutron studies on the small-angle diffractometer Membrana-2 will be performed in the monochromatic mode with a possibility of changing wavelength and in the polychromatic mode with application of the TOF technique (Fig. 11).

The parameters of the system are as follows: range of neutron wavelengths in use is 4.5–20 Å; monochromatization $\Delta\lambda/\lambda \leq 10\%$ (a possibility of monochromatization $\Delta\lambda/\lambda \leq 2$–26% with a pair of choppers in dependence of the chopper type and sample–detector distance is considered additionally); range of momentum transfers $q = 0.001$–0.5 Å^{-1}; beam divergence is varied in dependence of the number of collimating sections and the diaphragm size (from 10 × 10 to 30 × 30 mm); the sample size is 15 × 15 mm.

Small-angle polarized-neutron scattering set-up Tenzor. Small-angle polarized-neutron diffractometer Tenzor is designed for studying nuclear and magnetic inhomogeneities on the scale of 1–100 nm when carrying out investigations in the fields of materials sci-
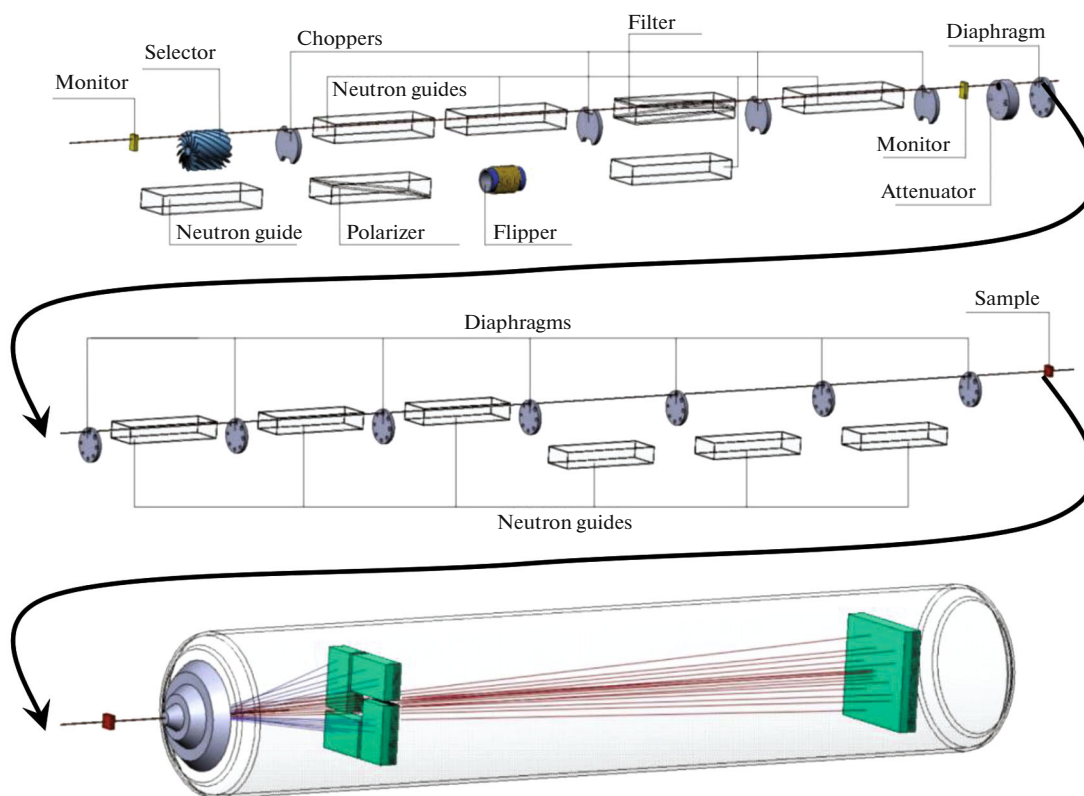
Fig. 11. Block diagram of small-angle neutron diffractometer Membrana-2.

ence (defects, porosity), physics of metals (released phases, clusters), technology of nanostructures and nanomaterials (mesoporous systems, membranes, photonic crystals), physics of complex magnetic structures, spin correlations at critical phenomena in ferromagnets, physics and chemistry of colloidal particles (microemulsions, colloidal solutions, liquid crystals), and physics of superconductors [3]. The use of polarized neutrons expands the range of studies and makes it possible, along with conventional selection of magnetic scattering, to study in SANS experiments the dynamics of spin correlations at small momentum transfers, many-body spin correlations, chiral properties of materials, and magneto-nuclear interference. Examples of SANS studies performed with polarized and unpolarized neutrons can be found in [35, 36].

The small-angle diffractometer Tenzor can be used to carry out measurements using both unpolarized and polarized neutrons and analyze the polarization of the beam transmitted through the sample. Neutron studies on the small-angle polarized-neutron diffractometer Tenzor will be performed both in the standard monochromatic mode ($\Delta\lambda/\lambda = 10\%$) with a variable neutron wavelength and in the highly monochromatic mode with the parameters $\Delta\lambda/\lambda$ on the order of few percent.

The diffractometer parameters are as follows: neutron wavelength range is 4.5–20 Å; monochromatiza-

tion $\Delta\lambda/\lambda \leq 10\%$; range of momentum transfers is 0.001–0.5 Å^{-1}; beam divergence is varied in dependence of the number of collimating sections in use and diaphragm size; sample size is 15 × 15 mm; and polarizer polarizing efficiency $P_P \geq 0.95$.

Small-angle polarized-neutron scattering set-up SANS2. Functionally, the small-angle polarized-neutron diffractometer SANS2 is a highly specialized analog of the Tenzor system. This instrument is focused on studying the physics of complex magnetic structures, spin correlations at critical phenomena in ferromagnets, spin waves, and physics of superconductors.

The parameters of the system are as follows: neutron wavelength range is 5.0–12 Å; monochromatization $\Delta\lambda/\lambda \leq 10\%$; range of momentum transfers is 0.001–0.1 Å^{-1}; beam divergence is varied in dependence of the number of collimating sections and the diaphragm size (from 10 × 10 to 30 × 30 mm); sample size is 15 × 15 mm; and polarizer efficiency $P_P \geq 0.95$.

Spin-echo small-angle neutron scattering set-up SESANS. The SESANS system (Fig. 12) is intended for studying large-scale objects of biology, colloidal and supramolecular chemistry, porous and membrane systems, and domain structure of magnetic materials [19, 37]. The spatial scale of the structures available for study on this device covers three orders of magnitude: from 100 nm to 40 μm. The technique of spin-echo
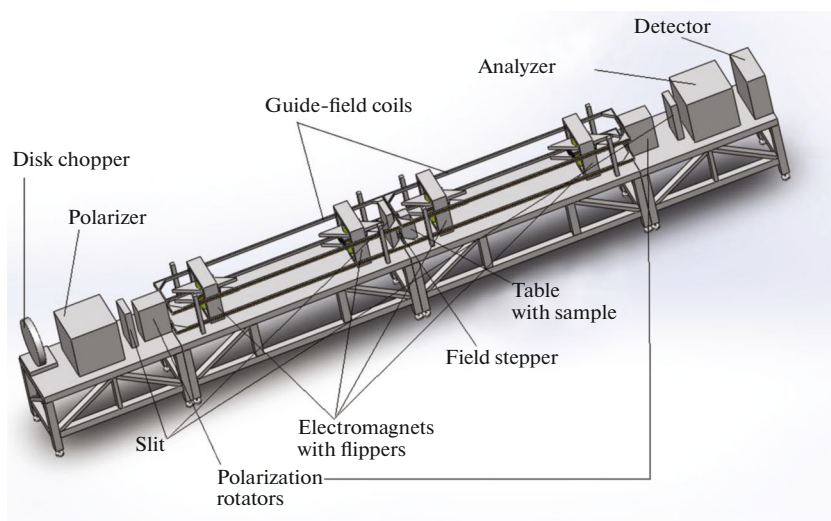
Fig. 12. Schematics of the SESANS system.

small-angle neutron scattering (SESANS) is used to investigate large-scale structural organization of chromatin in the living cell nucleus [38]. To extract the SESANS signal from samples of biological nature, which are characterized by weak scattering power, one must use a wide neutron wavelength range: from 0.1 to 1 nm [39].

The principle of operation of this device is based on one of the versions of spin-echo method. SESANS differs from classical spin-echo systems by the fact that precession regions have a form of a parallelogram. Due to this, after a change in the motion direction as a result of neutron scattering from the sample, the path length in the second arm of the system changes significantly, and the scattering angle turned out to be related to the measured change in polarization.

The parameters of the system are as follows: wavelength range is 3.5−12 Å; degree of monochromaticity (in the monochromatic mode) $\Delta\lambda/\lambda = 2\%$; range of measured scales is 0.1−40 μm; polarizing efficiency of polarizer and analyzer $P_P \geq 0.95$; neutron beam cross section on the sample is 10×10 mm²; horizontal scattering plane; and vertical divergence of neutron beam is 3′ or less.

1.4. Reflectometry Complex

In the last decade neutron reflectometry has become an efficient method for studying surfaces, thin films, and multilayer structures. The increase in the flux of neutron reflectometers due to their installment on more intense neutron sources and application of modern neutron optics made it possible to reduce significantly the measurement time and increase spatial resolution. The comparative simplicity of the analysis of data on specular neutron reflection facilitates its wide use for structure reconstruction and layer-by-

layer magnetometry based on deep profiles of scattering length densities. Currently, the range of application of the neutron reflectometry potential related to nonspecular scattering and grazing-incidence SANS is constantly widening.

High-intensity polarized-neutron reflectometer SONATA is intended for studying thin and atomically thin films; layered and laterally ordered structures; magnetism in these structures; and fast-kinetics processes occurring on boundaries, including the boundaries between solid and liquid phases. A schematic diagram of this device is shown in Fig. 13. The use of polarized neutrons increases significantly its potential, because this feature makes possible to study the magnetism of surfaces, as well as layered and laterally ordered structures. Along with the classical scheme of polarized-neutron reflectometry, it is planned to implement the scheme with vector analysis of polarization [40]. Thus, there will be a possibility to obtain more detailed and reliable information about the magnetic state of nanolayers, as well as to develop elements of innovation neutron spin (spin-manipulation) optics [41].

The interaction of incident neutrons with the sample surface leads to their scattering in three main channels (Fig. 14): specular reflection (the angle of incidence is equal to the reflection angle), nonspecular scattering (in the mirror-reflection plane), and grazing-incidence SANS (GISANS).

Specular reflectometry is used to reconstruct the deep profile of scattering length density, which gives information about the chemical (and isotopic) composition of reflecting layers on scales on the order of 1−100 nm. Polarized-neutron reflectometry can be used in layer-by-layer vector magnetometry. Structural and magnetic inhomogeneities on the scales of $10^2−10^4$ nm (variations in scattering length density) in
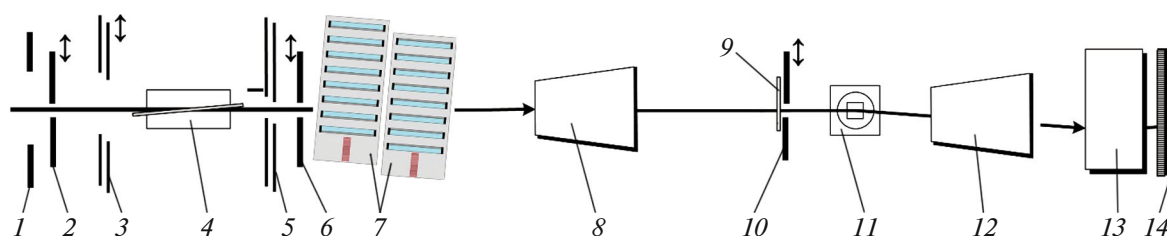
Fig. 13. Block diagram of neutron reflectometer SONATA: (*1*) output window of transport neutron guide, (*2, 6, 10*) 2D diaphragm, (*3*) first pair of chopper disks, (*4*) transmission flipper, (*5*) second pair of chopper disks, (*7*) beam combiner, (*8, 12*) flipper, (*9*) monitor, (*11*) sample unit, (*13*) fan-shaped analyzer, (*14*) 2D PSD. The elements located after the output window of transport neutron guide are as follows: three collimation slits, elements of triple-disk chopper of original design [9], transmission filter, beam combiner, two flippers, monitor, sample unit, fan-shaped analyzer, and 2D position-sensitive detector (PSD).

the mirror-reflection plane can be resolved using slit collimation in measurements with small grazing angles. Having collimated the incident beam in the horizontal and vertical planes, one can perform GISANS measurements on lateral inhomogeneities (variations in scattering length density) in the plane oriented perpendicular to the mirror-reflection plane. Thus, structural and magnetic inhomogeneities on the scales of 1–100 nm can be resolved.

The parameters of reflectometer SONATA are as follows. Time-of-flight measurements: working spectrum is 2–25 Å, variable range of λ and resolution $\Delta\lambda/\lambda$; measurements at a constant wavelength: working wavelengths are 2–25 Å, optimal wavelength is 5.2 Å, resolution $\Delta\lambda/\lambda \sim 3$–10%, maximum momentum transfers are no less than 1 Å^{-1} (specular scattering), 0.05 Å^{-1} (nonspecular scattering), and 0.2 Å^{-1} (GISANS); degree of beam polarization exceeds 98%.

Vertical scattering plane reflectometer HARMONY. Neutron reflectometer HARMONY is a time-of-flight device with a vertical scattering plane. The main lines of research for this reflectometer are as follows: air–liquid, liquid–solid, and solid–air interfaces; dynamic systems; diffuse (nonspecular) scattering; and thin magnetic films. The following device operation modes are implemented to solve the aforementioned problems: unpolarized-neutron reflectometry in the specular and nonspecular scattering modes and polarized-neutron reflectometry in the specular mirror and nonspecular scattering modes with polarization analysis. Investigations can be performed on the reflectometer in both measurement modes at reflection from the sample surface both from above and from below. The characteristic resolved sizes over the sample depth are 10–1000 Å.

The reflectometer parameters are as follows: working wavelength range 2–20 Å; range of momentum transfers to the sample surface (the perpendicular component) is $Q_z \sim 0.005$–0.5 Å^{-1}; degree of neutron beam polarization in the polarization mode up to $P \sim$ 96%; neutron beam cross section in the sample plane is (0.1×10)–(4.0×100) mm^2.

The reflectometer scheme will include innovation elements developed at the PNPI: a beam chopper [42, 43] and a compact transmission supermirror polarizer [44, 45]. The use of the proposed chopper will make it possible to reduce several times the sample measurement time in standard reflectometry experiments in comparison with the double-disk chopper that is widely applied in neutron centers [46].

Polarized-neutron reflectometer NERO is a highly specialized analog of the reflectometer SONATA, which operates in the specular reflection mode. It is intended mainly to study thin magnetic films and multilayer structures.
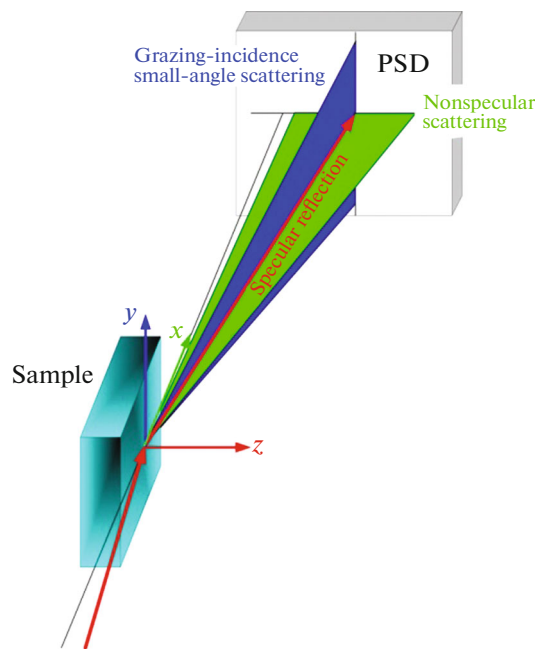

Fig. 14. Channels of neutron scattering neutrons from the sample surface under conditions of point geometry: specular reflection, nonspecular scattering in the specular-reflection plane *xz*; grazing-incidence small-angle neutron scattering (GISANS). For simplicity, GISANS is shown in only one plane; actually, it fills in the entire PSD window.
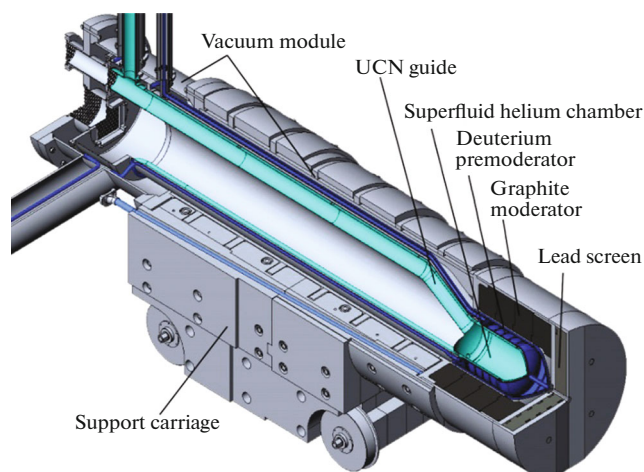
Fig. 15. Design of the UCN source on the PIK RC.

The reflectometer has the following parameters: neutron wavelength 4.5 Å; wavelength resolution $\Delta\lambda/\lambda = 0.02$ and 0.05 in the high- and medium-resolution modes, respectively; range of scattered-neutron detection angles $2\theta = 0°-10°$; degree of neutron beam polarization $P > 96\%$; and minimum size 10×10 mm.

Test neutron reflectometer TNR is intended for testing polarizing and unpolarizing neutron mirrors when designing neutron guides and other neutron optical devices for the PIK reactor complex (RC). The auxiliary character of the spectrometer is compensated by the fact that it is called for tracking the construction of the neutron-guide system, in particular, for estimating the quality of internal neutron-reflecting coating. The reflectometer provides four measurement modes; the choice of a particular mode is determined by the physical problem to solve: mode I for a "white" unpolarized beam, mode II for a "white" polarized beam, mode III for a monochromatic unpolarized beam, and mode IV for a monochromatic polarized beam.

The reflectometer parameters are as follows: operating wavelengths (time-of-flight measurements) range from 0.9 to 5 Å; monochromatization is $\Delta\lambda/\lambda \sim 1\%$; beam polarization $P > 99\%$; and available range of momentum transfers $Q_z \sim 0.003-0.3$ Å^{-1}.

2. PROGRAM OF STUDIES IN PHYSICS OF ELEMENTARY PARTICLES AND NUCLEAR PHYSICS

Modern physics of elementary particles is a close interweaving of cosmology and properties of Universe in the early stage of its formation, structure of elementary particles and their interactions, nuclear physics, and physics of phase transformations. One of the ways to obtain new data in this field is to increase the measurement accuracy in low-energy physics, in particular, in neutron physics. To this end, one needs high-intensity neutron sources, because statistics must be increased in order to increase the accuracy; in addition, new concepts, techniques, and nonstandard equipment are also called for.

2.1. High-Intensity Superfluid-Helium UCN Source Based on the PIK Reactor

Under development is a source of ultracold neutrons (UCNs) with a density 10–100 times higher than the UCN density on existing world sources (Figs. 15, 16; Table 1). This increase in the UCN intensity will be achieved due to the application of new technology with superfluid helium. A program of studying fundamental interactions on the UCN source, including the search for neutron electric dipole moment and precise measurement of its lifetime, is planned. Both problems are of key importance for the physics of elementary particles and cosmology. Researchers from the NRC KI and JINR and their foreign colleagues will work on UCN beams. Currently, these studies are carried out on the reactor at the Institute Laue−Langevin (ILL) (Grenoble, France). However, the first studies in the field of UCN physics were performed in Russia, and it is important to restore Russian priorities in this field.

2.2. Promising Experiments in Physics of Particles on the PIK Reactor

Magnetic resonance UCN spectrometer for measuring the neutron EDM. The experiment on searching for the neutron electric dipole moment (EDM) is related to the general problem of the theory of elementary particles: adequate description of the processes occurring with violation of spontaneous CP- and T-symmetry. The EDM arises in modern theoretical models in the first order of weak interaction and turns out to be at the level of $10^{-26}-10^{-28}$ e cm.

The most precise (to date) limitation on the neutron EDM value (less than 2×10^{-26} e cm) was obtained at the ILL, where one chamber for storing UCNs and a mercury comagnitometer for monitoring magnetic conditions were used. Systematic errors may occur in this scheme in the presence of magnetic field gradient. A differential magnetic resonance spectrometer with two UCN storage chambers, system for double analysis of polarization, and four detectors with a common constant magnetic field (Fig. 17) provide a radically different possibility for monitoring systematic effects. A test experiment was performed on the ILL reactor, where a limit less than 5×10^{-26} e cm was obtained. The development of a new UCN source on the PIK reactor with a density two orders of magnitude higher than that at the ILL will provide an EDM measurement accuracy at a level better than 10^{-27} e cm. The discovery of neutron EDM or new limitation on its magnitude at this level may become a decisive factor in the choice of a theory adequately describing the phenomenon of violation of CP symmetry.
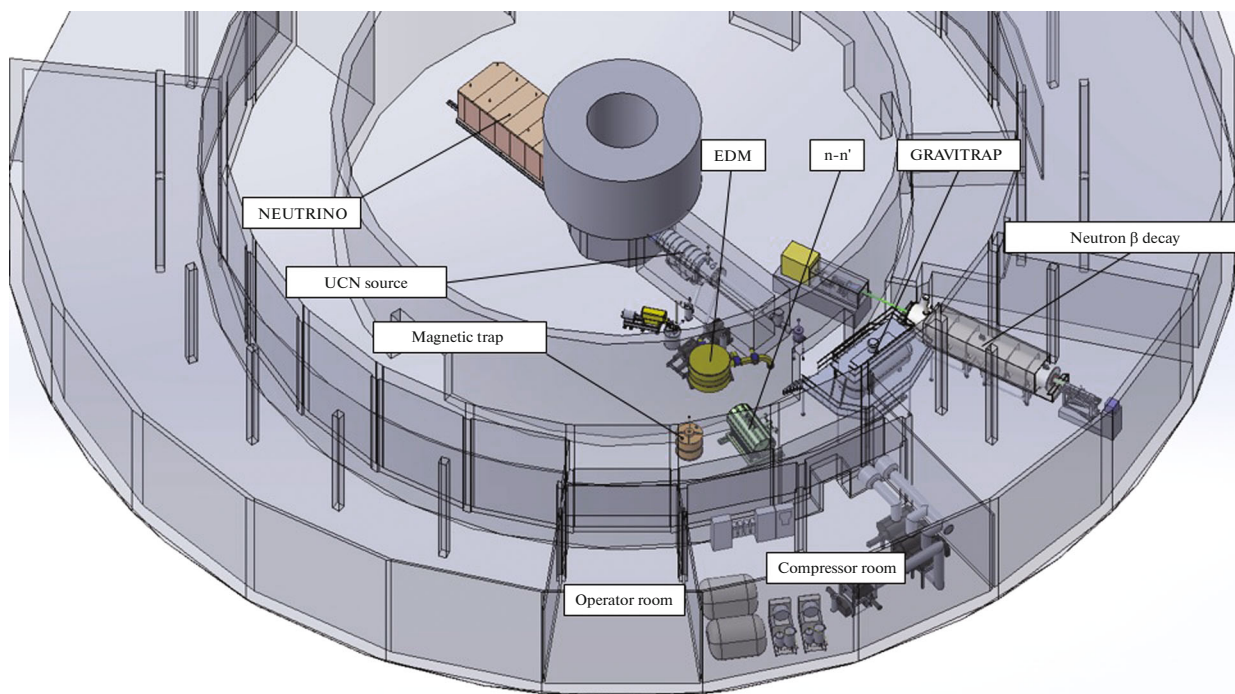
Fig. 16. Planned arrangement of the UCN source with superfluid helium and experimental setup on the GEK-4 channel of PIK RC.

"Neutron EDM determination by crystal-diffraction method" (DEDM) system. When designing an experimental platform with a large aperture and intensity on a cold-neutron beam in the neutron-guide hall, the top priority problem is to organize a crystal-diffraction experiment aimed at searching for the neutron EDM on the DEDM system. This tool will be a universal platform for studying the characteristics of neutron and fundamental interactions (Fig. 18). The main concept is the use of giant electric fields of noncentrosymmetric crystal. The magnitudes of fields on the entire neutron path through a crystal are in the range of 10^8-10^9 V/cm, which is 10^4 times higher than the fields attainable in laboratory by conventional methods. When searching for the neutron EDM, an accuracy of $(2-3) \times 10^{-27}$ e cm can be achieved using new-class crystals (BSO, BGO).

Large gravitational trap (GT) for measuring the neutron lifetime. The increase in the accuracy of neutron lifetime measurements will make it possible to verify the theoretical models of nucleosynthesis in the early Universe and the validity of the Standard Model of elementary particles. The system (Fig. 19) is based on the principle of gravitational gate for holding UCNs in a material trap. The UCN density in the new trap is higher than that in the previous one by a factor of about 30. The neutron-lifetime measurement accuracy in this system is expected to be 0.2 s.

System for measuring the neutron lifetime using magnetic trapping (MT) of UCNs. A schematic diagram of the experiments on measuring the neutron lifetime by storing UCNs in a magnetic trap fabricated with the aid of permanent magnets is presented in Fig. 19. Magnetic holding of neutrons makes it possible to exclude collisions of neutrons with walls. In a magnetic trap, UCNs of certain polarization are reflected by magnetic barrier and do not collide with walls. The goal of this experiment is to reach statistical sensitivity in measurements of the neutron lifetime at a level of 0.3 s.

"Neutron β-decay" system. The main goal of this experiment is to measure the electron asymmetry of neutron β-decay with a relative precision of $(1-2) \times 10^{-3}$. The experimental setup (Fig. 20) is based on a superconducting solenoid with a magnetic field strength of 0.35 T in the region of uniform field and 0.80 T in the region of magnetic plug at a current of 1000 A. The correlation coefficient in the neutron β-decay is measured due to the magnetic collimation of the electron escape angle and averaging over neutrino

Table 1. Parameters of UCN source

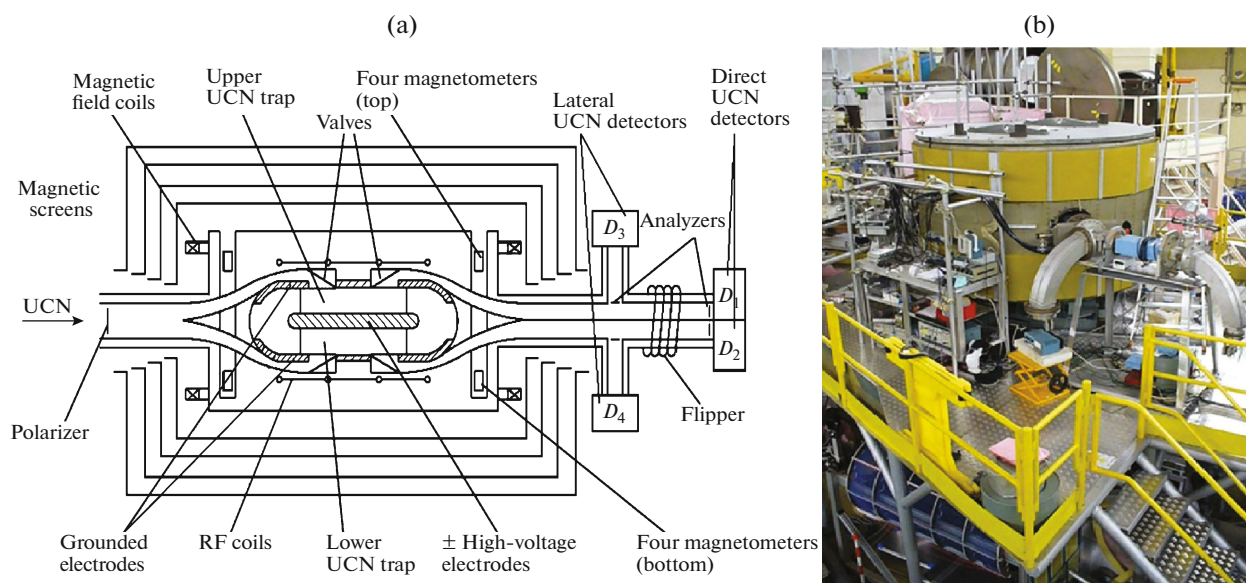| Parameter	Value
Total output, s^{-1}	7.8×10^6
Energy release in helium chamber, W	2
UCN flux density, n/cm^3	1.3×10^3
Volume of UCN source chamber, L	40
Working temperature of UCN converter, K	1.2

Fig. 17. (a) Schematic diagram of the EDM system and (b) PNPI EDM spectrometer on the ILL reactor (test experiment).
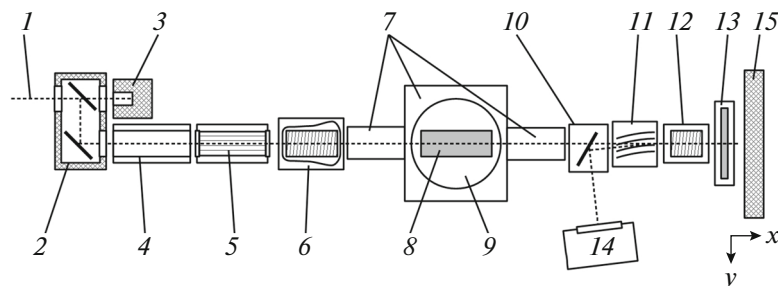

Fig. 18. Schematic diagram of the DEDM system: (*1*) neutron beam, (*2*) double-crystal monochromator, (*3*, *15*) beam trap, (*4*) neutron guide, (*5*) polarizer, (*6*) spin flipper, (*7*) 3D polarization analysis system, (*8*) working crystal unit, (*9*) nonmagnetic system of sample positioning, (*10*) single-crystal monochromator, (*11*) nonabsorbing supermirror analyzer, (*12*) spin-orienting coil, (*13*) crystal reflector, and (*14*) 2D PSD.

escape angles. Magnetic collimation is performed by a magnetic plug, and averaging over neutrino escape angles is performed by collecting all protons from the neutron β-decay using a distributed electric potential. The formation of polarization neutron beam and its analysis are proposed to perform using a supermirror multislit polarizer. The TOF technique with a beam chopper and rate selector is used. This approach will make it possible to fix the neutron decay point. The application of crossed electric and magnetic fields makes it possible to separate protons and electrons. Knowing the neutron decay point and using the TOF technique for protons, one can measure the longitudinal proton momentum. Due to this, one can pass to neutrino-asymmetry measurements. A neutron beam arrives at the decay region, limited by a cylindrical electrode. All protons are extracted from the neutron decay region by electric field and arrive at the proton detector. Electrons move to the electron detector.

"Neutrino" setup. Experimental search for possible neutrino oscillations into sterile state has been per-

formed for many years. Numerous experiments on accelerators, reactors, and artificial neutrino sources were aimed at solving this problem. Sterile neutrino is a candidate for dark-matter particles. The hypothesis of oscillations into sterile state can be verified by direct measurement of the dependence of neutrino flux and neutrino energy spectrum at different distances in the range of 6−12 m. The PIK reactor opens unique possibilities for these studies due to the compact core and high power of the reactor. The detection of reactor antineutrinos is based on the reaction of inverse β-decay and use of a liquid scintillator with gadolinium. Photomultipliers record two successive events: instantaneous flare from a positron and annihilation of 511-keV γ quanta, after which the delayed signal from γ quanta of the (nGd, γ) reaction with generated neutron is recorded. The energy spectrum of antineutrino is reconstructed from the energy spectrum of positrons. Detector will be located in the main hall under the transport corridor, where the best protection from cosmic rays is provided (Fig. 21). The minimum and
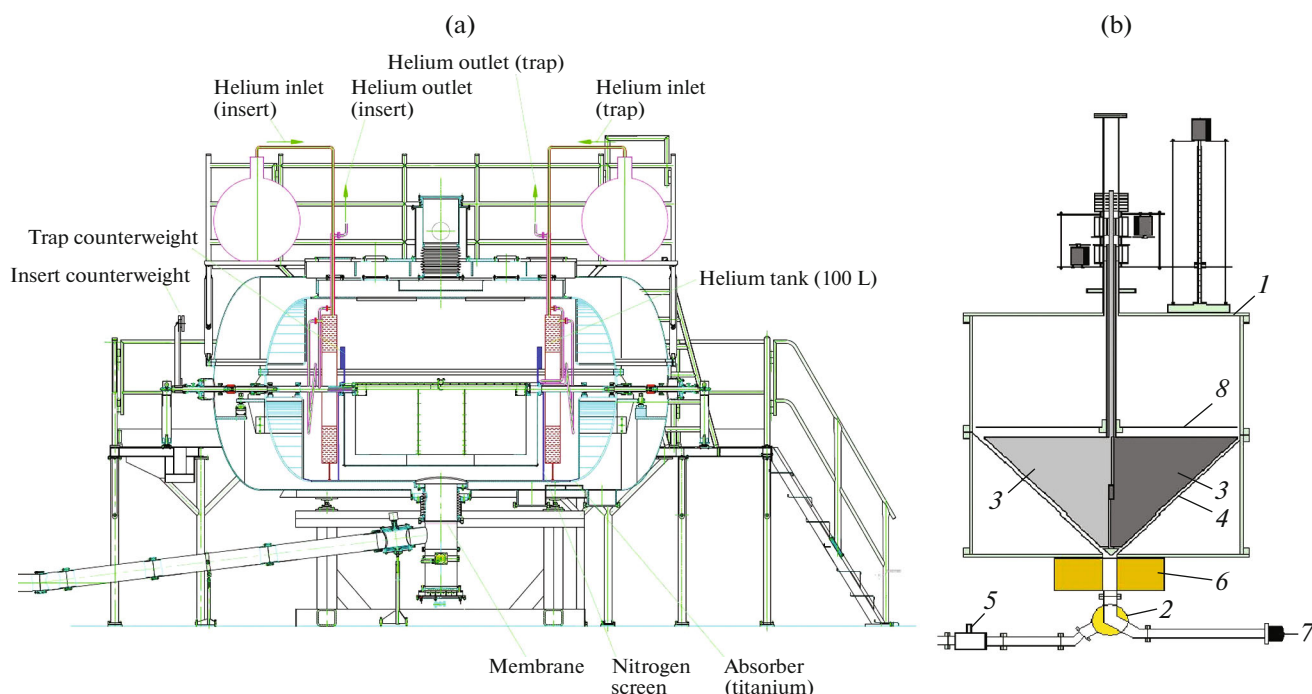
Fig. 19. (a) General view of the gravitational trap for measuring the neutron lifetime. (b) Schematics of the experimental setup for measuring the neutron lifetime using magnetic storage: (*1*) vacuum chamber, (*2*) switch of UCN motion direction, (*3*) rotating shutters, (*4*) magnetic trap, (*5*) neutron gate, (*6*) electromagnetic UCN gate, (*7*) UCN detector, and (*8*) neutron lid reflector.
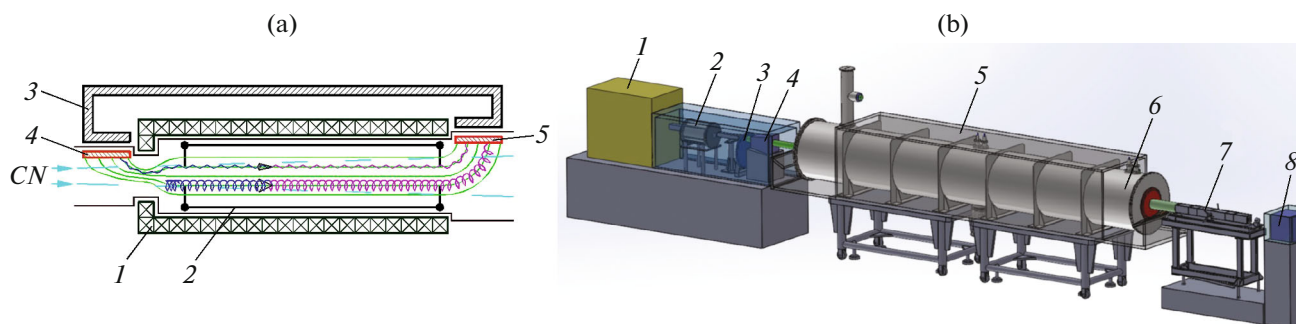

Fig. 20. (a) Schematic of the "neutron β decay" experiment: (*1*) superconducting solenoid, (*2*) cylindrical electrode, (*3*) iron yoke; (*4*) electron detector, and (*5*) proton detector. (b) Neutron instrumental complex: (*1*) supermirror polarizer, (*2*) monochromator, (*3*) chopper, (*4*) spin flipper, (*5*) magnetic screen, (*6*) superconducting solenoid, (*7*) device for measuring beam polarization, and (*8*) beam trap.

maximum distances from the detector to the core will be 6 and 15 m, respectively.

The preparation of experiment was started on the WWR-M reactor and continued on the SM-3 reactor. After launching the PIK reactor, it is planned to perform main measurements on it. The expected count rate of antineutrino events for a detector with a volume of 2 m³ at a distance of 8 m from the PIK reactor core may amount to ~800 a day.

Search for mirror dark matter in a laboratory experiment with UCNs. Because of the violation of the spatial invariance of weak interaction, our world turned out to be left-handed. The reason for this inequality of left and right is unknown. The Standard Model explains successfully the principles of weak interaction but does not answer the question why specifically the left-handed (V−A) version of the theory was chosen. In principle, if there is a left-handed asymmetry, why should not a right-handed one (i.e., its mirror reflection) exist?

The concept of the experiment is as follows. If a neutron and its mirror partner are strictly degenerate in mass and there are no external fields, with which they interact differently, their energy states are identical and then transitions or neutron–mirror neutron oscillations may occur. An UCN is stored in the trap due to the reflection from its walls; however, if a neutron passes to the specular state for the time of flight
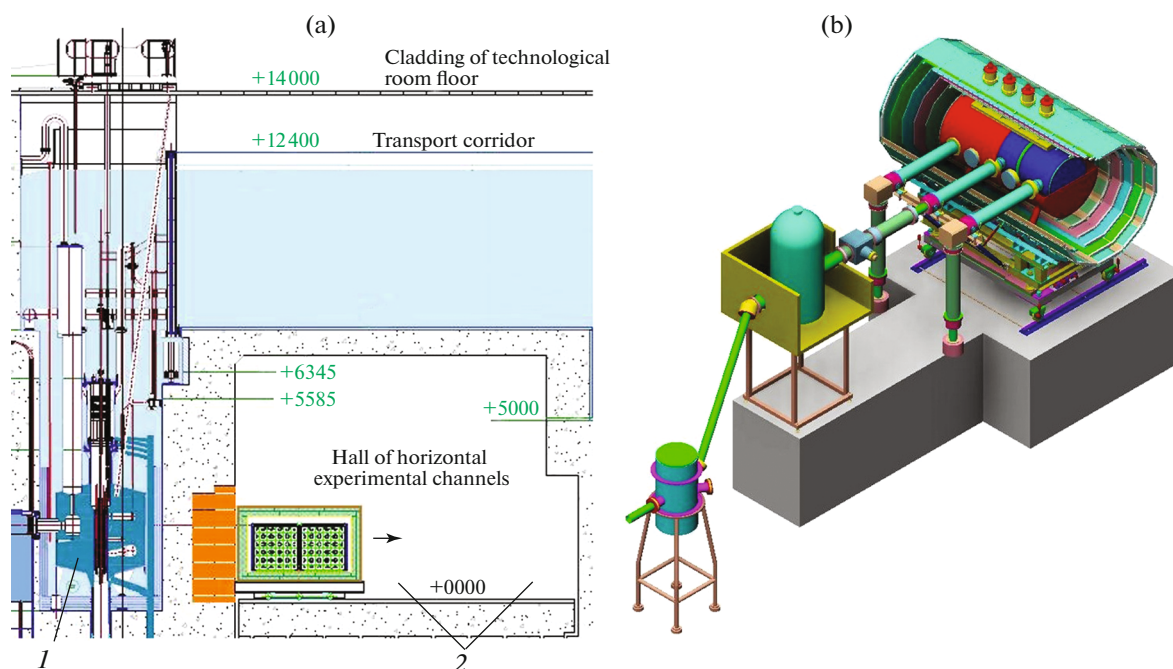
Fig. 21. (a) Schematic arrangement of antineutrino detector on the PIK reactor: (*1*) PIK reactor core (height 50 cm, diameter 40 cm) and (*2*) antineutrino detector displacement range: from 6 to 15 m from the PIK reactor core. (b) System for searching neutron transitions to the mirror (sterile) state.

from one wall to another, the mirror neutron will pass through the trap wall without interaction and leave the trap. A number of experiments were performed to verify this hypothesis. The PNPI experiment was carried out with a magnetic screen and main elements of the new spectrometer for searching the neutron EDM. Measurements were performed at the ILL on a UCN beam prepared at the PNPI for the EDM experiment. The oscillation effect was not found, and the limit on the oscillation time turned out to be 448 s; the corresponding limit on the mixing energy is 1.4×10^{-18} eV. This limit can significantly be improved on the PIK reactor due to the use of high-intensity UCN source (Fig. 21).

2.3. Promising Experiments in Nuclear Physics on the PIK Reactor

Mass-separator laser-nuclear complex IRINA. It is planned to develop a unique complex for producing and studying exotic short-lived isotopes on the PIK reactor within the project IRINA (Russian abbreviation for the "Study of Radioactive Isotopes on Neutrons"). This complex is expected to have record exit parameters of neutron-excess nuclei due to the high flux of thermal neutrons on a sample and optimal system for nuclei extraction. Study of neutron-deficient and neutron-excess nuclei near the proton and neutron drip line using the isotope separator on-line (ISOL) method is one of the most important development directions in physics of radioactive isotopes. In addition, the radioactive isotopes obtained by this

method are widely used in solid-state physics, nuclear medicine (for diagnostics and treatment of different diseases), and molecular-biological applications.

Currently the leading ISOL complexes—ISOLDE (CERN), TRIUMF (Vancouver, Canada), and IGISOL at University of Jyväskylä (Finland)—are intensively upgrading their scientific tools. An intense work aimed at designing and constructing relatively moderate ISOL systems for local programs of development in physics of radioactive isotopes is being carried out in a number of research centers: INFN (Legnaro, Italy), ITEMBA Labs (Stellenbosch, RSA), and RAON (Daejeon, Republic of Korea). Note that the best functioning ISOL systems have already practically exhausted their potential for studying nuclei more spaced from the β-stability line. The development of the leading ISOL complex SPIRAL2 (GANIL, France) was stopped, and the complex was repurposed. In this situation the ISOL complex IRINA, which is planned to be designed on the beam of PIK reactor, is expected to be unique in the world.

A schematic arrangement of the IRINA system on the channel GEK-5-5' in the experimental hall of the reactor is presented in Fig. 22. The target-ion unit is located in one of the PIK channels with a flux of 3×10^{13} n/(cm^2 s) on the target. The heat-resistant uranium carbide target contains 4 g ^{235}U (in the initial operation stage the mass is reduced to 2 g). Up to 10^{14} neutron-induced fission events per second occur in the target, as a result of which it is heated to a temperature above 2000°C. The high temperature pro-
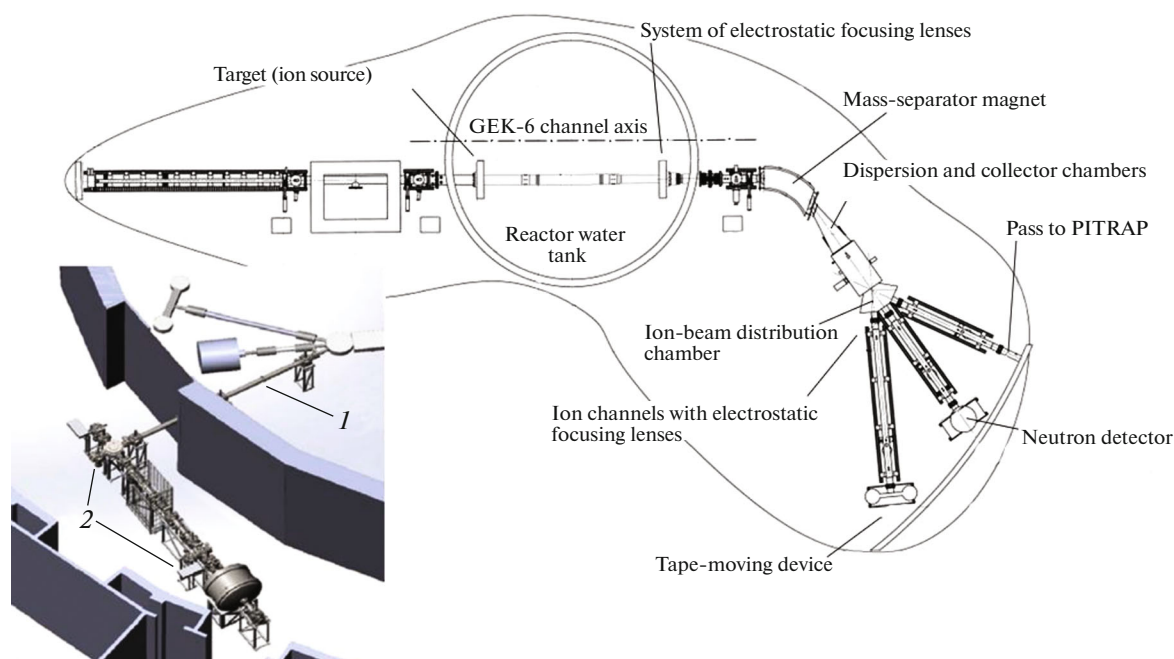
Fig. 22. General view of the planned arrangement of IRINA complex in the reactor hall of PIK RC: the reactor is arbitrarily shown in the center. The hot chamber and system of automatic target unit motion are on the left; the mass-separator with three ion channels and receiving stations is on the right; (*1*) system of matching the mass-separator IRINA with the PITRAP trap and (*2*) mass-spectrometry complex PITRAP in the PIK RC circular gallery.

vides efficient diffusion of fission fragments in the vacuum bulk of the target-ion unit, where atoms of desired element are subjected to high-selectivity laser ionization. The extraction-focusing electrostatic system directs the thus formed ion beam to the probe magnet of mass-separator, where mass-separation occurs with subsequent selection and extraction of the isotope chosen for study.

To study efficiently the nuclei lying close to the neutron stability drip line, it is of key importance to provide isobaric purity of beams, i.e., selective ionization of isotopes of one chosen element. Selective ionization of isotopes of a large number of elements can be provided only using laser resonance ionization, which was developed and successfully applied on the IRIS system (NRC KI−PNPI); currently, it is also used in other ISOL laboratories. This method makes it possible to ionize selectively atoms of ISOL-produced radioactive isotopes of many elements and measure with a rather high accuracy the isotope shifts and hyperfine splitting of atomic levels of obtained remote radionuclides. The laser ionization efficiency for many elements amounts to 10−15%. There is a possibility to obtain isobarically pure isotopic beams of Cu, Ni, Ag, Sn, Mg, Ga, Mn, Fr, Tl, and many other elements and measure simultaneously their isotope shifts and hyperfine splitting.

The planned fission rate of 10^{14} fissions per second on the IRINA system makes it possible to obtain yields of neutron-excess nuclei that multiply exceed the yields of the same nuclei on other systems. For exam-

ple, the yield of the "marker" isotope ^{132}Sn (doubly magic nucleus, remote from the valley of β-stability) on the ISOL system on the neutron beam of PIK reactor with an intensity of 3×10^{13} n/(cm^2 s) from a 4-g ^{235}U target will be about 10^{11} isotope particles per second. The corresponding yields on the functioning IRIS and ISOLDE systems are, respectively, 10^7 and 10^8 particles per second. The maximum calculated yield of this isotope on the next-generation ISOL system SPIRAL-2 (GANIL, France) would not exceed 10^9 isotope particles per second.

The use of an ion trap of the ISOLTRAP type on one of the ion channels of the IRINA system will allow to measure with high accuracy (few keV) the masses of many nuclei spaced from the β-stability valley to the neutron-excess region. The highly sensitive method of resonance laser-ionization spectroscopy will be applied to measure charge radii and electromagnetic moments of nuclei in the regions that are most interesting for nuclear physics: region of doubly magic nucleus ^{132}Sn and regions of nuclei with the magic number of neutrons $N = 50$ (neutron-excess isotopes of Ge, Ga, Zn, Cu, and Ni). In addition, ultrapure radionuclides for medical applications will be produced on the radioisotope complex IRINA.

System for testing fission fragment multiplicity (FISCO). The system developed is to be located in the hall of inclined channels on the NEC-2 neutron beam of the PIK reactor (Fig. 23). It is intended for correlation studies of nuclear fusion using different methods:
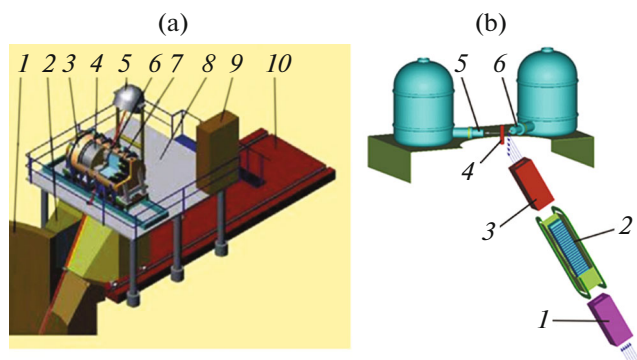
(a) (b)

Fig. 23. (a) General view of the FISCO system on NEC-2 beam: (*1*) PIK reactor vessel, (*2*) standard gate (with a possibility of additional arrangement of polarizer), (*3*) protection of multiplicity detector, (*4*) assembly of scintillation detectors, (*5*) beam trap, (*6*) detector of charged fission products, (*7*) photomultipliers, (*8*) overpass, (*9*) tool rack, and (*10*) platform. (b) General schematic arrangement of semiconductor γ spectrometers on an inclined channel of reactor PIK and experimental equipment: (*1*) neutron polarizer, (*2*) flipper, (*3*) collimator, (*4*) trap, and (*5*, *6*) radiation detectors.

Fig. 24. General view of the pneumatic transport system and control rack (prototype).

analysis of the distributions of neutron fission multiplicity in dependence of the characteristics of fission fragments and systems undergoing fusion, as well as study of angular and energy correlations for neutrons, γ quanta, and third particles in fusion.

Despite the significant progress in fusion theory, one cannot predict the observed values with an accuracy necessary for practical applications. In particular, when calculating reactors and other crucial systems, the error in determining the neutron yield must not exceed 0.1%. Attempts are made to develop systems for detecting masked nuclear materials, based on the principle of observing different correlations between fission products. These correlations can be obtained using the Monte Carlo method within the statistical theory. Experimental data on the angular and energy distributions of "instantaneous" fission neutrons and γ quanta are tools for debugging and verifying calculations. This information is important for further study of the nuclear fusion mechanism, because it allows one to determine the main characteristics of fissioning system, such as the parameters of level density for neutron-excess nuclei, deformations of both fragments near the "break point," and the properties of "break" neutrons.

Nuclear radiation spectrometer PROGRAS. The system consists of a logarithmic neutron guide and two high-purity germanium detectors mounted at its output (in the hall of inclined channels) (Fig. 23). The intrachannel neutron guide is used to extract the thermal neutron beam, providing a low background level from fast neutrons and γ quanta due to the efficient use of biological shielding of the reactor. The nuclear radiation spectrometer PROGRAS is proposed to study the structure of atomic nucleus in (*n*,γ) reactions on thermal neutrons based on coincidence spectra (γ−γ)

and neutron-radiative analysis of the elemental and isotopic composition samples, as well as to measure the interaction cross sections of neutrons with matter.

Instrumental neutron-activation analysis (INAA) system. This system will make it possible to determine the contents of Li, B, N, O, F, Ne, Al, V, and Pb in samples from their short-lived isotopes, which cannot be done using conventional methods of neutron-activation analysis. This feature opens up a unique possibility of detecting these elements in superhard and heat-resistant alloys (whose properties are determined to a great extent by the content of the aforementioned elements) and investigating geological samples and biological objects.

The measurement complex is designed for INAA based on a γ-radiation spectrometer and a pneumatic transport system (Fig. 24). INAA is automated due to the use of a pneumatic system for transporting samples from the laboratory to the PIK reactor channel for irradiation and backward to the laboratory for further spectrometric studies. The sample delivery time to the irradiation zone and backward is shortened, and any contact between the personnel and radioactive samples under study is excluded.

ADDITIONAL INFORMATION

REFERENCES

1. A. I. Kurbakov, A. N. Korshunov, A. N. Pirogov, et al., Crystallogr. Rep. **66** (2), 267 (2021).
2. I. A. Zobkalo, Crystallogr. Rep. **66** (2), 216 (2021).
3. V. L. Aksenov and M. V. Koval'chuk, *PIK Reactor Complex,* Vol. 4: *Concept of the Investment Project "Development of the Instrumental Base of the PIK Reactor Complex"* (Izd-vo FGBU PIYaF NITs "Kurchatovskii Institut," Gatchina, 2015) [in Russian].
4. A. M. Balagurov, I. V. Golosovskii, A. I. Kurbakov, et al., *Diffractometers on the PIK Reactor for Solving Fundamental and Applied Problems* (Izd-vo PIYaF, Gatchina, 2015) [in Russian].
5. F. Hippert, E. Geissler, J. L. Hodeau, et al., *Neutron and X-Ray Spectroscopy* (Springer, 2006).
6. H. Schober, *Neutron Applications in Earth, Energy and Environmental Sciences* (Springer, New York, 2009), p. 37.
7. B. T. M. Willis and C. J. Carlile, *Neutron Scattering: Fundamentals* (Elsevier, 2013).
8. A. Furrer, J. Mesot, and Th. Strassle, *Neutron Scattering in Condensed Matter Physics* (World Scientific, 2009).
9. P. W. Anderson, *Concepts in Solids: Lectures on the Theory of Solids (Lecture Notes in Physics)* (Worlds Scientific, 1963).
10. N. B. Brandt and V. A. Kul'bachinskii, *Quasiparticles in Physics of Condensed State* (Fizmatlit, Moscow, 2007) [in Russian].
11. D. Pines, *Elementary Excitations in Solids* (W.A. Benjamin, 1963).
12. M. I. Kaganov and I. M. Lifshits, *Quasiparticles* (Nauka, Moscow, 1989) [in Russian].
13. B. Dorner, *Coherent and Inelastic Neutron Scattering and Lattice Dynamics, Springer Tracts in Modern Physics,* Vol. 93 (Springer, Berlin, 1982).
14. P. W. Anderson, *Basic Notions in Condensed Matter Physics* (Addison-Wesley, 1984).
15. D. Pines, *Elementary Excitations in Solids* (W.A. Benjamin, 1963).
16. Yu. A. Izyumov and N. A. Chernoplekov, *Neutron Spectroscopy* (Energoatomizdat, Moscow, 1983) [in Russian].
17. F. Mezei, C. Pappas, and T. Gutberlet, *Neutron Spin Echo. Lecture Notes in Physics,* Vol. 601 (Springer, Heidelberg, 2003).
18. R. Hempelmann, *Quasielastic Neutron Scattering and Solid State Diffusion* (Oxford University Press, 2000).
19. F. Mezei, Z. Physik **255**, 146 (1972).
20. Ch. Franz and Th. Schröder, J. Large-Scale Res. Facilities **1**, A14 (2015).
    https://doi.org/10.17815/jlsrf-1-37
21. D. V. Lebedev, M. V. Filatov, A. I. Kuklin, et al., FEBS Lett. **579**, 1465 (2005).
22. C. Sanson, O. Diou, J. Thévenot, et al., ACS Nano **5** (2), 1122 (2011).
    https://doi.org/10.1021/nn102762f
23. D. Chen, A. Nakahara, D. G. Wei, et al., Nano Lett. **11** (2), 561 (2011).
    https://doi.org/10.1021/nl103482n
24. W. Xie, J. He, H. J. Kang, et al., Nano Lett. **10** (9), 3283 (2010).
    https://doi.org/10.1021/nl100804a
25. C. Hardacre, J. D. Holbrey, C. L. Mullan, et al., J. Chem. Phys. **133**, 074510 (2010).
    https://doi.org/10.1063/1.3473825
26. G. Cheng, P. Varanasi, C. Li, et al., Biomacromolecules **12** (4), 933 (2011).
    https://doi.org/10.1021/bm101240z
27. G. Gröger, W. Meyer-Zaika, C. Bottcher, et al., J. Am. Chem. Soc. **13** (23), 8961 (2011).
    https://doi.org/10.1021/ja200941a
28. M. Yoonessi and J. R. Gaier, ACS Nano. **4** (12), 7211 (2010).
    https://doi.org/10.1021/nn1019626
29. L. Chiappisi, S. Prévost, I. Grillo, and M. Gradzielski, Langmuir **30** (7), 1778 (2014).
    https://doi.org/10.1021/la404718e
30. V. Raghuwanshi, R. Harizanova, S. Haas, et al., J. Non-Cryst. Solids **385**, 24 (2014).
    https://doi.org/10.1016/j.jnoncrysol.2013.10.007
31. S. V. Grigoriev, S. V. Maleyev, A. I. Okorokov, et al., Phys. Rev. B **73**, 134420 (2005).
32. S. Muhlbauer, B. Binz, F. Jonietz, et al., Science **323**, 915 (2009).
33. A. I. Okorokov, Crystallogr. Rep. **56** (7), 1131 (2011).
34. A. D. Bianchi, M. Kenzelmann, L. DeBeer-Schmitt, et al., Science **319** (5860), 177 (2008).
    https://doi.org/10.1126/science.1150600
35. S. V. Grigor'ev, E. V. Altynbaev, and N. M. Chubova, Crystallogr. Rep. **66** (2021) (in press).
36. S. V. Grigor'ev, E. V. Altynbaev, and K. A. Pshenichnyi, Crystallogr. Rep. **66** (2020) (in press).
37. M. T. Rekveldt, W. G. Bouwman, W. H. Kraan, et al., *Neutron Spin Echo Spectroscopy. Basics, Trends, and Applications,* Ed. by F. Mezei (Springer, Berlin, 2003), p. 100.
38. M. T. Rekveldt, W. G. Bouwman, W. H. Kraan, et al., *Neutron Spin Echo Spectroscopy. Basics, Trends, and Applications,* Ed. by F. Mezei (Springer, Berlin, 2003), p. 87.
39. E. G. Iashina, E. V. Velichko, M. V. Filatov, et al., Phys. Rev. E **96**, 012411 (2017).
40. E. G. Iashina, W. G. Bouwman, C. P. Duif, et al., J. Phys.: Conf. Ser. **862**, 012010 (2017).
41. N. K. Pleshanov, L. A. Aksel'rod, V. N. Zabenkin, et al., Poverkhn.: Rentgenovskie, Sinkhrotronnye Neitr. Issled., No. 11, 3 (2008).
42. N. K. Pleshanov, Nucl. Instrum. Methods Phys. Res. A **872**, 139 (2017).
43. V. G. Syromyatnikov, J. Phys. Soc. Jpn: Conf. Ser. **22**, 011005 (2018).
44. V. G. Syromyatnikov, RF Patent No. 2680713 (March 30, 2018).
45. V. G. Syromyatnikov, RF Patent No. 2624633 (June 21, 2016).
46. A. A. Van Well, Physica B **180−181**, 959 (1992).

Translated by Yu. Sin'kov