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Neutron physics at JINR: 60 years of the I M Frank Laboratory of Neutron Physics

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Abstract. **26 March 2016 marked 60 years since the Joint Institute for Nuclear Research was founded in 1956 and within which the Laboratory of Neutron Physics was established. Already four years later, in 1960, the world's first pulsed fast reactor (known by its Russian acronym as IBR) operating in the periodic mode was put into operation, followed in 1984 by IBR-2. The research achievements over the last decade are summarized, the state-of-the-art laboratory hardware is discussed, and the prospects for the future are reviewed.**

Keywords: pulsed fast reactor, neutron scattering, neutron–neutron scattering, spatial parity violation in neutron reactions, cold neutrons

1. Introduction

Initiated by D I Blokhintsev, the first director of the Joint Institute for Nuclear Research, the Laboratory of Neutron Physics (LNP) was founded within the institute in 1956, with I M Frank as its first director. At the very beginning, the laboratory embarked on developing a fast pulsed neutron reactor, a facility whose principle had been proposed by Blokhintsev a year earlier at a seminar at the Physics Energy Institute, Obninsk. In June 1960, the IBR (Russian abbreviation for Fast Pulsed Reactor) achieved pulsed criticality for the first time [1, 2]. The modernization of the cooling system increased the reactor's average project power from the original 1 kW to 6 kW within only two years. When operated at a power of 3 kW and a pulse rate of 5 Hz, the instantaneous reactor power was 15 MW, with a pulse duration of about 50 μs [3].

The systematic development of the first pulsed reactor led to a reduced pulse duration (due to operation in the booster regime using an electron accelerator as the injector [4]) and to an increased averaged power (due to a new active zone design). This facility, later named IBR-30 [5], has the LUE-40 linear electron accelerator and a 30 kW active zone. Currently, the Laboratory of Neutron Physics is working on developing a new source of resonance neutrons, IREN [6], based on the LUE-200 linear accelerator with a nonmultiplicating neutron-producing natural uranium target.

The success of the first IBR reactor and its modified version IBR-30 stimulated design efforts to achieve an average power of a few megawatts. The work on the design and manufacture of such a reactor was successfully completed by the end of the 1970s, and in 1978, a pulsed fast reactor with an average power of 2 MW, IBR-2 [7], was put into operation. Between 1984 and late 2006, the reactor was operated as an open access facility, providing researchers from JINR member countries with access time to the output beams. Aksenov [8] provides a detailed historical review of the development of pulsed neutron sources at the LNP up to that time.

On 25 December 2006, the reactor was stopped in order to conduct a thorough upgrade program. Within four years, the key reactor components — the housing and sodium pipelines — were replaced, the control and management system was overhauled, and other improvements made. On 17 December 2010, the start-up stage was begun by putting the first four fuel assemblies into the reactor housing. By mid-2011, the first power stage was complete, and in 2012 the IBR-2 facilities renewed their service programs [9].

An important feature of the upgraded IBR-2 reactor is its system of cryogenic neutron moderators. Currently, the first phase of this complex (KZ-202) is being carried out, which ensures neutron spectrum modification resulting in an increased cold neutron yield on beams 7, 8, 10, and 11 (Figs 1 and 2) [10]. Planned before 2018 is also the manufacture and

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launch of cryogenic moderators for beams 4, 5, 6, 9, 2, and 3. The KZ-202 cryogenic moderator already in operation and KZ-201 and KZ-203 still under development are unique facilities. For the first time in the world, the moderator chamber is charged not with a cryogenic liquid or an iced operating material but with balls 3–5 mm in diameter. The working material chosen was a mixture of mesitylene and m-xylol, whose amorphous structure provides an increased cold neutron yield compared to pure mesitylene due to the increased density of the low-lying molecular energy levels. The rationale for this choice came from a study conducted by JINR physicists on IBR-2 in the premodernization period of the inelastic scattering of slow neutrons by aromatic hydrocarbons at low temperatures [11] and of the radiation resistance of various hydrogen-containing materials [12]. The result was a cryogenic moderator that retains the positive properties of its liquid hydrogen counterpart but is much safer and cheaper to manufacture and use.

Since the creation of the first pulsed reactor in Dubna, work on the neutron spectroscopy of nuclei began at the LNP. Already by the mid-1960s, unique experimental facilities were developed, including POLYANA, a spectrometer for polarized neutrons and nuclei [13]. This spectrometer allowed discovering the violation of spatial parity on the 0.75 eV resonance in ^{139}La [14]. Also in the mid-1960s, studies on the inelastic scattering and diffraction of neutrons from a pulsed source on condensed media began [3]. The lead scientist of the project was F L Shapiro, whom Frank had invited in 1958 to the position of deputy director of the LNP. Eyewitness accounts have it that it was the tandem efforts of these two prominent scientists which made the work of the laboratory a success [15, 16].

In 1968, on Shapiro's proposal, an experiment on the search for ultracold neutrons (UCNs) was implemented [17]. Currently, a number of LNP groups are working with cold neutrons, a line of research that contributes to new insights into such aspects of the field as the energy quantization of neutrons interacting with moving diffraction gratings and accelerated matter [18–20], testing the weak equivalence principle for neutrons [21], neutron lifetime measurement [22], neutron quantum states in the gravitational field of Earth [23], and the 'weak heating' of ultracold neutrons interacting with the surface of a material (see Section 3.3 below).

All these research areas are currently being successfully pursued in the laboratory. Highlights of results from the period until 2000 may be found reviewed in Refs [24–27].

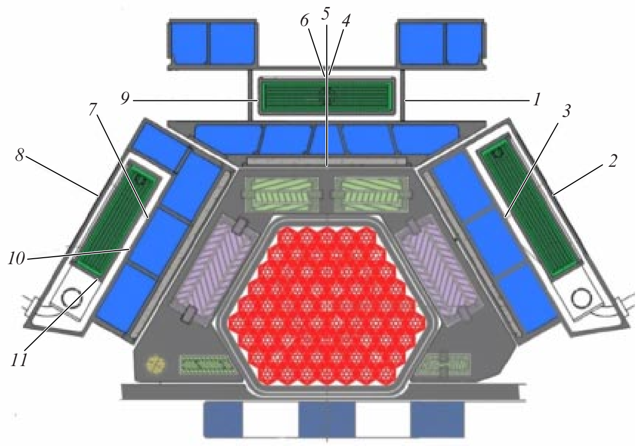

Figure 1. Cryogenic moderator system of the IBR-2 reactor. Numbers indicate the experimental channels controlled by the respective moderators.

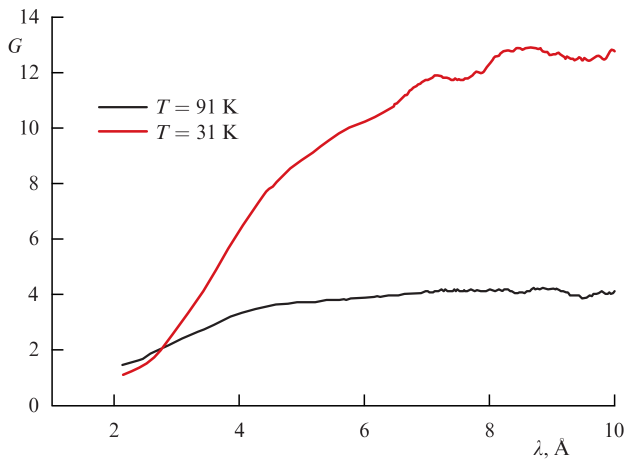

Figure 2. Gain factor (the ratio of the neutron flux density from the cryogenic moderator at a given temperature to the flux density from a water moderator at 300 K) measured during the operation of KZ-202.

2. Condensed matter studies using neutron scattering

The IBR-2 reactor, being one of the world's five most 'bright' sources, is also equipped with a unique system of neutron spectrometers that enable a wide range of interdisciplinary condensed-matter studies covering materials science, chemistry, biology, geophysics, pharmacology, medicine, nuclear physics, ecology, etc. [28]. The 2007–2010 shutdown period was effectively used to upgrade the existing and develop new facilities; in particular, the in-operation spectrometers for condensed matter studies have increased in number from 11 to 14 over the last five years. Among the new facilities were DN-6, a high-intensity diffractometer for investigating microsamples; a multifunctional reflectometer GREINS; and a neutron radiography–tomography spectrometer. Figure 3 schematically shows the arrangement of facilities in the experimental hall of IBR-2.

The spectrometers currently used in condensed matter research consist of the following: seven diffractometers, three reflectometers, one small-angle scattering spectrometer, two inelastic neutron scattering spectrometers, and one spectrometer for neutron radiography and tomography. The predominance of diffractometers is, to some extent, due to historical reasons, but there are also a number of objective ones, including the emergence of a new unique Fourier diffractometry technique, which allows diffraction experiments with a high interplane distance resolution (up to $\Delta d/d \approx 0.1-0.2\,\%$) to be carried out on crystalline materials, and the large application potential of the diffraction methodology in interdisciplinary research from condensed matter physics to biophysics and geophysics to medicine.

Using the IBR-2 spectrometer system, a user program was realized. Applications to conduct experiments are collected twice a year, and the beam time is distributed based on their assessment by international committees consisting of highly qualified experts. For example, in 2013, the applications numbered two hundred and came from fifteen countries, mostly from external organizations.

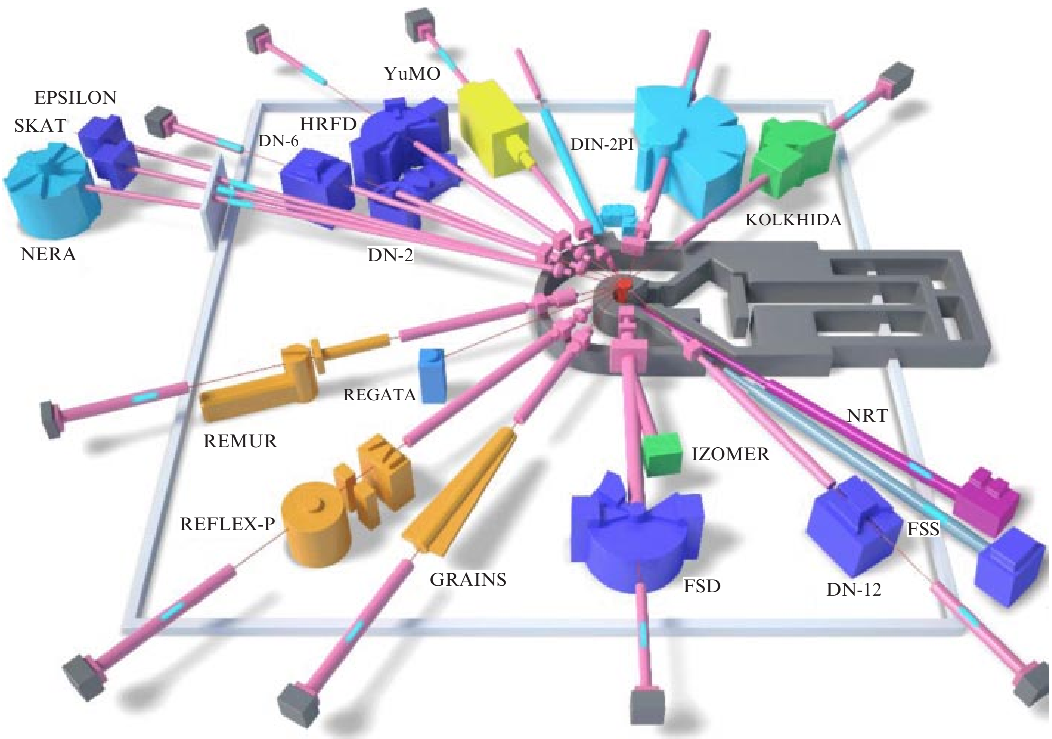

Figure 3. Experimental hall layout of IBR-2 (schematic).

Using neutron methods in condensed matter research has a number of advantages over other methods, in particular, over those using X-ray and synchrotron radiation [29]. Neutrons interact with nuclei, not with electronic shells. The fact that the neutron scattering length can be very different for different isotopes of the same element allows applying the method of contrast variation and, when analyzing the structure of the material, determining the position of light atoms against the background of heavy ones more accurately compared to the X-ray and synchrotron radiation methods. These capabilities of neutron scattering manifest themselves best in hydrogen-containing systems such as polymers, biological systems, and organic and water solutions. We also note that the neutron has its own magnetic moment, making neutron scattering methods the most direct and informative tools for determining the magnetic structure of materials, including bulk systems, thin films, and layered nanostructures. Due to the weak interaction with the material, the neutron methods can be applied nondestructively even to delicate biological systems, and due to the high penetration ability of neutrons, the neutron scattering methods are capable of obtaining bulk material characteristics even from samples located in complex environments, such as complex cryostats, high-pressure chambers, and electromagnets.

These features of neutron scattering methods define the range of problems to which it can be most effectively applied. The neutron scattering methods are undoubtedly advantageous when studying the nanolevel properties of nanosystems and materials containing hydrogen and other light atoms (Li, O, etc.), isotopic nanomaterials, magnetic nanosystems, and biological and polymer materials. We note that it is precisely functional materials with light atoms and magnetic atoms that are currently widely used in or being introduced into technologies in the fields of electronics, information recording and storage, and hydrogen power. This is the reason why the scientific community is showing increasing interest and the demand for neutron-scattering-based research is growing.

In view of the foregoing, the following areas of fundamental and applied condensed matter research at IBR-2 are of current topical interest:

— physics and chemistry of new functional materials;

— physics of nanosystems and nanoscale phenomena;

— physics and chemistry of complex liquids and polymers;

— molecular biology and pharmaceutics;

— materials science and engineering science.

We take a more detailed look at some of the research results. One of the currently topical problems in modern materials science is that of developing new functional materials capable of improving the characteristics and performance of lithium-ion rechargeable batteries, which are the power source for a variety of devices and systems, from mobile phones to aircraft. For this purpose, it is important to have information on changes in the micro- and crystalline structures, in particular, changes that occur as the battery operates. The structural behavior of novel modified $LiFePO_4$-based electrode materials directly during the charging and discharging of the accumulator and under steady-state conditions was studied at IBR-2 using the neutron diffraction method [29]. The experiments provided detailed information on transitions occurring in electrodes directly in the course of charge–discharge cycles, and the structural reasons for the improved electrode characteristics were identified. It was established that modifying $LiFePO_4$ by adding vanadium increases the conductivity due to the increased crystallite size, rather than, as believed earlier, due to vanadium substituting other ions in the crystal structure of the initial cathode material.

The study of the structural and magnetic properties of materials under extreme conditions of high external pressure is another interesting line of research. The effect of applying a

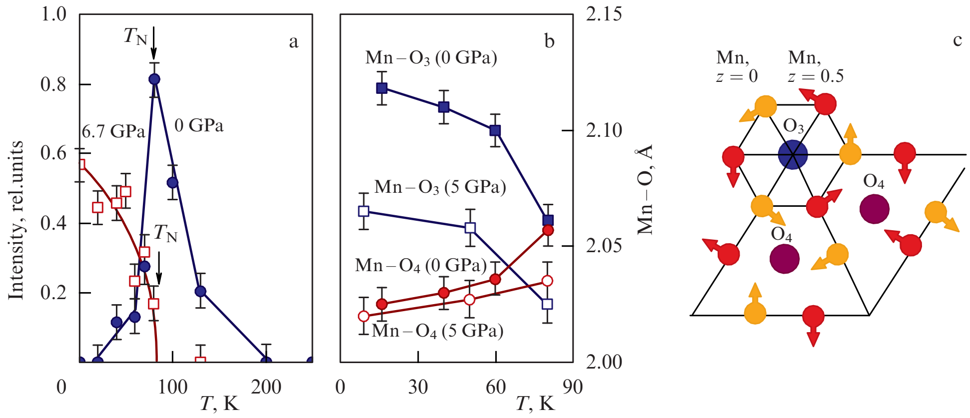

Figure 4. (a) Temperature evolution of magnetic diffuse scattering in $YMnO_3$ at pressures of 0 and 6.7 GPa demonstrating the suppression of the initial long-range antiferromagnetic order and the appearance of a new magnetic state with a short-range magnetic order and strong spin fluctuations. (b) Temperature dependence of Mn– O interatomic bonds that determine the balance between the competing magnetic super-exchange interactions on a triangle lattice. (c) Schematic of the hexagonal structure of $YMnO_3$ with a quasi-two-dimensional magnetic lattice of Mn ions. (Data from Refs [32, 33].)

high pressure to a material is a reduction in the interatomic distance and changes in the potential energy of the interatomic interactions, which creates new forms of matter with possibly highly unusual properties. Magnetic order in magnetic materials under compression generally becomes more stable due to the increased exchange interactions, a point which Bloch formulated in one of his papers [31]. In the course of neutron studies of a complex oxide, the multiferroic $YMnO_3$ with the classical spin $S = 2$ and a geometrically frustrated quasi-two-dimensional triangular lattice (Fig. 4), it was recently demonstrated that the opposite effect is also possible, in which the long-range magnetic order is destroyed to give way to a dynamically disordered state similar to the spin liquid state, which, as previously thought, occurs only for a quantum magnet with the spin $S = 1/2$ [32, 33]. Another finding is that there is a direct relation between the degree of distortion of the triangular lattice and the magnitude of spin fluctuations.

An important component of most types of animal and plant cells are mitochondria, organelles whose key function is to produce energy for cellular processes. Unlike synchrotron radiation, which causes great damage to living cells, neutron radiation allows experimenting with living biological subjects without their losing their functionality. The first studies to examine living functioning mitochondria in specific incubation media and under specific conditions were conducted at IBR-2 using small-angle neutron scattering [34, 35]. The studies revealed the structural features of the inner mitochondrial membrane under conditions of decreasing osmoticity of the incubation medium. It has been shown that the mitochondrial membrane produces unusual ordered structures under certain conditions (Fig. 5). In particular, the membrane

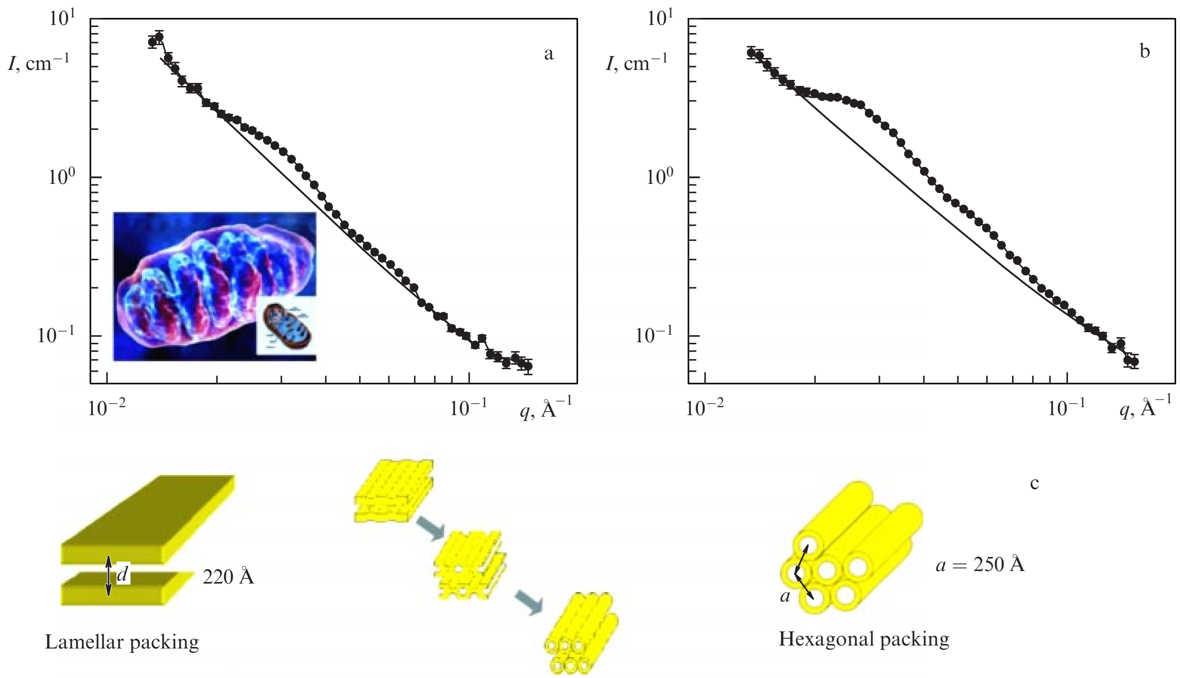

Figure 5. Curves of small-angle neutron scattering from heart mitochondria of a rat in (a) an isotonic (250 mOsm) and (b) a hypotonic (90 mOsm) media. Inset: schematic of a mitochondrion. (c) Structural change in a mitochondrial membrane from lamellar to hexagonal packing under hypotonic conditions.

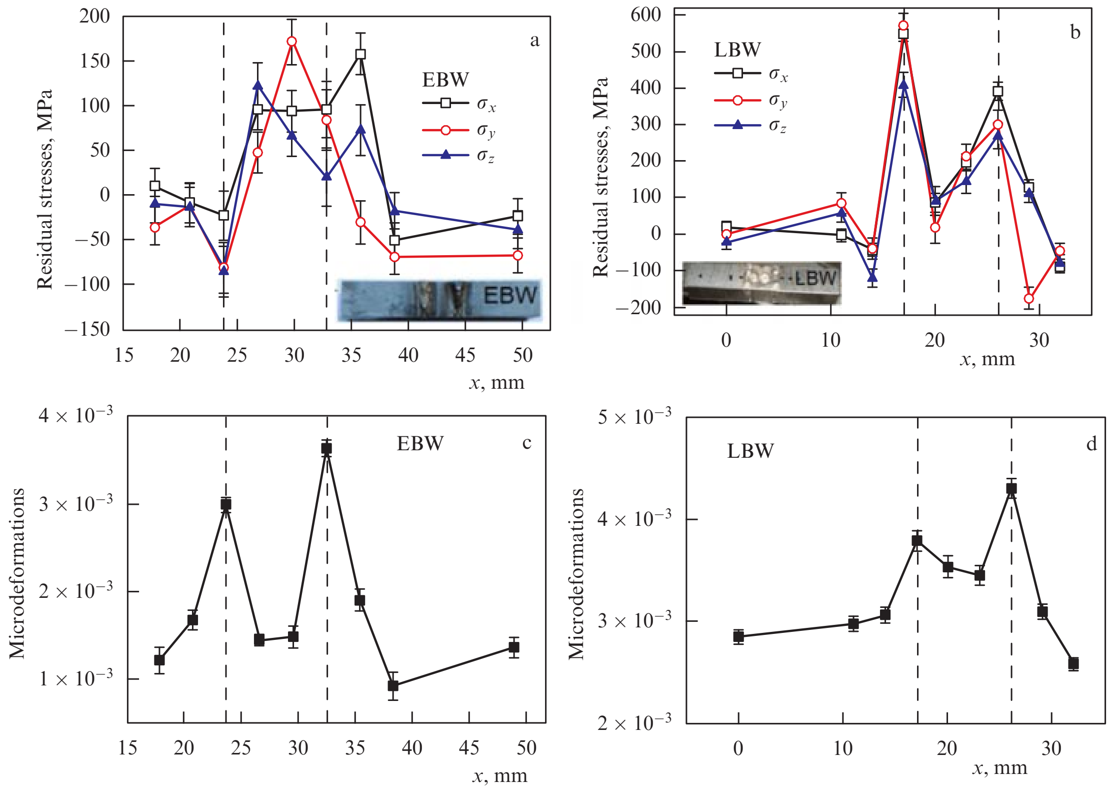

Figure 6. (a, b) Residual stress and (c, d) microdeformation distributions in samples restored by electron-beam and laser-beam welding (EBW and LBW) techniques; measurements are performed by neutron beam scanning along the sample axis x. Insets in panels a and b show photos of the samples.

packing changes from lamellar (planar) to hexagonal. Using neutron scattering also allowed obtaining scattering patterns for the lipid and protein mitochondrial components separately when investigating the structure of virgin mitochondria, as well as gaining information on the protein and lipid distribution in the inner mitochondrial membrane.

Due to the high penetrating power of neutrons, neutron scattering provides an effective tool for nondestructive control of internal stresses in bulk materials and in devices. An important problem in modern nuclear power industry is that of monitoring the state of the reactor pressure vessel's metal over the entire service life of the reactor to ensure its integrity both under normal operating conditions and in case of possible failures. An important source of information on the degradation of the mechanical properties of neutron-irradiated pressure vessel steels are sharpy samples placed on the inner walls of the reactor pit. To increase the number of irradiated samples of pressure vessel steel, a technology is used in the process of reactor operation that allows restoring sharpy samples (after their mechanical test) by using various welding techniques (electric arc, electron beam, laser, etc.). Separating the effects of neutron radiation and the sample restoration procedure by the mechanical properties requires knowing the level of welding-induced residual stresses in the restored sharpy samples. In the studies on IBR-2, the residual stress distribution in sharpy samples following electron beam welding (EBW) and laser beam welding (LBW) was measured [36]. It was found (see Fig. 6) that the residual stresses in an LBW sample are higher than in an EBW sample and reach 550 MPa at the welding seam. Also, from the diffraction peak broadening, the level of residual microdeformations, which characterizes the dislocation density in the material being studied, was calculated to be 3.5×10^{-3} in an EBW sample and somewhat more, 4.5×10^{-3}, in an LBW sample. Accompanying this effect is a significant increase (by about a factor of 2.5) in microhardness in the welding seam zone, possibly due to the formation of the martensite (or martensite–bainite) structure in the welding seam region and the thermal influence zone.

There is also a range of other research areas that have yielded noteworthy results in recent years and which include the following: the effect of controlling the size of nanoparticles in magnetic fluids [37]; the phenomenon of the coexistence of superconductivity and magnetism in layered magnetic nanostructures [38], structural organization of lipid nanosystems that model the upper skin layer of humans and other mammals [39]; tailoring the optical properties of novel nanostructured materials, the so-called luminophores [40]; the structural and magnetic properties of RCo_2 intermetallics under conditions of varying thermodynamic parameters (temperature, pressure) [41, 42]; interrelations of rock texture, phase transformations in geomaterials, and seismotectonic effects [43].

3. Neutron nuclear physics research

3.1 Preparing experiments to directly measure the neutron–neutron cross section at the YAGUAR reactor (RFNC–VNIITF, Snezhinsk); first results

In order to experimentally resolve the question of the degree of charge symmetry breaking in nuclear forces, measurements of the scattering of free neutrons on one another appear to be a very interesting approach. Because a pure neutron target does not exist in nature, the only way to perform such an experiment is by using intensive neutron sources. Kolesov [44] notes that the advantages of a pulsed reactor for implementing such an experiment were first recognized as far back as 1969 [45]. Measuring the neutron–neutron scattering cross section was among the priorities of the scientific program envisaged for the IBR-2 reactor as it was developed at the LNP, JINR. In the 1990s, LNP researchers considered the possibility of using the BIGR reactor at VNIIEF, Snezhinsk, to implement the experiment [46, 47]. Many other projects have also been proposed outside the USSR and then Russia, but none of them reached the implementation stage.

Early in 2000, following a proposal by Kolesov, the first feasibility discussion of using the YAGUAR aperiodic reactor to perform the experiments was held at the Khariton thematic scientific readings [49]. The idea, first calculations, and the results of neutron field measurements in the reactor through a channel were reported at a number of meetings and published in the literature [49–51]. As a result, the DIANNA collaboration was formed in 2003 among the LNP, RFNC–VNIITF, TNL (USA), and Gettysburg College (USA), which set out, with the financial backing of the International Science and Technology Centre (ISTC), to implement the project of developing the experimental facility, a task which was completed in 2008.

Over that period, a great amount of work has been done, including neutron field calculations, background condition calculations for specialized protection, experimental tests of model protection calculations, the development of the experimental setup, collimation system optimization calculations, reactor hall redesign (to add a 10-m-deep pit under the reactor and to arrange a hole for the neutron channel in the hall ceiling), and the development of an experimental facility, which includes a 28 m vacuum channel, a unique neutron beam collimation system, and a unique neutron detector with a data collecting system (see Refs [52–61] for the details and results).

A schematic of the experimental facility is shown in Fig. 7.

During the approximately 1 ms reactor operation pulse, neutrons collide with each other in the vacuum channel that passes through the moderator in the active zone. Only a neutron that has undergone scattering by other neutron(s) (or by the residual gas in the deep-vacuum pumped channel) can move along the channel axis on which the detector is located. Owing to the collimation system, the detector 'does not see' the channel walls. The separation of the useful signal from the background is achieved by using a special collimation system, by applying the time-of-flight method, and by measuring how the observed signal depends on the neutron pulse intensity (this dependence should be proportional to the neutron density squared).

In an important aspect of the work, test and gauge measurements were successfully performed. The first attempt to measure the nn-scattering cross section revealed a neutron background that is quadratic in the reactor pulse energy and exceeds the expected effect by a factor of about 30 [54]. This dependence, together with the spectrum of detected neutrons, indicates that the background is due to the hydrogen that penetrates the vacuum channel due to radiation desorption from the walls [61].

Because of the upgrade, the reactor was out of service between 2009 and 2014. Further progress in this area fundamentally requires that the observed background be suppressed by a factor of at least 100. Presently, it can be argued that the first attempt to implement the experiment to directly measure the neutron–neutron scattering cross section has encountered challenges that require copious resources to overcome.

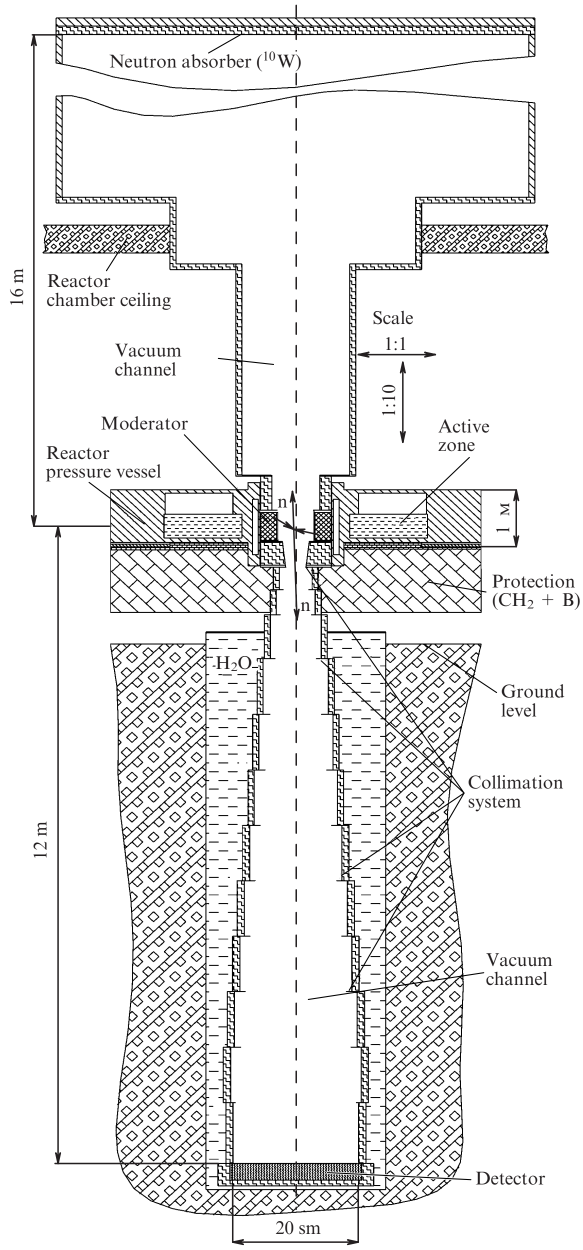

Figure 7. Schematic of the experimental facility.

3.2 Measuring the P-odd asymmetry of the products of reactions between light nuclei and cold polarized neutrons

Between 2002 and 2009, a series of experiments were done to measure the coefficient of the spatial-odd (P-odd) asymmetry in the angular distributions of the products of reactions between light nuclei ^{6}Li(n, α)^{3}H and ^{10}B(n, α)^{7}Li* $\rightarrow$ γ $\rightarrow$ ^{7}Li(o.c.) with cold polarized neutrons. The fundamental problems to which the research was addressed were the search for neutral currents in weak nucleon–nucleon (N–N) interactions at low energies (in leptonless quark-flavor-conserving processes) and testing the validity of using the one-boson-exchange potential (OBEP) model [62] to describe weak N–N interactions. The specific problem is to determine the weak π-meson coupling constant f_π (h_π^1) of the parity-violating N–N potential.

The OBEP model treats the parity-violating interaction by means of exchange by the lightest muons $\pi^{\pm}$, ρ, and ω between the nucleons, as in parity-conserving nuclear interaction [63]. But unlike the nuclear interaction, the mesons result from the weak quark–quark interaction within one of the nucleons.

The parity-violating potential is parameterized by a set of six dimensionless weak constants $h_M^{\Delta T}$. P-odd effects in N–N interactions and nuclei are associated with the physics of weak quark–quark interactions with weak constants. These constants can be calculated from the principles of the Standard Model, based on the quark structure of nucleons, etc. [61–65], but the complexity of strong interaction effects lead to a sufficiently wide range of predictions for the values of the constants. The π-meson constant is important in that the $\pi^{\pm}$-meson exchange is due to the interaction of neutral currents.

The scientific community has spent much effort for over forty years on the search for neutral currents in nuclear reactions and the experimental determination of the weak coupling constant, but no significant success has been achieved. The experimental and theoretical problems that hamper progress in this areas originate in the fact that for complex nuclei (where P-odd effects are enhanced) uncertainties in nuclear wave functions make it virtually impossible to calculate the P-odd effects, whereas for bare nucleons and few-nucleon systems, the effects are small ($\sim 10^{-7}$) and experiments are difficult to carry out. To date, few experiments have achieved sufficient accuracy to estimate the weak constants (see Refs [63–67]). We note that in experiments on the scattering of polarized protons by a proton target, in which the P-odd effect is determined by charged currents, the values of the corresponding constants agree well with the so-called 'best values' in [63], validating the one-meson exchange model and proving the presence of weak charged currents in N–N interactions. On the other hand, the effect was not observed in the measurements of the circular polarization of the γ quanta from ^{18}F, where the interaction is exclusively due to the neutral current. The pion coupling constant is found to be strictly bounded as $f_\pi \leqslant 1.1 \times 10^{-7}$, but this value is about one fourth the 'best value'. Estimates for f_π from other experiments, in which the effects are determined by combinations of constants, range from zero to $\sim 9 \times 10^{-7}$. The problem concerning the value of f_π is best approached by measuring the asymmetry of γ quanta in the np $\rightarrow$ dγ reaction with polarized neutrons. However, the small cross section of the reaction and the small expected magnitude of the effect make this measurement difficult to perform.

At the LNP, JINR, and Petersburg Nuclear Physics Institute (PNPI), experiments on the lightest nuclei were proposed, for which asymmetry measurements appear to be more realistic. The P-odd effects in the reactions that were studied were calculated in the framework of the cluster approach [68, 69]. The expected correlation values lie in the range $10^{-8} - 10^{-7}$. A large interaction cross section, and hence a relatively small contribution from background reactions, is one of the advantages of these reactions.

Experiments to measure the P-odd asymmetry of the form $\alpha^t_{\rm PNC}(s_n, p_t)$ in the reaction ^{6}Li(n, α)^{3}H and of the form $\alpha^\gamma_{\rm PNC}(s_n, p_\gamma)$ in the reaction ^{10}B(n, α)^{7}Li$^* \rightarrow \gamma \rightarrow {}^7$Li(o.c.) were performed on cold ($\langle \lambda_{\rm n} \rangle = 4.7$ Å) and polarized (94%) neutrons of the PF1B beam at the ILL reactor (Grenoble), which provides an integral intensity of (4–5) $\times 10^{10}$ s^{-1}. The experiments used the so-called integral method of measuring small effects, which allows using high-intensity neutrons and excludes spurious apparatus effects. Underlying and included in the methodology are the current-based event-counting technique, the technique for compensating reactor power fluctuations, periodic direction switching of the neutron-spin-guiding magnetic field, and carrying out zero experiment. A 48-section ionization chamber was used as a triton detector, with its 28 ^{6}LiF targets absorbing more than 60% of the intensity. When conducting zero experiments, the lithium targets were additionally coated with aluminum foil that totally absorbed the tritons, and measurements were done under the same conditions as for the main experiments [70, 71]. Experiments on ^{10}B used a system of two NaI(Tl) detectors and a sample that absorbed neutrons completely. The experiments performed in 2001, 2002, and 2007 are described in [72, 73]. To reduce the effect of reactor power fluctuations, an improvement of the integral measurement method was used, which permitted operating at neutron spin switching frequencies higher than the primary reactor power fluctuation frequencies [74]. The final result is presented in Ref. [75].

The experiments showed that for the ^{6}Li(n, α)^{3}H reaction, the asymmetry is $\alpha^t_{\rm PNC} = -(8.6 \pm 2.0) \times 10^{-8}$, and an estimate for the pion coupling constant is $f_\pi \leqslant 1.1 \times 10^{-7}$ (90% confidence level). The asymmetry of γ quanta in the ^{10}B reaction is $\alpha^\gamma_{\rm PNC} = (0.7 \pm 2.3) \times 10^{-8}$ and $f_\pi \leqslant 0.7 \times 10^{-7}$ at a 90% confidence level. In both cases, the constant is less than the 'best value' $f_\pi = 4.6 \times 10^{-7}$ [63] defined in the Desplanques–Donoghue–Holstein approach.

Due to the disagreement between the experimental data and the results from the OBEP model, the view of an increasing number of investigators is that the weak N–N interaction is controlled by a more complex mechanism. Accordingly, new theoretical approaches are being advanced [76]. From the standpoint of neutron experiments, the study of few-nucleon systems and the lightest nuclei remains the most promising research route.

3.3 Ultracold neutron 'small heating' phenomenon: discovery and observation

The discovery of the 'small heating' of UCNs resulted from the search for the reasons for the anomalous loss of UCNs from material traps. The use of UCNs in physical experiments is attractive because they can be kept for a long time in a closed volume (trap). Experiments with UCNs have produced the most accurate current value of the free neutron lifetime [77] and placed the strongest constraint on the existence of the neutron electric dipole moment [78]. Work is currently being conducted at various research centers to develop such experiments and to increase their accuracy.

Since the discovery of UCNs, all UCN storage experiments have shown traps to be much more lossy than theoretically expected (for example, by two to three orders of magnitude for weakly absorbing materials such as beryllium and solid oxygen).

The correct consideration of neutron losses from traps and of changes in the UCN spectrum during the storage process in many respects determines the systematic accuracy of UCN experiments like neutron lifetime measurements, in which these losses compete with neutron β decay and the change in the spectrum makes it necessary to introduce the corresponding systematic corrections into the results.

Besides the neutron β decay, there are only two channels by which UCNs can escape the hermetic material trap according to the traditional view of the UCN–matter interaction: the capture by nuclei in the trap wall material and heating on the trap walls (inelastic scattering). The latter implies that UCNs are most probably scattered into the energy region that corresponds to the trap wall temperature and exceed their kinetic energy by five orders of magnitude.

There is a rather long history (see Ref. [79]) behind the idea that the additional UCL losses from traps may be due to the anomalous inelastic scattering of UCNs from the surface with an energy increase to values much lower than the thermal energy. Due to their low energy, such neutrons would be captured by the construction materials and would not therefore reach detectors mounted in facilities used in experiments aimed at investigating normal inelastic scattering [80, 81].

Finally, in 1997, an additional escape channel was discovered for UCNs, which involves their scattering as they hit the surface with an energy increase by about 10^{-7} eV, with a probability in the range of $10^{-8}-10^{-5}$ per impact [82, 83], a value many orders of magnitude larger than the theoretical expectation. A neutron leaves the trap if its energy after such an inelastic scattering exceeds a certain critical value. This process is reminiscent of the evaporation of UCNs from traps, and hence such neutrons came to be known as 'vaporized ultracold neutrons' (VUCNs), and the process itself, unlike the well-known heating into the thermal region, as small UCN heating. A reverse effect, in which UCNs decrease in energy (cool down) when interacting with the surface of hydrogenless fomblin oil, is reported in [82].

To choose from a number of proposed UCN–surface interaction mechanisms responsible for the observed small heating, an experimental investigation of the parameters of the new phenomenon was carried out using the Large Gravitational UCN Spectrometer specifically designed to study the small heating of UCNs (see Ref. [83] for a detailed description of the instrument and the measurement method). The facility can be operated at temperatures from 250 °C to the liquid nitrogen temperature, has equipment for rapidly replacing study samples (at room temperature), contains a complex of variable-length barriers, and allows using a gravitational barrier at the input variable-height neutron guide to work with narrow initial UCN spectra. Of the two absorbers used, one, a titanium absorber, is intended for work in a regime involving the heating of the spectrometer, and the second, a polyethylene absorber with a developed surface, ensures the sharpest possible cutoff of the initial UCN spectrum, thus narrowing the energy range in which the facility is insensitive to small energy changes.

Both the surface of the spectrometer and various samples located within the spectrometer were used to perform the measurements. The sensitivity of the facility at the Grenoble UCN source allows measuring the small heating probability at a level of 10^{-8} per impact on the surface for a surface area of about one square meter. The samples used were foils of various materials pretreated in different ways: plates of single-crystal sapphire, nanodiamond powders, and foils coated with various hydrogenless oils.

Based on the analysis of experimental data, it seems appropriate to discuss small heating on solid and liquid surfaces separately: for solids, only one currently available small heating mechanism [86] is capable of accounting for the entire body of experimental data. According to this mechanism, UCNs are inelastically scattered by nanoparticles that are in a relatively free state near the surface (the state of physical adsorption [87, 88]). For liquid surfaces, alternative explanations — for example, scattering by viscoelastic surface waves [89, 90] — are available.

Listed below are the major experimental results and some of the conclusions they suggest.

— Concerning the study of the small heating of UCNs, it is established that the effect results in about a 50 neV average energy increase due to reflection from the metal surface.

— The measured flow of VUCNs varies with temperature much less than for the usual phonon heating to the thermal region, but this is not inconsistent with the assumption, for example, of the VUCN regeneration varying linearly with temperature.

— It is established that the probability of small UCN heating on the surface of stainless steel and copper can be highly dependent on the surface preparation procedure (predegassing temperature and processing reagents). In our particular case, the maximum probability observed was $(4.5 \pm 0.3) \times 10^{-6}$ per impact on the surface.

— It is found that at the temperature corresponding to a sharp increase in the small-heating probability, a nanostructure with a characteristic grain size of about 10 nm forms.

— No correlation exists between the small-heating probability and the loss coefficient.

— In measurements on single-crystal sapphire, small heating is not observed at the level of sensitivity of the facility, and no nanoparticles are found to reside on the sapphire surface.

— It is demonstrated that coating the sample surface with nanoparticle powder results in an increase by several orders of magnitude in the small-heating probability and that the spectral and temperature dependences of small heating are similar to those obtained for temperature-treated metallic samples.

— The observed small-heating probability is much higher for liquids than for solids.

— The temperature dependence of the UCN small heating on the surfaces of hydrogen-free oils was measured.

Based on the analysis of this data, the most probable mechanism to account for the experimental data from solid samples is UCN scattering by free particles (clusters) about 10 nm is size moving at thermal velocities. We also note that, irrespective of the size distribution of the particles, the neutrons 'by themselves' choose nanoparticles of the order of the neutron wavelength in size, thus decisively identifying the most probable energy transfer per impact, which is of the order of 10^{-7} eV if the trap is at ambient temperature [91].

For liquids, the identification of the UCN small heating mechanism remains a challenge. The observed temperature dependence of the small heating probability is well accounted for by the hypothesis of surface wave scattering, whereas for spectral measurements, the hypothesis of scattering by near-surface nanodroplets is a better explanation. This situation suggests the need for further development of this hypothesis to enable a prediction of the temperature dependence.

4. Conclusion

It is sixty years now that the Frank Laboratory of Neutron Physics, JINR, has been using neutrons in its physical research — both as an object of study and as a powerful tool for investigating the properties of atomic nuclei and condensed media. Currently, when new neutron sources capable of producing a high-density flux of thermal neutrons are being developed based on proton accelerators, the IBR-2 reactor remains among the five 'brightest' sources available. Presently under development is a new neutron source based on the IREN electron accelerator, which has the fast neutron pulse duration 20–200 ns, the repetition frequency 120 Hz, and the integral yield 10^{13} n s^{-1}. Other current activities include the ongoing modification of the facilities for neutron scattering studies of condensed media, the renovation of the detector base, the development of new electronics for collecting, storing, and visualizing data, and a program of applied research using neutrons (neutron-activation analysis in the life sciences, development of neutron and gamma detectors, the study of the radiation resistance of materials and electronics components). The results obtained either within the laboratory research program or within research programs of the users are presented on a regular basis at scientific events such as conferences and schools, many of which are hosted by the laboratory.

The Frank Laboratory of Neutron Physics at the Joint Institute for Nuclear Research remains one of the world's leaders in the field of neutron physics.

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