FRANK LABORATORY OF NEUTRON PHYSICS

In 2010, the FLNP scientific programme was realized under four research themes of the JINR Plan for Scientific Research and International Scientific and Technical Cooperation and was aimed at obtaining new results in condensed matter physics (theme 04-4-1069-2009/2011 «Investigations of Nanosystems and Novel Materials by Neutron Scattering Methods», headed by V. L. Aksenov, A. M. Balagurov and D. P. Kozlenko) and neutron nuclear physics (theme 06-4-1036-2001/2010 «Nuclear Physics with Neutrons — Fundamental and Applied Investigations», headed by V. N. Shvetsov and Yu. N. Kopatch). To effect scientific research, work was continued to develop and modernize the FLNP basic facility, the IBR-2 (theme 07-4-0851-87/2010 «Upgrade of the IBR-2 Complex», headed by A. V. Belushkin and A. V. Vinogradov) as well as the IBR-2 spectrometer and computation complex (theme 04-4-1075-2009/2011 «Novel Development and Creation of Equipment for IBR-2M Spectrometers Complex», headed by V. I. Prikhodko and S. A. Kulikov).

CONDENSED MATTER PHYSICS

In view of the IBR-2 reactor shutdown for modernization, the experimental activities conducted by the personnel of the FLNP Department of Neutron Investigations of Condensed Matter (NICM) were carried out in neutron and synchrotron centers in Russia and abroad. This work was performed in accordance with the existing cooperation agreements and accepted beam time application proposals. The activities on the IBR-2 reactor were carried out in accordance with the modernization plan for the spectrometers.

Scientific Results. The magnetic and crystal structures of the complex cobalt oxide $Pr_{0.5}Sr_{0.5}CoO_3$ have been studied using neutron diffraction and synchrotron radiation in the temperature range from 1.5 to 1120 K. Unlike other $Ln_{0.5}Sr_{0.5}CoO_3$ compounds, it exhibits both a paramagnetic–ferromagnetic transition at $T_C \approx 226$ K and one more magnetic phase transition at $T_A \approx 120$ K accompanied by a change in the behavior of magnetization in external magnetic fields and by an anomalous behavior of elastic properties of the material. Successive structural transitions with the reduction of the crystal symmetry from cubic (space group $Pm\bar{3}m$) to rhombohedral ($R\bar{3}c$), then to orthorhombic (Imma) and triclinic ($P\bar{1}$) are detected at temperatures of about 800, 300 and 120 K. The obtained results have helped to refine the earlier suggested models of the crystal structure of various phases. The anomalies in the temperature behavior of some interatomic distances and angles, as well as the reorientation of cobalt magnetic moments are observed at the transition to $P\bar{1}$ phase.

The structural and magnetic phase transitions in the multiferroic $BiMnO_3$ complex oxide have been studied at high pressures [1]. A unique feature of this compound as compared to other multiferroics is the combination of magnetoelectric effects with ferromagnetic ordering. A structural phase transition between two monoclinic modifications of $C2/c$ symmetry was observed at a pressure of 1 GPa. The structural phase transition occurs with a change in the character of magnetic ordering from ferromagnetic ($T_C = 100$ K) to antiferromagnetic ($T_N = 90$ K) one with a propagation vector $k = (1/2\,1/2\,1/2)$. With a further increase in pressure at $P \sim 8$ GPa a structural phase transition to the orthorhombic phase of $Pbnm$ symmetry was observed. The obtained results made it possible to reveal the role of competing superexchange interactions in the mechanism of occurrence of magnetoelectric phenomena.

Structural characteristics of nanostructured silicon glasses containing cerium and titanium oxides have

been investigated by small-angle neutron scattering [2]. It has been found that optical properties of glasses, in particular, the transmission coefficient, are strongly dependent on the mean size of Ce-Ti-O clusters that are formed in the process of doping with CeO_2 and TiO_2.

Structural characteristics of biocompatible ferrofluids [3] synthesized for treating human brain cancer tumors have been determined using small-angle neutron scattering. The double layers of myristic (MA + MA) or lauric (LA + LA) acids were used to stabilize magnetite nanoparticles (size of $\sim$ 10 nm, polydispersity $> 50\%$) in a liquid medium. The presence of nanoparticle clusters with a characteristic size of 30–40 nm has been revealed in the samples. It has been found that the clusters in the samples of the LA + LA type consist of magnetite particles completely coated with a surfactant shell about 3.5 nm thick, while in the samples of the MA + MA type the clusters comprise magnetite particles partially coated with surfactants (Fig. 1).

In the frame of investigations of fullerene solutions with intermediate polarity ($\varepsilon \sim 10-50$), the C_{60}/N-methyl-pyrrolidone (C_{60}/NMP) system has been studied. It is characterized by the formation of large (size of up to 500 nm) but stable clusters of fullerene molecules with time (about one month after dissolution) [4]. It has been proposed to follow the cluster growth with the help of the extraction into an organic solvent immiscible with NMP (e.g., hexane). The cluster formation correlates with the temporal solvatochromic effect and stops after all C_{60} transfer to unextractable clusters in C_{60}/NMP. On addition of water to the system, the extraction resumes, which suggests that the clusters are destroyed as a result of the detachment of single C_{60} molecules. The appearance of separate molecules in the solution has been testified by mass-spectrometry, and a decrease in the cluster size has been detected by small-angle neutron scattering.

Aqueous solutions of multilamellar vesicles of the membranes modeling the lipid component in the mucous membranes of the oral cavity of mammals based on ceramide-6 and membranes in its structure (mixtures of sphingomyelin/ dipalmitoylphosphatidylcholine/ dipalmitoylphosphatidylethanolamine with ceramide-6), have been investigated by means of synchrotron radiation diffraction in the temperature range of 20–80 (90) °C. It has been found that at high temperatures (70–80 °C) the mixture of sphingomyelin/phospholipids tends to form an inverse hexagonal phase. Ceramide-6 at a mole fraction of 0.2–0.3 increases the repeat distance in multilamellar vesicles of the sphingomyelin/phospholipids mixture by ~ 1 Å and hinders the formation of the inverse hexagonal phase at high temperatures.

The experimental investigations of the problem of the coexistence of ferromagnetism (F) and superconductivity (S) in layered heterostructures have been continued [5]. The inverse proximity effect in a superconductor-ferromagnet V/Fe heterostructure has been observed and explained by the polarization of Cooper pairs in the superconducting layer. The dependence of the effect on the structural and magnetic parameters has been studied.

Theoretical calculations for the small-angle scattering study of deterministic fractals — generalized Cantor fractals — have been performed [6]. Deterministic fractals are a model of strictly self-similar structures of nanoobjects, which now can be obtained due to the development of modern nanotechnologies. The form

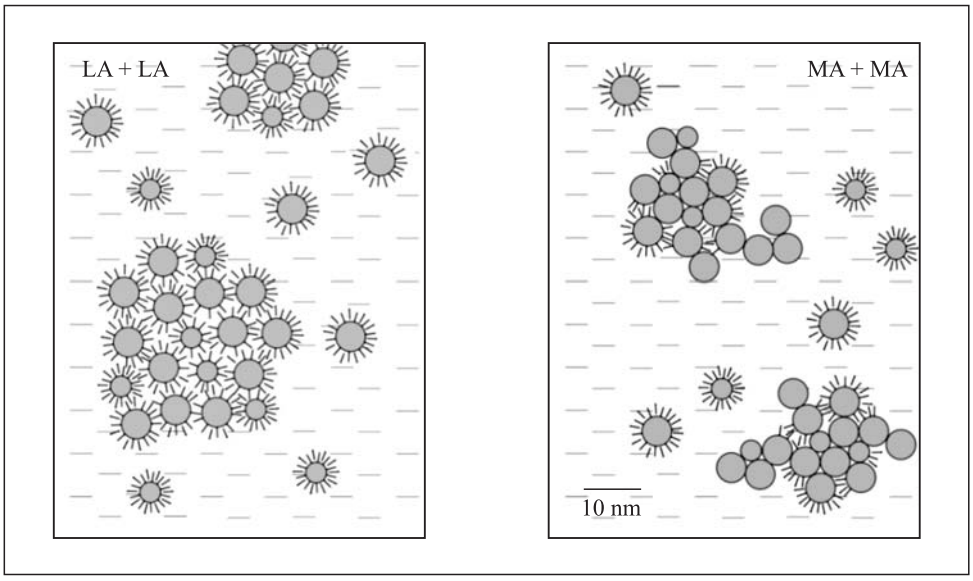

Fig. 1. Schematic representation of the cluster structure in two biocompatible water ferrofluids with double-layer stabilization of magnetite nanoparticles by lauric (LA + LA) and myristic (MA + MA) acids on the basis of contrast-variation small-angle neutron scattering data (Cooperation with Romania)

factor of the generalized Cantor fractal has been calculated analytically for arbitrary values of the wave vector and any finite iterations of the fractal, which makes it possible to use it for describing the scattering from orientationally ordered fractal sets. For randomly oriented fractals, the scattering intensity from mono- and polydisperse fractals has been obtained in the form of simple integrals.

The investigations of the structural characteristics of dendrimers have been continued [7]. With the help of small-angle neutron scattering and the contrast variation technique it has been shown that the scattering density distribution in the dendrimer volume is uniform within the experimental error. The quantitative estimate of the volume accessible for the solvent penetration inside a dendrimer has been made for various concentrations.

Experiments to study elastic wave propagation in model inhomogeneous anisotropic media — samples of plexiglas + single-crystal quartz, plexiglas + polycrystalline graphite (with a known texture), epoxy resin + biotite — have been carried out. It has been shown that in the model materials of «epoxy resin + biotite» differing by an order of magnitude in the grain size of biotite (0–0.4 mm and 2–5 mm), the velocities of longitudinal elastic waves with various frequencies coincide. It has been suggested that a discrete wavelet-transform method be used for the analysis of acoustic signals and determination of transverse elastic wave velocities. The comparison of theoretical calculations with the ultrasonic data from physical models has been conducted and a satisfactory agreement of the results has been obtained.

Neutron diffraction studies of residual stresses in a cross-shaped sample of austenitic stainless steel AISI 321 subjected to biaxial strain-stress cycling have been carried out. Under the action of plastic deformation, the austenitic matrix underwent partial transformation, which caused the formation of a new ferromagnetic martensitic phase in the sample. The total residual stresses as well as macro- and microstresses in both phases of the cycled sample were measured using the time-of-flight neutron diffraction technique.

Using the data analysis of the texture measurement of polyphase granite gravel from the Erzgebirge, the magmatic flow and oriented crystal growth in an anisotropic stress field have been demonstrated to be the major texture formation processes. Texture measurements of rock salt from different sources in North Germany have been performed to study active deformation mechanisms. It has been concluded that during deformation processes texture does not develop or previously existing texture is destroyed because of the grain boundary migration processes.

The spin dynamics in the $Ce_{(1-x)}Y_xAl_3$ system at a transition from a heavy fermion (HF) state at $x = 0$ to a mixed valence (MV) state at $x = 0.5$ has been investigated by inelastic neutron scattering [8]. It has been shown that the substitution of yttrium for cerium results in a strong transformation of spectrum components of the magnetic response due to an increase in the $k - f$ hybridization.

Instrument Development. The installation of the beam chopper and the head part of the mirror neutron guide for the new DN-6 diffractometer for microsample investigations has been completed on beam 6b of the IBR-2M reactor. The manufacturing of mirrors for the tail part of the neutron guide has continued. The technical documentation for manufacturing of the mechanical part of DN-6 has been prepared. The manufacturing of a gas position-sensitive detector has started in the FLNP Spectrometers' Complex Department (SCD).

The installation of the head part of the new multifunctional reflectometer GRAINS on beam 10 of the IBR-2M reactor has been completed (Fig. 2). The vacuum housing of the beam-forming system has been manufactured, assembled and tested for vacuum. The manufacturing of the background neutron drum chopper with a horizontal slit and the construction of an autonomous vacuum system for the reflectometer have continued. The designing and manufacturing of a control system for stepper motors of the instrument and the software for the reflectometer have started. A 2D position-sensitive neutron detector has been manufactured and tested (in cooperation with SCD).

Work on the installation and adjustment of mechanical units and mirror segments of a neutron concentrator for the DIN-2PI spectrometer has been completed.

A project of the creation of a neutron spectrometer for studying transient processes in real time at the IBR-2M reactor has been prepared.

Fig. 2. The head part of the GRAINS reflectometer installed in the ring corridor of the IBR-2M reactor (Cooperation with Germany, Hungary, Romania)

The development work on the production of polarized neutron microbeams ~ 1 μm wide has been conducted. It has been demonstrated that the combination of a non-magnetic waveguide and a polarized neutron reflectometer is the most promising configuration for investigations of magnetic nanostructures with the help of a polarized neutron microbeam.

NEUTRON NUCLEAR PHYSICS

In cooperation with ITEP (Moscow) a T-odd three-vector correlation in the emission of prompt neutrons in the polarized-neutron-induced fission of ^{235}U nuclei has been studied in the MEPHISTO polarized cold-neutron beam from the Munich FRMII reactor of the Technical University of Munich (TUM). The sought-for correlation has not been found within the measurement error of $2.3{\cdot}10^{-5}$. The upper limit for the asymmetry coefficient was determined to be $|D_n| < 6 \cdot 10^{-5}$ at the 99% CL. Simultaneously a five-vector correlation was measured in the emission of fission neutrons, which describes the effect of rotation of a fissioning nucleus at the instant of its scission. At an angle of 22.5° to the fission-fragment separation axis, the correlation coefficient proved to be $(1.57 \pm 0.20) \cdot 10^{-4}$, whereas at an angle of 67.5° it is equal to zero within the measurement errors [9].

A theoretical analysis of the experiments on the measurement of spin relaxation of polarized ^{3}He in gas cells has been performed in order to infer constraints on P,T-non-invariant long-range interaction. New constraints on the P,T-non-invariant nucleon–nucleon interaction in the range of $(10^{-4} - 1)$ cm have been obtained. The gradient of a long-range spin-dependent nucleon–nucleon interaction between ^{3}He nuclei and nucleons of the walls of a cell containing polarized ^{3}He gas should affect its spin relaxation rate. The constraints have been obtained from the available experimental data on the longitudinal spin-relaxation of polarized ^{3}He [10].

In cooperation with the specialists from ILL and Joseph Fourier University (Grenoble, France) a project of a new high-intensity UCN source with a production rate of $10^7{-}10^8$ UCN/s and in which the volume density of UCN can be as high as 10^5 n/cm^3 has been suggested. These parameters are three orders of magnitude greater than those of the currently existing sources. The source is a spherical vessel filled with liquid helium at a temperature of 0.6 K and surrounded by a solid methane moderator. Such scheme of the source allows one to use it on extracted thermal neutron beams, thus many times reducing the thermal load on the source and consequently its cost. This makes it possible to greatly widen the range of application of UCN not only for scientific purposes, but also for applied and educational uses [11].

The results of the investigation of properties of prompt fission neutrons (PFN) emitted in spontaneous fission of ^{252}Cf and the research of properties of nuclear fission by fast neutrons in the energy range of 0.4–3.0 MeV using digital signal processing techniques, have been presented in a series of works devoted to the study of the prompt neutron emission in the low-energy neutron-induced nuclear fission. The aim of the works was to study the nature of the experimentally observed anomalous (from the viewpoint of modern theoretical concepts of the PFN emission process) dependence of the average number of PFN on the total kinetic energy of fission fragments. It has been demonstrated that the influence of energy losses of fission fragments in a target substrate is one of the main sources of errors and the factor that restricts the application of twin ionization chambers in the experiments on the study of properties of PFN emitted in the fission of ^{235}U, ^{239}Pu, etc. Some modifications of the traditionally used experimental techniques have been proposed in order to eliminate typical systematic inaccuracies [12].

A new version of the system for measuring small ($< 10^{-7}$) effects of spatial parity violation in nuclear reactions with polarized cold neutrons has been developed, constructed and tested. The system is based on the use of a digital signal processor. The developed version of the integrated method makes it possible to operate in a wide range (0.1–50 Hz) of neutron polarization switching frequencies, and at the same time the procedure of compensation of synchronous fluctuations of signals can still be employed. The tests were carried out at the PF1B cold polarized neutron beam facility (ILL, Grenoble). It has been experimentally shown that if the signal being measured is characterized by the spectral power that decreases with increasing frequency, the measurement at a higher switching frequency allows one to reduce the error of measurements in a single channel down to the value determined only by the statistics of the reaction in question and makes it possible to work with a single detector. This permits one to fairly easily analyze P-odd effects in total and radiation cross-sections, in which it is difficult and sometimes even impossible to single out two channels with opposite signs of the effects for compensating synchronous noises [13].

The time dependence of the delayed neutron yield from a massive (315 kg) deeply subcritical uranium target irradiated by relativistic deuterons has been measured. The treatment of the results has shown that nuclear fission of ^{238}U in the target occurs at secondary neutron energies of 15–25 MeV and that the number of fissions in the volume of the target increases approximately by a factor of eight (with an accuracy of 20%) with increasing incident deuteron energy from 1

to 4 GeV. Thus, despite the limited size of the target, which causes a considerable neutron leakage, some evidence on the possible growth of the power amplification coefficient of the incident beam in a multiplying medium has been obtained for the first time [14].

In cooperation with the Andronikashvili Institute of Physics (Tbilisi, Georgia) and Delft University of Technology (Delft, the Netherlands), neutron activation analysis (NAA) of samples of *Arthrobacter globiformis* 151B bacteria has been performed to study their ability to detoxify chromium and mercury. In 2010, challenging studies were started on biotechnology of silver and gold nanoparticles using bacteria *Streptomyces glaucus* 71 MD and blue-green algae *Spirulina platensis* [15].

In cooperation with the Low Background Laboratory of the Comenius University in Bratislava, Slovakia, and NECSA (Pretoria, South Africa), the measurements of the content of Cs^{137} and Pb^{210}in the moss samples collected in the territory of Belarus 20 years after the Chernobyl accident have been completed. The comparison of the obtained results with the data of analysis of aerosol filters of Slovakia has shown the efficiency of using the method of moss-biomonitors for radiological monitoring of the environment in Belarus [16].

THE IBR-2 PULSED REACTOR

1. In January-February 2010, after completion of the adjustment work on the sodium cooling system of the reactor, the heating of circuits and filling cooling loops with sodium were performed successfully and the circulation of sodium was started in a standby mode. The purification of the coolant, calibration tests of the level gauges of the expansion tanks and vessel of the reactor, calibration of the flowmeters were carried out.

2. After installation of actuating mechanisms (AM) of the Safety Control System (SCS) at regular places, the adjustment of the system controlling the movements of the actuating devices was performed. The emergency protection system of the reactor was tested. The obtained results are positive and meet the design requirements. No faults in the operation of AM were revealed. The SCS AM were tested for electromagnetic compatibility and the results of these tests are positive.

3. The equipment for Automatic Safety Control System (ASCS-12R) was installed, adjusted and tested. In November, the ASCS-12R complex was presented to the Working Commission for carrying out the physical start-up of the reactor.

4. The spent IBR-2 fuel assemblies were removed from the main storage facility to an additional one, which was assembled at the end of 2009. The main fuel assembly storage is ready for the physical start-up.

5. All technological systems of the reactor passed complex tests before the physical start-up.

6. The reactor successfully passed the inspection by the Working Commission for readiness for physical start-up.

7. **The modernized IBR-2 reactor physical start-up was commenced according to the plan.**

NOVEL DEVELOPMENT AND CONSTRUCTION OF EQUIPMENT FOR IBR-2M SPECTROMETERS COMPLEX

A full-scale test stand of a **cryogenic moderator** has been developed and assembled in the IBR-2M experimental hall. It includes a system for delivering aromatic hydrocarbon beads to the moderator chamber, a technological system to control the stand as well as a simulation chamber for the moderator prototype. At present, the test stand and the control system undergo trial operations. In October 2010, an encouraging result concerning the delivery of beads to CM was obtained: the chamber was filled to 30% of its volume (Fig. 3).

At the IBR-2M reactor the work has started to construct **a new high-resolution Fourier diffractometer** intended to be used for studying internal stresses in constructional materials and industrial products as well as for testing new equipment for further development of the Fourier correlation method and for testing detectors and other spectrometer elements developed in FLNP, i.e., it will serve as a **test beam**.

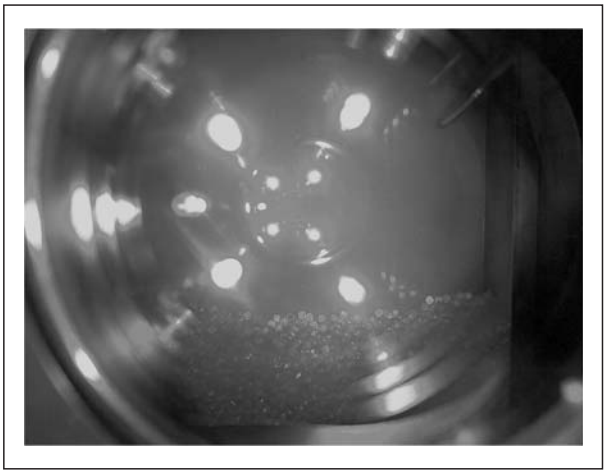

Fig. 3. A photo of mesitylene beads in the simulation chamber taken by a Web-camera

Neutron Beam-Forming Systems. In cooperation with the German Institutes and PNPI (Gatchina) the reconstruction of neutron guides for beam 7 of IBR-2M and the modernization of the EPSILON and SKAT diffractometers (in accordance with the plan-schedule of the BMBF–JINR project) continued (Fig. 4). Work on the reconstruction of the neutron guide for the NERA-PR spectrometer has started.

Fig. 4. First sections of curved neutron guides for EPSILON (left) and SKAT (right) (Cooperation with Germany)

Calculations of Spectrometers. The calculations of neutron spectra, simulation and optimization of beam geometry from the moderator to the sample position for the spectrometers located on beams 4 (YuMO) and 10 (GRAINS) of the IBR-2M reactor have been completed. The simulation of all elements of the prototype of the new instrument with polarized neutrons GRAINS has been performed. The results of the simulation have practically coincided with the analytical results. Several new modules for the VITESS software package have been developed.

The design of a **helium-3 purification system** has been done. The drawings have been forwarded to the Scientific Production Association «Atom» for production.

Choppers and Actuating Mechanisms. The choppers of beams 4, 7 and 8 with new variable-frequency drives have been tested in the phase stabilization mode. Tests of the drum-type DC-motor-based choppers have been carried out in the ring corridor on beams 6a and 6b. The phase stabilization accuracy was 25–50 μs.

The modernization of the sample-changing system on beam 4 (YuMO) at IBR-2 has been carried out. The modernization project for the control system of a goniometer and a platform with a detector on the REMUR spectrometer has been developed. Within the framework of the project, a structural scheme of the unified control system of stepper motors and systems of data acquisition from sensors has been proposed, which can be used for modernization of control systems of actuating mechanisms (AM) on other IBR-2M spectrometers as well.

Detectors. For the PSD of the GRAINS spectrometer work on the optimization of the firmware for a new electronic block of acquisition and accumulation of data from the detector has been completed and the development of PC software has started. This detector has also been tested with De-Li-DAQ1 electronics on beam 4 of the LVR-15 reactor at the Nuclear Research Institute (NRI) in Řež (Czech Republic). The results of the measurement of basic characteristics of the detector coincide with the results obtained last year at the IR-8 reactor in the RRC «Kurchatov Institute» and correspond to the design values. Thus, the PSD has passed through testing in various operation conditions. Since 2010, the specialists from NRI (Řež) have been participating in the development and construction of a **ring-shaped multisection detector (RSD)** of thermal neutrons for the DN-6 diffractometer.

Electronics. The architecture and electrical circuits of a unified block for data acquisition and accumulation (DAA) from multicounter detector systems of the EPSILON, DN-6, HRFD diffractometers and others, have been developed. At present, the prototype of the DAA system for 16 detector elements (DAA-16) is being tested. It is intended for use at the REFLEX spectrometer and can be employed at other instruments, where the number of detector elements does not exceed 16.

FLNP Local Area Network. A new Switch Catalyst 3560E-24TD-E router has been installed in the IBR-2M experimental hall. It should provide switching and transferring data at a rate ranging from 10 Mbit/s to 10 Gbit/s; intrasegment data transfer via twisted pair and fiber-optic cables; connection with the central network segment via a fiber-optic line. At present, in cooperation with the specialists from the Laboratory of Information Technologies the adaptation of the router to the existing FLNP network and the JINR network is carried out.

Software. In 2010, work to develop and improve the software package Sonix+ proceeded (adaptation of Sonix+ for the FSD diffractometer, preparation of a version of Sonix+ for the REFLEX spectrometer, changeover of Sonix+ to Visual Studio 2008, increase in the number of drivers, etc.) The development of an adjustment programme common to the REFLEX, REMUR, and GRAINS reflectometers has started. A new version of the WebSonix site has been prepared and put into service http://sonix.jinr.ru.

CONFERENCES

The anniversary workshop «50 years since the start-up of the IBR reactor» was organized on June 23. More than 40 physicists and technicians, participating in the IBR reactor start-up in 1960, were invited to share their memories of how the first world's pulsed reactor was created with their younger colleagues from FLNP JINR.

Three scientific schools for advanced training of young scientists were organized by or in collaboration with the Frank Laboratory of Neutron Physics in 2010: the III Advanced Courses of CIS Countries for young researchers, Ph.D. students and graduate students on modern methods in investigations of nanosystems and materials «Synchrotron and Neutron Investigation of Nanosystems» (SYN-NANO-2010) (July 4–17, Moscow–Dubna), the II All-Russian Neutron School for Young Scientists and Students «Modern Neutron Diffraction Studies: Interdisciplinary Research of Nanosystems and Materials» (October 25 – November 2, Dubna) and the All-Russian Scientific School for Young Scientists and Students «Instruments and Methods of Experimental Nuclear Physics. Electronics and Automatics of Experimental Facilities» (November 11–13, Dubna). These Schools continued the tradition of the FLNP Schools for young scientists devoted to the fundamental and applied aspects of neutron research in the fields of condensed-matter physics, materials science and related topics.

The 18th edition of the traditional International Seminar on Interaction of Neutrons with Nuclei: «Fundamental Interactions & Neutrons, Nuclear Structure, Ultracold Neutrons, Related Topics» took place in May 26–29.

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