# FRANK LABORATORY OF NEUTRON PHYSICS

In 2005, the FLNP scientific programme was realized under five research themes of the Topical Plan for JINR Research and International Cooperation and was aimed at obtaining new results in condensed matter physics (theme 07-4-1031-99/2008 «Neutron Investigations of Structure and Dynamics of Condensed Matter», headed by V. Aksenov and A. Balagurov) and neutron nuclear physics (theme 06-4-1036-2001/2007 «Nuclear Physics with Neutrons — Fundamental and Applied Investigations», headed by V. Shvetsov and Yu. Kopatch). To effect scientific research, work was continued to develop, modernize, and construct the FLNP basic facilities, IBR-2 (theme 07-4-0851-87/2007 «Upgrade of the IBR-2 Complex», headed by V. Ananiev and E. Shabalin) and IREN (theme 06-4-0993-94/2005 «IREN Project», headed by W. Furman and I. Meshkov), as well as the IBR-2 spectrometry and computing complex (theme 07-4-1052-2004/2008 «Development and Creation of Elements of Neutron Spectrometers for Condensed Matter Investigations», headed by A. Belushkin and V. Prikhodko). Also, FLNP took part in the JINR themes: «ATLAS. General-Purpose *pp* Experiment at CERN's Large Hadron Collider» (theme 02-0-1007-94/2005, headed by N. Russakovich), «Theoretical and Experimental Investigations of the Electronuclear Method of Energy Production and Radioactive Waste Transmutation» (theme 03-0-1008-95/2005, headed by A. Sissakian, I. Puzynin, S. Taczanowsky, and I. Shelaev).

This report contains a brief account of 2005 scientific results. The FLNP annual report for 2005 will give a more comprehensive account of 2005 results.

## CONDENSED MATTER PHYSICS

The problem under study and the main objective of investigations within the theme was the application of neutron physics methods to study the structure and dynamics of condensed matter, the obtaining of new data on microscopic properties of systems under study, experimental verification of theoretical predictions and models and the revealing of new laws. Correspondingly, work in the framework of the theme was carried out in two main directions: conducting of experimental investigations at the IBR-2 spectrometers and of routine technical work aimed at modernizing the available spectrometers and creating new instruments at IBR-2. This work was performed by the specialists of the FLNP Department of Neutron Investigations of Condensed Matter (NICM), structurally organized in the form of sectors (including the teams responsible for the spectrometers) in basic research directions.

**Experimental Equipment.** For the most part, the experiments were carried out at the IBR-2 reactor, the FLNP basic facility. In addition, the physicists of the NICM Department participated in a number of experiments in neutron centres of Europe. At the IBR-2 reactor the Department employees were in charge of operation and development of instruments and performance of physics experiments at 13 spectrometers: HRFD — High-Resolution Fourier Diffractometer, DN-2 — multipurpose diffractometer for experiments on poly- and single crystals, SKAT — diffractometer for texture investigations, EPSILON — diffractometer for internal stress investigations, FSD — Fourier diffractometer for internal stress studies, DN-12 — diffractometer for experiments at high external pressures, YuMO — small-angle scattering spectrometer, REMUR — polarized neutron spectrometer, REFLEX-P — polarized neutron reflectometer, DIN-2PI — direct-geometry inelastic scattering spectrometer, NERA-PR — multicrystal inelastic scattering spectrometer, KDSOG-M — inverted-geometry inelastic scattering spectrometer. At all the spectrometers, except for KDSOG-M, experiments are carried out in accordance with the user policy programme. Below are the main scientific results obtained during the reported year.

**Main Scientific Results.** Neutron diffraction studies of manganites $R_{0.5}Sr_{0.5}MnO_3$ (R = Sm, $Nd_{0.772}Tb_{0.228}$ and $Nd_{0.544}Tb_{0.456}$) aimed at establishing microscopic reasons for a giant oxygen isotope effect discovered recently in $Sm_{0.5}Sr_{0.5}MnO_3$ have been conducted. It has been demonstrated that in all the studied compositions at low temperatures there coexist two crystal phases with different types of Jahn–Teller distortions of oxygen octahedrons and different types of magnetic ordering. The diffraction data have made it possible to suggest the scenario of the observed phase transitions and to establish that the metal-insulator transition in the compositions with Sm upon $^{18}O$ for $^{16}O$ substitution has a percolation nature; i.e., the substitution of oxygen isotope results in a sharp decrease (from 65 down to 13%) in a ferromagnetic metal phase volume. This work can be considered to be final in a series of studies concerned with the reasons for a giant isotope effect in manganites — a change from low-temperature metal state to insulator state upon $^{18}O$ for $^{16}O$ substitution. It has been found that in compositions with a doping level of $x = 0.5$, as well as in manganese oxides with $x = 0.3$, the effect exists only if there is a phase-separated state on a mesoscopic scale. The main reason for equilibrium phase separation is the occurrence of a random stress field on incoherent boundaries of the coexisting phases [1].

At the DN-12 diffractometer the effect of high pressures of up to 5 GPa on the crystal and magnetic structure of hexagonal manganite $YMnO_3$ in a temperature range of 10–295 K has been studied. At normal pressures in this compound at $T \sim T_N = 70$ K, a spin liquid state is observed caused by magnetic frustration effects on a triangular lattice formed by Mn ions, whereas at $T < T_N$ an ordered triangular antiferromagnetic (AFM) state arises with a symmetry of irreducible representation $\Gamma_1$. As the pressure increases up to 5 GPa, a decrease in the value of the ordered magnetic moment of Mn ions from 3.27 down to 1.52 $\mu_B$ is observed at $T = 10$ K and the amplification of diffuse scattering at temperatures near $T_N$ is also noted. The observed effects can be explained in the framework of the model of coexistence of an ordered antiferromagnetic phase and a spin liquid state without a long-range magnetic order, whose volume fraction rises with increasing pressure due to the enhancement of frustration effects. In addition, the exposure to high pressures results in spin reorientation of Mn magnetic moments and in a change in symmetry of AFM structure, which may be described by a combination of irreducible representations $\Gamma_1 + \Gamma_2$ [2].

At the YuMO spectrometer, liquid dispersions of detonation nanodiamonds have been studied by small-angle neutron scattering. Detonation nanodiamonds are formed by explosion of oxygen-unbalanced explosives in the absence of any additional sources of carbon. The resulting nanodiamond crystals are extremely interesting and promising material for nanotechnologies. However, they are hard to free from explosion by-products. This is due to the formation of complex multilevel aggregation of nanodiamonds in the process of synthesis, which involves elements different from carbon. Disperse nanodiamond powders (prepared in zirconium mills) placed in various liquids form unusually stable colloidal solutions without addition of any surfactants. This phenomenon may be effectively used to study the internal structure of nanodiamond aggregates by small-angle neutron scattering. The obtained curves of scattering by nanodiamonds in various solvents show similar behavior. Nanodiamond particles (characteristic size of 5–6 nm) are organized in clusters structurally close to Gaussian polymers, with a size of more than 120 nm. The internal structure of clusters does not depend on their concentration in solution. The estimate of mean scattering density of clusters using contrast variation in aqueous dispersions (light/heavy water) gives smaller value than the scattering density of a pure diamond. This points to the existence of a component different from diamonds in an elementary unit of aggregates. In particular, it can be a nondiamond shell which, on the one hand, is responsible for aggregation of particles during explosion and, on the other hand, provides stability of disperse particles due to interaction with a solvent.

At the REMUR spectrometer the phenomenon of coexistence of ferromagnetism and superconductivity in layered structures, which is of importance from both fundamental and practical points of view, has been investigated. It is well known that ferromagnetic and superconducting states cannot simultaneously coexist in homogeneous systems. But in inhomogeneous systems, which is the case for layered nanosystems, this coexistence is possible. These studies are of much practical importance, since they make it possible to develop essentially new nanodevices whose operation logic is determined simultaneously by changes in magnetic state and temperature within a small range. The experimental technique for studying this phenomenon is based on the generation of a neutron field of standing waves by reflecting a neutron wave from a periodic structure, and on a neutron polarization analysis and detection of specularly and diffusely reflected neutrons. Neutron investigations have been carried out on the structure Pd(2 nm)/V(33 nm)/Fe(3 nm)/ 20× [V(3 nm)/Fe(3 nm)]/MgO over a magnetic field intensity interval of $0.2-4$ k$\Omega$ in a wide temperature range. It has been found that in the range $1.6-3.5$ K the superconducting state of the V(33 nm) layer changes the magnetic ordering in the periodic structure and the magnetization profile at the boundary between the Fe layer and the V(33 nm) layer. It has been also revealed that in the range $7-30$ K the magnetic state of periodic structures varies with temperature. The latter is associated with the ferromagnetism of interfaces. In a model diagram of magnetization distribution in nanostructures, the number of bilayers with antiferromagnetic ordering is $N_1$; without it, $N_2$. The $N_1$ bilayers are immediately adjacent to a thick vanadium layer and are followed by the $N_2$ bilayers. The calculations show that $N_1$ is in the range $2-8$ and $N_2$ is in the range $18-12$. Thus, a thick vanadium layer changes the type of ordering in the nearest adjacent bilayers of the periodic structure.

At the NERA inverted-geometry spectrometer the comparison characteristics of substances-candidates for neutron cold moderators at IBR-2: methane, methanol, mesitylene and water, have been studied. The criteria were the amount of hydrogen in a substance, the appropriate density of phonon states and radiation resistance. Solid methane at $T < 20$ K is in crystal phase II in a partially ($\sim 25\%$) disordered state. At low temperatures methanol can be either in crystal or amorphous phases with either translational or orientational disorder. Mesitylene is a rather promising substance for use in cold moderators due to a high content of hydrogen, good moderating properties and radiation resistance. Figure 1 illustrates the comparison of densities of phonon states obtained on the basis of single-phonon approximation from the incoherent inelastic scattering spectra for the specified substances. On the basis of these data, as well as the results obtained in the course of the URAM-2 programme, it may be concluded that mesitylene in glass-like state exhibits the best characteristics for moderating neutrons at helium temperatures.

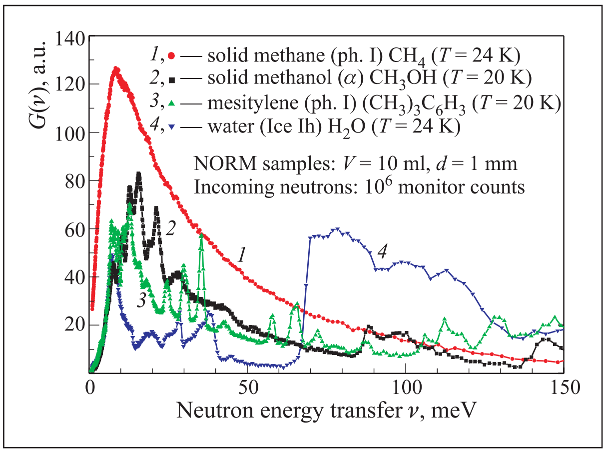


Fig. 1. Comparison of densities of phonon states obtained on the basis of single-phonon approximation from the incoherent inelastic scattering spectra for methane, methanol, mesitylene and water

At the DIN-2PI spectrometer the neutron diffraction experiment to study the microstructure of Li–N melts with a concentration of nitrogen impurity of 1.3 and 3.5 at.% and at a temperature of 823 K has been performed. The basic microstructural characteristic of the substance — the total structural factor $S(Q)$, as well as the partial structural factors $S_{\alpha\beta}(Q)$ of melt components and corresponding radial distribution functions $g_{\alpha\beta}(r)$ and $g_{CC}(r)$ (Fig. 2), has been obtained. It has been determined that at a concentration of impurity component less than 4 at.% the so-called «prepeak», which is an indicator of existence of clusters of particular size in melts, is missing from the structural factor of Li–N melts. The analysis of the partial structural characteristics of the melt suggests that nitrogen impurity is present in $Li_{0.987}N_{0.013}$ and $Li_{0.965}N_{0.035}$ melts as lithium nitride $Li_3N$.

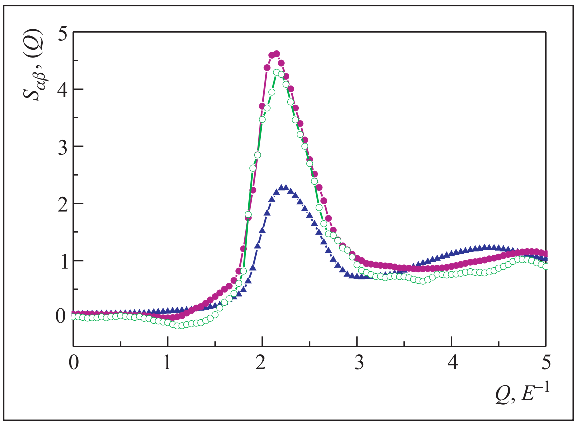


Fig. 2. Partial structural factors of liquid lithium and nitrogen for $Li_{0.987}N_{0.013}$ and $Li_{0.965}N_{0.035}$ melts. Triangles — structural factor of lithium $S_{\rm LiLi}(Q)$, solid and open circles — $S_{\rm NN}(Q)$ for concentrations of 1.3 and 3.5 at.%, respectively

A series of investigations, which sums up almost a 20-year debate on one of the key problems of statistical physics — interaction of fluctuating random surfaces, has been completed by the physicists of the small-angle neutron scattering group. A wide class of objects, from biological membranes to strings in the contemporary field theory, belongs to random fluctuating surfaces. This is one of the reasons why the attention of contemporary theoretical physics is drawn to biological membranes, in particular, to lipid membranes. As a result, new approaches have been developed to study intermembrane interactions and to detect a universal constant on the basis of investigation of temperature dependence of intermembrane interactions with the help of complementary use of small-angle neutron scattering and high-resolution diffraction on a synchrotron source. The value of the interaction constant has been obtained, which is $3\pi^2/256$ and agrees with the theoretically predicted one. It has also been shown that the transition from multilayer membranes to single ones proceeds in accordance with the theoretically predicted model of two states. In addition, it has been shown for the first time that the undulation forces make a significant contribution to the balance of intermembrane interactions and what is more, these forces become dominant at distances of more than 20 Å [3].

For the first time the dynamics of crystal lattice of the superionic conductor AgCuSe has been studied by inelastic neutron scattering. In a low-temperature phase the low-energy modes have been detected, which are most likely of acoustic phonon nature. The density of phonon states $G(\varepsilon)$ in $\alpha$- and $\beta$-AgCuSe is characterized by a non-Debye behavior. At the transition from $\beta$ to $\alpha$ phase the spreading of phonon state density spectrum and hardening of the spectrum as a whole are observed [4].

**Development Activity.** In 2005 the technical works to modernize the IBR-2 spectrometers complex continued. For the most part, they concerned the detector systems of the spectrometers. In particular, at the Fourier specialized diffractometer FSD, work to construct the detector system continued (six out of 14 detector modules are ready), test filling of two-dimensional detector for YuMO was carried out and one-dimensional PSD with a resolution of 1.8 mm was tested in actual operating conditions.

## NEUTRON NUCLEAR PHYSICS

**Experimental Investigations.** In 2005 the FLNP experimental investigation programme in neutron nuclear physics included traditional directions of fundamental and applied research carried out on the IBR-2 and EG-5 beams and in collaboration with nuclear centres in Russia, Bulgaria, Poland, Czechia, Germany, Republic of Korea, France, USA, and Japan.

With the purpose of verifying the earlier experimental results to search for the negative neutron $p$-resonance in lead isotopes, the modernization of the COCOS gamma spectrometer on channel No. 1 of the IBR-2 reactor was carried out. As a result of installation of a new semiconductor gamma-quantum detector GMX30-PLUS and specialized electronic modules, the spectrometer efficiency increased more than twice and its processing speed enhanced as well. The experiments to search for the negative neutron $p$-resonance in lead isotopes are under way: a series of measurements with a natural Pb sample was carried out.

On channel No. 11 of the IBR-2 reactor the modernization of the IZOMER setup with the aim of obtaining data on yields and decay constants of delayed neutron groups in minor actinide fission was completed. As a result of the modernization, the parameters of the setup were improved and its possibilities were enlarged. At the modernized setup the measurements were performed and the data on the delayed neutron yield in thermal neutron fission of $^{237}$Np isotopes were obtained.

The construction of the KOLKHIDA setup intended to study the interaction of polarized neutrons with polarized nuclei was completed. To polarize nuclei of the target by the «brute force» method, a $^3$He in $^4$He dilution cryostat with a superconducting magnet was constructed. A bench test of the cryostat with a magnet was performed. The following parameters were obtained: minimal temperature on the sample $T = 23$ mK, magnetic field intensity $H = 5.8$ T at field homogeneity in the centre of the magnet $\Delta H/H = 10^{-4}$.

Work to investigate samples to verify $T$-noninvariance in nuclear interactions continued. Two single crystals of lanthanum aluminate $LaAlO_3$ with a paramagnetic impurity $Nd^{3+}$: 0.3 and 0.08%, received from Japan, were studied. The amplified NMR signals were detected confidently on both crystals. A shift of the NMR lines of La and Al at rotation of crystals in a magnetic field was also observed.

In the framework of the experiments to search for neutral currents in nucleon–nucleon interactions and to determine a weak $\pi$-meson coupling constant at the PF1B cold polarized neutron beam (ILL, Grenoble), a regular 48-day run of measurements of $P$-odd asymmetry $(\boldsymbol{\sigma}_n \mathbf{p}_t)$ of triton escape in the reaction $^6\mathrm{Li}(n,\alpha)^3\mathrm{H}$ ($\boldsymbol{\sigma}_n$ is neutron spin, $\mathbf{p}_t$ is triton pulse) was conducted. Judging from the sum of the results of three cycles, an obvious effect is observed in the main measurements $\alpha_t = -(8.6 \pm 2.0) \cdot 10^{-8}$ with allowance made for corrections for neutron polarization and triton escape angle. A number of check experiments were also carried out [5].

Work to test the equipment of the PF12 channel of the LANSCE neutron source (Los Alamos) and the equipment for the experiment to measure $P$-odd asymmetry of $\gamma$ quanta in the reaction $np \to d\gamma$ aimed at determining a weak $\pi$-meson coupling constant was performed by the NPDG collaboration together with the FLNP specialists [6].

In the framework of the preparation of the experiment of direct measurement of neutron–neutron scattering cross section, works to calibrate the neutron detectors used in the test experiments at the YAGUAR reactor (VNIITF, Snezhinsk) in 2005 were carried out at the neutron setup of the Institute for Physics and Power Engineering (Obninsk). The analysis showed that the results of the calculations of expected neutron backgrounds made by the group from Snezhinsk for a depth of more than 2 m (depth of the shaft is 12 m) are in complete agreement with the results of the measurements [7]. On the building of the YAGUAR reactor the back flight base of the experimental setup was installed. The working draft of the whole experimental setup was completed.

Joint experiments to investigate the fission of $^{239}$Pu nuclei induced by resonance neutrons are carried out on the GELINA setup (IRMM, Belgium). In the framework of the development of the method for investigating fluctuations of prompt neutron multiplicity and the total kinetic energy of fission fragments, the measurements of fission prompt neutron multiplicity in correlation with fragments are performed.

At the K-130 accelerator in Finland, in cooperation with the FLNP specialists, a multiparameter experiment to measure mass energy distributions of $^{238}$U fission fragments induced by $\alpha$ particles was carried out. The data processing aimed at searching for the true ternary collinear decay in the fission is under way. The preparation to carry out a similar experiment to measure neutron-induced fission on beam 6b of the IBR-2 reactor started.

At FLNP's EG-5 facility the investigation of the $^{20}$Ne$(n,\alpha)^{17}$O reaction was carried out. Neutrons were produced in the D$(d,n)^3$He reaction using a gas deuterium target at a deuteron energy $E_d \approx 2$ MeV. The obtained neutron energy range $E_n = 3.7{-}4.1$ MeV covered a group of neutron resonances of $^{20}$Ne. Some discrepancies between the obtained data and the resonance positions recommended for this reaction in neutron atlases were revealed. A number of works to reequip the EG-5 beam to measure angular correlations in the $(n,p)$, $(n,\alpha)$ reactions were conducted.

At the EG-4.5 at the Institute of Heavy Ion Physics (Peking University, China), measurements of cross sections and angular distributions of the $^{64}$Zn$(n,\alpha)^{61}$Ni and $^{10}$B$(n,\alpha)^7$Li reactions at neutron energies of 4, 5, 6 MeV were carried out. The neutron source was the D$(d,n)^3$He reaction on a gas deuterium target. A two-section grid ionization chamber was used as an $\alpha$-particle detector. The obtained multidimensional data are being processed.

In the framework of a new method of extracting the $n,e$-scattering length $b_{ne}$ from data of neutron diffraction by noble gases, the data obtained in Grenoble on the diffraction of neutrons with a wavelength of $\sim 0.7$ Å by gaseous $^{36}$Ar were processed at four different densities and for seven different states of liquefied Kr. Two mathematically different approaches to the solution of the multiparameter task gave the results for $^{36}$Ar: $b_{ne} = -(1.33 \pm 0.28 \pm 0.57) \cdot 10^{-3}$ fm and $b_{ne} = -(2.15 \pm 0.49) \cdot 10^{-3}$ fm. The preliminary result of the data analysis for Kr, which is not completed yet, is $b_{ne} = -(1.36 \pm 0.14) \cdot 10^{-3}$ fm [8], which is so far 3–4 times worse in accuracy than the best results. In order to considerably improve the accuracy of the derived value of $b_{ne}$, a new experiment is being developed for the same setup in Grenoble. The construction of the setup to measure $b_{ne}$ by scattering slow neutrons by gases Ar, Kr and Xe of low pressures ($\sim 1$ atm) using the time-of-flight method on neutron sources in Troitsk and at IREN-1 is in completion stage.

In the framework of studies of the interaction of neutrons with nanostructures and investigations of a possibility of effective cooling of very cold and cold neutrons into the region of ultracold neutrons, the measurements on beams PF1b and PF2 of the high-flux ILL reactor (Grenoble) have been carried out. The probability of scattering neutrons with the velocities from 30 to 1000 m/s depending on the scattering angle from the samples of nanodiamond powders and on the structure of weakly bound nanoparticles $D_2O$ and $D_2$, which were in superfluid helium (gel), has been measured. The obtained experimental data will suffice to test the validity of the theory of neutron diffusion in finely dispersed and nanodispersed media. The results show that the probability of neutron scattering from samples is rather high and if the processes of energy transfer from a neutron to a sample proceed rather intensively, then the gel may be used for cooling of very cold and cold neutrons into the ultracold neutron region.

At the PF2 beam of the ILL reactor, total and differential cross sections of very slow neutrons for liquid fluoropolymers at 80–300 K were measured to study the limiting UCN storage period and an experiment to investigate the UCN «small heating» at UCN reflection from solid surface [9]. A considerable heating effect into the $\mu$eV energy region was revealed for the first time.

A new experiment to observe the neutron energy change in passing through the accelerated substance was carried out. The existence of the effect follows from the validity of the equivalence principle and detailed neutron-optical calculations, which was experimentally confirmed for the first time. The neutron energy change detected in the experiment was of the order of $2 \cdot 10^{-10}$ eV. The neutron energy change was detected by the UCN gravitational spectrometer (ILL, Grenoble) with interference filters in phase with the sample motion [10].

A new experiment to test the validity of the $1/v$ law in the interaction of UCN with a sample of natural gadolinium (radiative capture cross section is of the order of 25 Mb) has been conducted. It has been found that the $1/v$ law is accurate to the order of $0.1\%$ for the interval of velocity change from 4 to 35 m/s.

The data on level densities and force functions of primary gamma transitions have been derived from the intensities of two-step quantum cascades measured by now in 51 nuclei ($27 < A < 201$) between the neutron resonance and the low-lying levels of the compound nucleus. This has been done for the nucleus excitation energy interval from $\sim 5$ to $\sim 9$ MeV. These data have been obtained for the first time without resorting to any nuclear models or unverified hypotheses. The level densities and radiative force functions obtained in this way have considerably fewer (practically by an order of magnitude) systematic errors than any available analogous data. The improved accuracy has made it possible to observe strong effect of the structure of the nucleus on these main parameters of its cascade gamma decay [11].

**Applied Research.** At FLNP's EG-5 the investigations of oxide layers of silicon implanted by germanium ions and of layered semiconductor structures $Si/HfO_2/Ru$ annealed at various temperatures were carried out using nuclear physical techniques PIXE and RBS. Depth profiles of elements for 34 samples were obtained. Also, at the EG-5 the investigations of elemental composition of teeth of people of various professions living in different conditions and the composition of aerosols in the air of Ulaanbaatar were conducted using the techniques PIXE and RBS. In the studied samples the following trace contaminants were detected: F, Na, Mg, Al, S, Cl, K, Ca, Ti, Mn, Fe, Cu, Zn, As, Sr, Zr, Ba.

In the framework of the international programme «Atmospheric Depositions of Heavy Metals in Europe — Estimates Based on the Analysis of Mosses-Biomonitors» involving simultaneous collection of biomonitors in 2005–2006, this year moss samples (passive biomonitoring) have been collected in a number of regions in Central Russia, Belarus, Bulgaria, Slovakia, Serbia and Montenegro, Macedonia, Romania, and Turkey for neutron activation analysis at the IBR-2 reactor [12]. The results of the analysis for 10 elements (As, Cd, Cr, Cu, Fe, Hg, Ni, Pb, V and Zn) will be handed over to the European Atlas of Atmospheric Depositions of Heavy Metals, which is published every five years under the aegis of the UNO. (Copper and lead are determined by the atomic absorption spectrometry.) The analysis of moss samples collected in Mongolia and in South Vietnam has been carried out. Work to study atmospheric depositions of heavy metals, rare-earth and other elements by the active biomonitoring method in industrial areas of Baia Mare (Romania), Poznan (Poland) and Athens (Greece) was continued.

The analysis of the samples of plant and animal origin in the framework of the project of technical cooperation with IAEA (2003–2005) to control the quality of food grown in industrially contaminated areas was completed. The results were reported at the IAEA Workshop (14–16 November 2005, Dubna).

New results of NAA to determine chrome in bacterial samples of *Arthrobacter oxidans* granted by the biochemists of the Institute of Physics of the Georgian AS were obtained [13].

The analysis of 50 archeological samples of ceramics (early Neolithic age) from burial mounds of the Smolensk Region and from the Maikop burial mound in the Northern Caucasus was performed for the State Hermitage (St. Petersburg).

In 2005 work to study the effect of fission-spectrum neutrons on physical properties of fine-grained diamonds obtained at the Institute of Solid State and Semiconductor Physics of NAS of Belarus (Minsk) was continued [14].

## NEUTRON SOURCES

**The IBR-2 Pulsed Reactor.** In 2005 the IBR-2 reactor operated $\sim 1831$ h for physical experiments.

Main results of the IBR-2 modernization in 2005:

1. New fuel charge.

• Work to create a working site for assembling fuel elements into a fuel rod array was completed. The working site was approved to be put into service by a commission of representatives of JINR, GSPI, VNIINM, NIKIET.

• At present, the procedure of obtaining license for assembling fuel elements is under way.

2. Main equipment of the IBR-2M reactor.

• At NIKIET the manufacturing of a new reactor jacket continued.

• The manufacturing of an intra-jacket fuel-handling machine was completed.

3. At JINR EW the haulage equipment to place moderators for the IBR-2M reactor was manufactured.

4. CSS of IBR-2M.

• At NIKIET the development of the design documentation of the AES actuating mechanism was completed.

• A prototype of an actuating mechanism for an automatic controller was manufactured at JINR EW.

• At SNIIP-SYSTEMATOM the development of ACSS was completed, the manufacturing of a prototype is under way.

• Work to create a system to control technological parameters was started (INEUM).

To provide the financing of work on the IBR-2 modernization in 2005, a sum of 890 k$ (including JINR — 490 k$, Rosatom — 400 k$) was expended as of 30 December 2005.

**Development of the complex of broad spectrum neutron moderators («combi-moderators») for the modernized research reactor IBR-2M.**

1. Calculations of spectral characteristics of neutron beams have been completed, the design procedure has been substantiated by way of comparison with known experimental data.

2. The design phylosophy of cold moderator has been worked out. It is based on usage of balls made of frozen mixture of mesitylene and $m$-xylene providing for the maximum possible flux of cold neutrons (at the level of the designed solid methane moderator

of the second target of the ISIS source) at continuous operation.

3. Experiments to evaluate the properties of solid mesitylene necessary for designing ball cold moderator have been carried out. In particular, the technique to obtain balls of mixture of mesitylene and $m$-xylene has been worked out, the shock strength of the balls has been estimated, preliminary tests to transport the balls in the gas flow in straight tube have been performed.

4. The theory has been elaborated and the programme to calculate the ball motion in a tube of arbitrary configuration has been worked out, the test-bench to carry out experiments of ball transportation in the tube, which is close in configuration to the real one, has been manufactured.

5. Conceptual design of the moderator cooling system, of the ball transportation into the moderator chamber and of the tracing of tubes of helium cooling has been worked out.

6. Requirements specifications to the design moderator complex and the system of their cooling have been worked out (together with NIKIET and GSPI).

7. The project has been carried out and the modernized variant of the irradiation installation URAM-2 (named URAM-3M) has been partially manufactured to conduct experiments in 2006 to confirm continuous efficiency of mesitylene cold moderator.

As a result of the research performed in 2005, the data have been obtained necessary to start designing of the moderator complex at the IBR-2M.

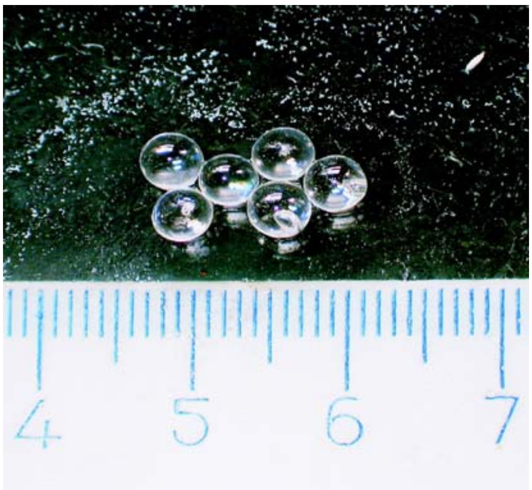


Fig. 3. Balls of frozen mixture of mesitylene and $m$-xylene at the temperature of liquid nitrogen

**The IREN Project.** The main efforts and funds have been focused on the completion of preparation and carrying out of work to dismantle the IBR-30 reactor.

In order to secure the positive ecological assessment of the IBR-30 decommissioning project, a system of key wells to control the condition of groundwater has been designed and created in the DLNP area. The final training of the staff to perform specific technological operations of dismantling the reactor equipment and defueling has been conducted. Due to the painstaking work of the FLNP administration and the laboratory technical subdivisions, in the middle of October it became possible to start the reactor decommissioning. A major part of the reactor activated equipment was disassembled and transported to bldg. 117/b for temporary storage. By the middle of November the drilling-out of uranium inserts from the moveable parts of the IBR-30 core was completed. The removed fuel was evacuated for storage to DRFM, JINR. By the end of 2005 it is planned to complete the defueling of the main reactor core and to transport the spent fuel for storage to DRFM, JINR. The completion of disassembling of the rest of the IBR-30 reactor equipment is scheduled for the first half of 2006.

Some progress has been made in the construction of the LUE-200 linac. After the purchase of a missing part of a special copper tube, work to wind the coils of a solenoid for a magnetic focusing system (suspended in September 2004) was resumed. By the beginning of the 4th quarter this work was completed. The conducted magnetic measurements have shown that the parameters of the manufactured coils conform to the design values. The assembling of the modulator M350 has been completed in the accelerating hall of bldg. 43. At present, the testing of the modulator systems and the preparation for its startup are in the completion stage. The vacuum tests of the magnetic spectrometer equipment have been successfully carried out. Work on its test assembling on a test bench is started.

Computational investigations to model the electron beam dynamics in the accelerating tract of the LUE-200 have been conducted with the purpose of optimization of the focusing system and minimization of particle losses, the criteria of allowing for errors of magnetic fields in the accelerator tract have been determined.

Detail designing of the water-cooling system of the LUE-200 linac has been performed by the specialists of JINR and GSPI. Its completion is scheduled for the end of 2005.

The work on a working draft of a power supply system for the accelerator has been started.

The development of the project of reconstruction of the LUE-200 control room and rooms in bldg. 43 intended to house the power-supply and water-cooling systems has been completed. Work to repair and reequip the above-mentioned rooms has been started.

The equipment necessary for the completion of the assembling and complex adjustment of the LUE-200 equipment will be delivered in 2006.

Unfortunately, activities on the LUE-200 linac planned for 2005 were not performed in full measure, because of delay or lack of planned financing. Nevertheless, the necessary reserve to carry out the tasks specified in the JINR Topical Plan for 2006 has been created with an ultimate aim to start up the first stage of the IREN facility with a nonmultiplying neutron-producing target and a test bench for applied investigations by the end of 2007.

## DEVELOPMENT AND CREATION OF ELEMENTS OF NEUTRON SPECTROMETERS FOR CONDENSED MATTER INVESTIGATIONS

In 2005 work in the framework of the theme was carried out in the following main directions:

— creation of neutron detectors;

— development of sample environment systems;

— development of data acquisition systems and computing infrastructure.

**Creation of Neutron Detectors.** In 2005 pilot models of 1D detector and 2D monitor were constructed and tested on a test bench with a source and at the IBR-2 beams [15, 16]. Both detectors are based on multiwire proportional chambers with delay line data readout. This allowed us to unify to a maximum extent the readout electronics (preamplifiers, discriminators, etc.) and data acquisition electronics (data conversion and filtering, histogramming, etc.), as well as basic program modules and interfaces. Data accumulation and visualization are carried out on personal computers [17].

The methodological studies conducted earlier and the prototyping of individual units made it possible to plan with a high degree of reliability the following characteristics of the 2D monitor and 1D detector (see the table).

The trials of the monitor and 1D detector performed during two spring and three autumn cycles at IBR-2 have lent support to the validity of the specified characteristics.

During the 6th cycle of the IBR-2 reactor (17–28 October 2005), test and routine measurements of diffraction spectra were carried out at the TEST spectrometer (beam 6b) and the HRFD diffractometer (beam 5). The coordinate resolution dependence on anode and drift voltages was studied as well. $+Hv = 4200$ V, $-Hv = -3000$ V were chosen as working values. The coordinate resolution at the centre of the detector was 1.6 mm, at edges 1.9 mm. At HRFD, using the 1D detector, the diffraction spectra of $(La_{0.1}Pr_{0.9})_{0.7}Ca_{0.3}MnO_3$ (manganite with CMR effect in which an AFM phase occurs at low temperatures) were obtained at $T = 10$ and 290 K. Spectrum accumulation time was about 2 h.

The total time of measurements with the 1D detector on beam 5 was about 180 h. During the experiments the electronics and software operated trouble free in all measuring modes.

**Development of Sample Environment Systems.** At the FSD diffractometer 16 additional modules of the ASTRA scintillation detector, along with the mechanical positioning system, control and data acquisition electronics, have been installed. The detectors have been tested and put into trial operation.

At the YuMO spectrometer a device for moving PSD along the neutron guide and a device for vertical and horizontal positioning of PSD have been put into service.

At the REMUR spectrometer a device for moving a diaphragm, a control device for two goniometer axes and for moving a pivoting platform on the basis of high-current motors DBM120 have been installed.

The first stage of work to replace the power drives EKT2 of neutron beam choppers that had exhausted their resource by new drives EKT4 has been completed. The new drive has been put into trial operation at beam 10 of IBR-2. It provides an accuracy of chopper phase stabilization of 185–200 $\mu$s.

For beams 6a and 6b, test-bench trials of drum choppers (manufactured by the JINR Experimental Workshop) to suppress background and of chopper control systems have been carried out. The accuracy of phase stabilization is 25–50 $\mu$s.

For the NERA-PR spectrometer a cryostat with a refrigerator on pulsed tubes PT405 (Cryomech, USA) with a working temperature range of $250-3$ K has been developed and tested. At present, a temperature of 2.8 K has been achieved.

| Gas mixture | 2D monitor<br>50 mbar $He^3$ + 950 mbar $CF_4$ | 1D detector<br>2000 mbar $He^3$ + 1000 mbar $CF_4$ |
|---|---|---|
| Efficiency, % | 0.1 | 40 |
| Sensitive area, mm | 100 × 100 | 200 × 80 |
| Coordinate resolution, mm | 4 × 4 | 2 |
| Count rate, events/s | up to $10^5$ | up to $10^5$ |
| Differential nonlinearity, % | $< 5$ | $< 5$ |
| Readout | Delay line | Delay line |

**Development of Data Acquisition Systems and Computing Infrastructure.** Among the most important results in the reported year are the purchase of a new central server *Sun Fire X4200*, bulk storage device *Storage Array* (6.4 Tbyte) and acquisition of two high-speed network switches *Cisco 3750* (1 Gbit).

As is known, at present the central file-server *Enterprise 3000* of the firm *SUN Microsystem* (two processors *ULTRA SPARC* 250 MHz, RAM — 250 Mbyte, HDD — 200 Gbyte) is the only powerful computer and provider of shared disk space in the FLNP LAN. The server has been in service for eight years, which is an impermissibly long service life period for computing devices. In addition, the cost of providing service and upgrading of the SUN equipment currently in use on the basis of *RISK* architecture (*Enterprise 3000*, *Sun Workstations*) is unacceptable for us. At the same time, a sharp increase in computing power of computer systems based on *X86* architecture and evolution of *AMD-64* platform are observed. These factors have predetermined the replacement of basic servers of the FLNP computing cluster by modern powerful systems on the basis of Intel Pentium IV Xeon and AMD Opteron 64. The available server *Enterprise 3000* will be used for work with applications written for the old operating system till it exhausts its resource completely.

Along with the installation of servers, it is planned to create a new architecture of FLNP LAN and to change over to *Gigabit Ethernet* for the main backbones. At present, the central switch of FLNP LAN *Cisco 8510CSR* is connected to the JINR network via two links with total throughput of 200 Mbit/s. Under conditions of ever increasing traffic and load on the routing equipment, this connection cannot provide stable service for users any more. Besides, *CSR8510* does not make it possible to effectively control data transfer at virus and DDOS attacks. A change-over of the available switches of the network core to routing switches Cisco 3750, the installation of interface with 1 Mbit/s to *CSR8510* and the application of high-speed communication in the main FLNP LAN links will make it possible to solve the specified problems, to enhance the reliability of network operation and to provide connection with the JINR network and other networks at Gigabit rates.

The program package *Sonix+* has been put into operation at the REMUR spectrometer. In the framework of Sonix+ complex:

• a new version of modules responsible for script interpretation was developed;

• a new spectrum visualization program *Spectra Viewer* for data from 1D and 2D detectors in Sonix+ format was designed;

• work to improve the package components, script libraries, etc. was carried out.

Along with the above-mentioned installation of DAQ and control electronics for scintillation detectors at the FSD spectrometer, work to develop and test the DAQ board software for MWPC detectors has been carried out. In particular, two versions of FPGA programs for operation of the board with one-dimensional detectors and with a built-in monitor counter have been designed and tested. The development of new DAQ electronics with USB interface for multicounter systems is in progress.

Electronic and software support was constantly provided during the IBR-2 reactor cycles.

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