PREFACE

We would like to offer the readers the scientific activity report of the Frank Laboratory of Neutron Physics for 2012. The first part of the report presents a brief review of the experimental and theoretical results achieved in the main scientific directions – condensed matter physics, neutron nuclear physics, applied research and development and creation of elements of neutron spectrometers for condensed matter investigations. The second part includes the reports on the modernization of the IBR-2 pulsed reactor and the development of the IREN neutron source. A list of publications for 2012, the information regarding the seminars and conferences organized in FLNP and a statistical view on the FLNP personnel structure are presented as well.

In 2012 the main achievements of the Laboratory were:

- obtaining of the license for regular operation of the IBR-2M reactor;
- resumption of the user program at the IBR-2M spectrometers;
- successful start-up of the cold neutron moderator at the IBR-2M reactor.

Both of the FLNP basic neutron sources, the IBR-2M reactor and the IREN facility, operated for about 1500 hours for physics experiments.

FLNP has cooperation agreements in the field of neutron investigations with almost 200 scientific institutes and universities from 39 countries from all over the world. A significant contribution to this cooperation is made by the JINR Member States.

The FLNP staff consists of more than 400 employees. The scientific staff includes 71 Ph.D. and 19 D.Sci. researchers and 70 researchers and specialists from the JINR Member States (besides the Russian Federation) with more than two thirds of them under 35 years of age.

The organization of annual conferences and schools covering all FLNP research fields helps to recruit young specialists — one of the top priority tasks of the FLNP Directorate.

All these facts confirm that the Laboratory continues to develop successfully and dynamically, carrying out investigations in the interests of the JINR Member States.

In 2012 the world scientific community celebrated 80 years since the discovery of the neutron by James Chadwick. The cover of the FLNP Annual Report is devoted to this significant event featuring J.Chadwick's portrait and fragments of his paper that brought him the Nobel Prize in Physics.

A.V. Belushkin

Director

At the end of 2012 the Directorate of the Laboratory completed its term of office. Among its members were:

BELUSHKIN
Alexander
Vladislavovich
Director
since 2001

Deputy Directors for Science

SHVETSOV
Valeryi
Nikolaevich

since 2001

SANGAA
Deleg

since 2009

KOZENKOV
Sergey
Vyacheslavovich
Deputy Director
for General Issues
since 1989

VINOGRADOV
Alexander
Vital'evich
Chief Engineer
since 2007

CULICOV
Otilia Ana

Scientific secretary
since 2008

1. SCIENTIFIC RESEARCH

CONDENSED MATTER PHYSICS

The main objectives of research in the framework of the theme involved the application of neutron scattering techniques and complementary methods to investigate the structure, dynamics and microscopic properties of nanosystems and novel materials, which are of great importance for the development of nanotechnologies in the fields of electronics, pharmacology, medicine, chemistry, modern condensed matter physics and interdisciplinary sciences. In the first half of 2012 until the license for the operation of the IBR-2M reactor was issued, 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. These activities were performed in accordance with the Topical Plan for JINR Research and International Cooperation under the existing cooperation agreements and accepted beam time application proposals. In May, 2012, the research activities on the IBR-2M reactor were resumed in accordance with the FLNP User Program. Also, the activities on the modernization of the available spectrometers and the development of new instruments were carried out in accordance with the development program plan for the IBR-2M spectrometers. Most attention was given to the realization of the top-priority projects (construction of the new DN-6 diffractometer for studying microsamples, multipurpose GRAINS reflectometer and modernization of the SKAT/EPSILON spectrometers for geophysical research).

Within the framework of investigations under the theme, the employees of the NICM Department maintained broad cooperation with many scientific organizations in Russia and abroad. The cooperation, as a rule, was documented by joint protocols or agreements. In Russia, especially active collaboration was with the thematically-close organizations, such as RRC KI, PNPI, MSU, IMP, ISSP RAS, IC RAS, and others.

A list of the main scientific topics studied by the employees of the NICM Department includes:

- Investigation of structure and properties of novel crystal materials and nanosystems by neutron diffraction;
- Investigation of magnetic colloidal systems in bulk and at interfaces;
- Investigation of structure of carbon nanomaterials;
- Magnetism of layered nanostructures;
- Investigation of nano-scale structure and functional characteristics of biological, colloidal and polymeric nanodispersed materials;
- Investigation of nanostructure and properties of lipid membranes and lipid complexes;
- Investigation of atomic dynamics of nanosystems and materials by neutron inelastic scattering;
- Investigation of texture and properties of minerals and rocks;
- Analysis of internal stresses in bulky materials and factory-made goods.

I. Scientific results.

Structure investigations of novel oxide and nanostructured materials.

The crystalline and magnetic structures of deuterated herbertsmithite $ZnCu_3(OD)_6Cl_2$ have been studied by means of neutron powder diffraction and magnetic susceptibility measurements in a wide range of temperatures (1.5-300 K) and pressures (0-10 GPa) [1]. The given compound exhibits the most ideal (among crystalline structures) realization of the 2D magnetic Kagome lattice of Cu ions with a spin s = ½ which has a ground state of a quantum spin liquid. It has been found that the application of pressure P = 2.5 GPa induces a phase transition from a quantum-disordered spin-liquid state to an antiferromagnetic ordering with the Néel temperature T_N = 6 K and magnetic elementary cell $\sqrt{3}\,a \times \sqrt{3}\,a$ (**Fig. 1**). The anomalies in the pressure behavior of Cu-O bond length and Cu-O-Cu, Cu-Cl-Cu bond angles have been revealed in the phase transition region. Possible mechanisms of these phenomena have been analyzed.

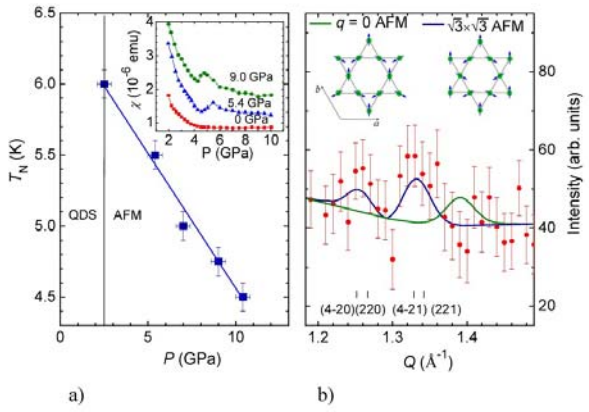

Fig. 1. a): magnetic phase diagram of herbertsmithite obtained from magnetic susceptibility measurements. b): magnetic contribution to the neutron diffraction spectrum of herbertsmithite at P = 2.7 GPa obtained by subtracting the spectrum taken at T = 50 K from the spectrum recorded at T = 1.4 K. Experimental points and model curves for two possible magnetic structures are shown.

At the HRFD diffractometer a structural phase transition in copper ferrite $CuFe_2O_4$, which is characterized by a decrease in the symmetry from a high-temperature cubic phase (*Fd*3*m*) to a tetragonal phase ($I4_1/amd$) has been studied. It has been revealed that the structural tetragonal-to-cubic phase transition (**Fig. 2**) occurs in a wide temperature range of 400 – 440°C and the equilibrium coexistence of both structural phases can be observed. The studied composition is a fully inverted spinel in a cubic phase, and the parameter of inversion in a tetragonal phase does not exceed several percent ($x = 0.06 \pm 0.04$). At the same time, the phase appeared on cooling has the classical tetragonal distortion ($\gamma \approx 1.06$). The character of the temperature changes in the structural parameters during the cubic-to-tetragonal phase transition suggests that it is based on Jahn-Teller distortions in $(Cu,Fe)O_6$ octahedrons (**Fig. 2**), but not on the boundary migration of copper and iron atoms.

Diffraction real-time *ex-situ* and *in-situ* experiments have been conducted for the first time on the HRFD diffractometer to study the structural changes that occur in chemical sources of electric current (lithium accumulators) with working substance of olivine doped with vanadium ($LiFePO_4$+xV, x = 0, 0.75%, 2% and 5%) in the course of their charging/discharging (redox-processes) in a high-resolution mode ($\Delta d/d \sim 0.001$). The ultra-low doping with vanadium makes it possible to significantly improve the properties of olivine ($LiFePO_4$) as a cathode material — electrical conductivity increases 108 times and the capacity grows by 33%. Two batteries, in one of which $LiFePO_4$ was doped with 0.75% of vanadium were studied in the *in-situ* mode in the course of charging/discharging (**Fig. 3**).

1. SCIENTIFIC RESEARCH

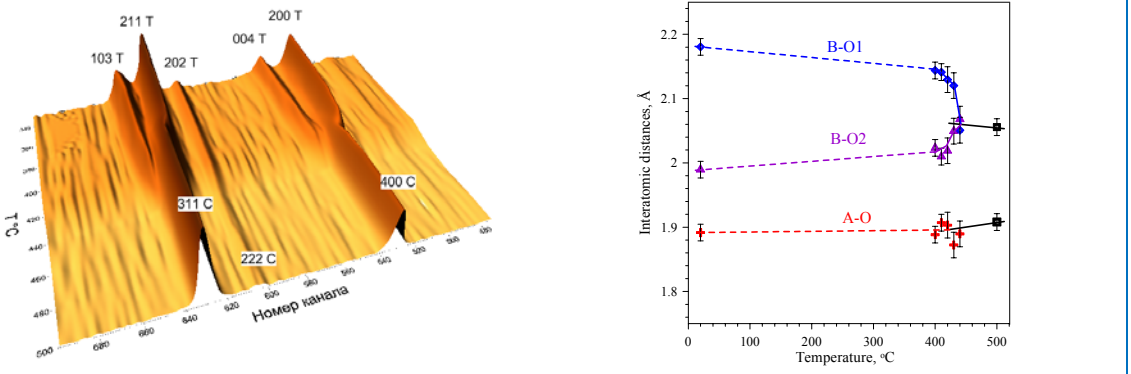

Fig. 2. Evolution of diffraction spectra of $CuFe_2O_4$ on heating from 340 to 500 °C, which evidences a structural tetragonal-to-cubic phase transition (at the top). The axis 'channel number' corresponds to interplanar distance. Miller indexes of the diffraction peaks are given with T symbol for a tetragonal phase and C symbol for a cubic phase. Dependences of interplanar cation-oxigen distances in tetrahedrons and octahedrons on temperature determined by the Rietveld method (at the bottom). In P_C phase the tetrahedrons AO_4 and octahedrons BO_6 are regular, while in P_T phase the octahedrons are stretched along the tetragonal axis (B-O1) and contracted in the perpendicular plane (B-O2).

During the charging of a battery a graphite unit cell (serves as an anode) enlarges because of the penetration of lithium ions into the structure of graphite and vice versa, diminishes down to standard sizes in the course of discharging and, correspondingly, migration of lithium ions back to a $LiFePO_4$ electrode. The enlargement and restoration of a crystal lattice of graphite, as well as the number of embedded lithium ions in Li_xC affect the position and intensity of some diffraction peaks of graphite. Phase transition $LiFePO_4 \leftrightarrow FePO_4$ was clearly observed: at $d \sim 2.4$ Å in the charged accumulator there appear two intense diffraction peaks that are characteristic for the $FePO_4$ phase. After several cycles of battery charging/discharging no degradation of the crystal structure of working electrodes was revealed.

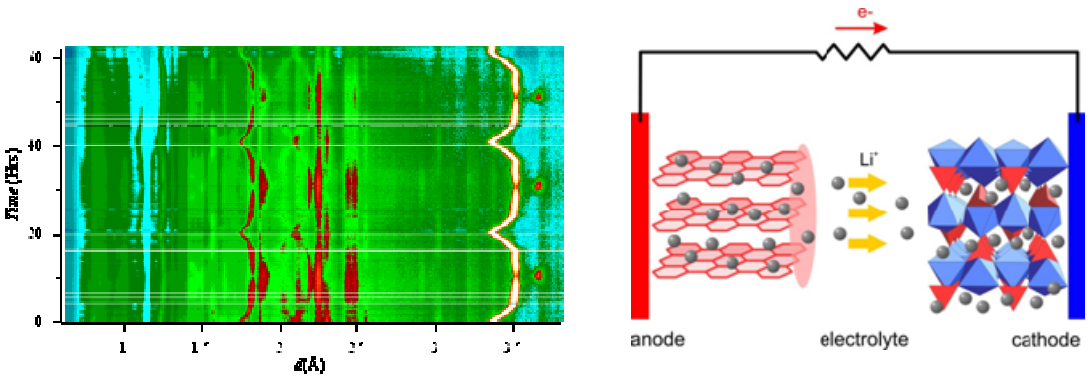

Fig. 3. At the left: evolution of neutron diffraction spectra from lithium-based electrical current source in the process of three charging/discharging cycles. Each full charging/discharging cycle takes about 20 hours. An intense peak at $d \approx 3.5$ Å is from graphite anode; peaks in the region of 2 - 2.5 Å are from olivine. At the right: illustration of the lithium ion migration during a charging/discharging cycle for a $LiFePO_4$-based Li-ion battery (cathode is at the right). During the charging process lithium ions are intercalated into the graphite lattice making it to expand; and vice versa, during the discharging process lithium ions leave the graphite lattice and its standard structural parameters are restored. From *Janina Molenda and Marcin Molenda (2011).*

1. SCIENTIFIC RESEARCH

The features of the crystalline structure of crystallophospors $Lu_3Al_5O_{12}:Ce^{3+}$ produced by the colloidal chemical method have been investigated by means of neutron diffraction at room temperature and the influence of the peculiarities of high-temperature annealing on the crystalline structure and spectral luminescent properties of the samples have been studied. The results of the research show that at a certain annealing temperature the growth of the interatomic bonds of oxygen octahedrons slows down as well as the intensity of luminescence. It is suggested that this effect is related to the peculiarities of the formation of a defect structure in $Lu_3Al_5O_{12}:Ce^{3+}$ and probable precipitation of cerium in other crystallographic positions different from those of lutetium Lu. This fact is confirmed by the appearance of additional peaks in the luminescence spectra, which are due to the occurrence of new channels of optical relaxation.

The effect of the synthesis conditions on the structure and sorption properties of titanium-based nanosorbents has been studied (**Fig. 4**). The morphology of the synthesized nanosorbents has been determined using scanning electron microscopy. The crystalline structure and sorption properties have been found by X-ray powder diffraction.

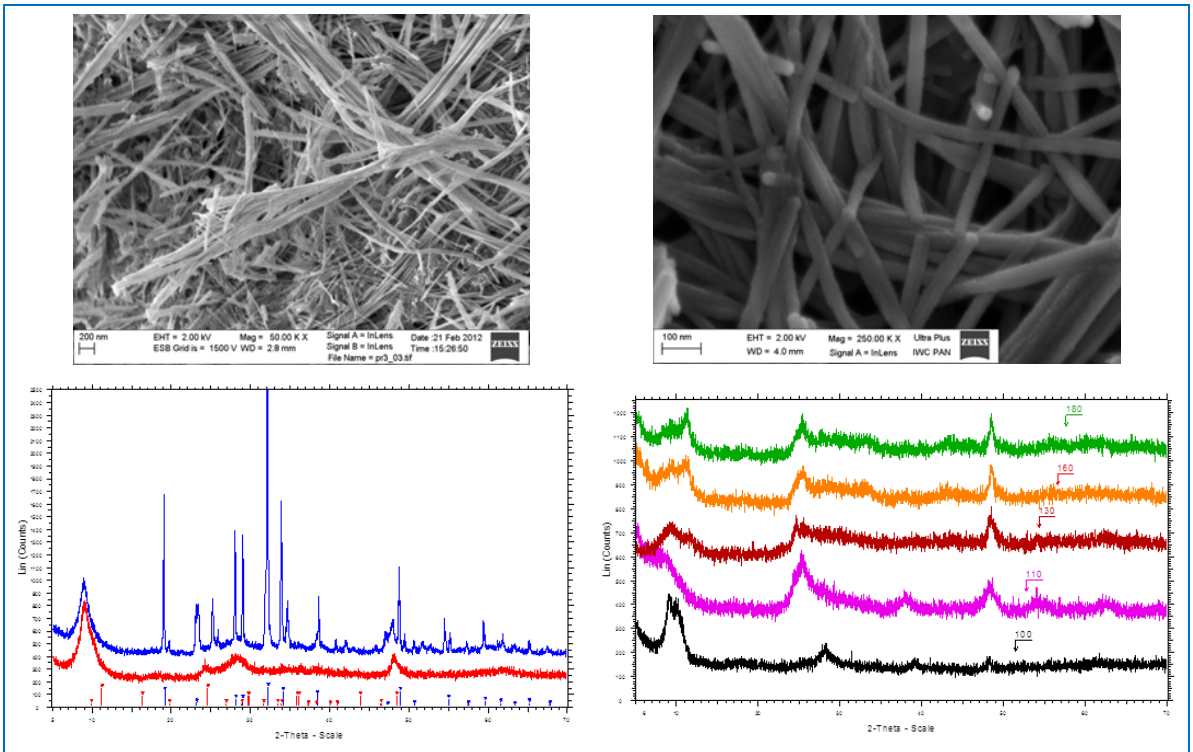

Fig. 4. At the top: nanosorbents based on $TiOSO_4$, temperature of synthesis 120°C (at the left), and TiO_2, temperature of synthesis 120°C (at the right). At the bottom: diffraction patterns from nanosorbent (blue line – nanosorbent after synthesis of $TiOSO_4$ with NaOH in ethanol at a temperature of 120°C), (red line – nanosorbent after washing with water) – at the left. Diffraction patterns from nanosorbents synthesized at various temperatures, after sorption of cesium – at the right.

1. SCIENTIFIC RESEARCH

Investigation of magnetic fluids and nanoparticles.

Small-angle neutron scattering has been applied for studying solutions of magnetoferritin—artificial biological complex on the basis of apoferritin in whose cavity the synthesis of iron oxides is initiated by chemical methods. By means of the contrast variation method the mean scattering length density of magnetoferritin and its relative composition have been determined depending on the loading factor LF, which is the mean number of iron atoms per one apoferritin complex. The measurements have revealed a significant shift in the match point of magnetoferritin with increasing LF, which is probably related to a partial distortion of the apoferritin shell (**Fig. 5**) [2].

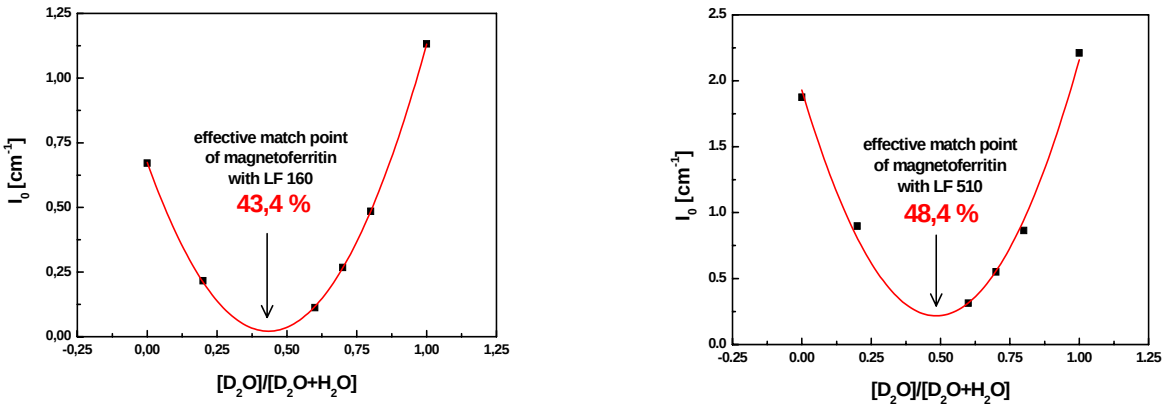

Fig. 5. Dependence of forward SANS intensity (YuMO, IBR-2M) on the relative content of deuterated component in the mixture D_2O/H_2O for solutions of magnetoferritin at two values of the loading factor LF. The arrows denote the match points.

The structural parameters of various components of magnetic fluids based on decaline with an excess of surfactant (oleic acid) have been obtained basing on the data of small-angle neutron scattering (instruments Yellow Submarine of the Budapest Neutron Center and SANS-II of the Paul Scherrer Institute). It has been shown that the structural changes concern mainly the character of the interaction between free surfactant molecules in the bulk of the magnetic fluids. However, an increase in the attraction between the surfactant molecules in the presence of magnetic particles is significantly less in decaline than in the analogous systems based on benzene. This correlates with the fact that, in contrast to benzene, decaline-based magnetic fluids remain aggregatively stable in a range of the surfactant excess up to 25 vol. %. Thus, from the microstructural viewpoint the solute-surfactant interaction plays a significant role in the stabilization of the given systems at the surfactant excess.

The experiments on neutron reflectometry (reflectometer with horizontal sample plane NREX, reactor FRM-II, Munich) have been carried out to study the structural organization of nanoparticles of two magnetic fluids at the interface with crystalline silicon. The effect of the introduction of biocompatible polymer (polyethyleneglycol) into the particle composition of the initial electrostatically stabilized magnetic fluid (magnetite coated with sodium oleate in water) has been investigated.

At the first stage of the complex investigation of the effect of magnetic nanoparticles on the conformation of amyloids the structure analysis of amyloidal fibrils of hen egg white lyzosyme stabilized in acidic medium has been carried out using small-angle neutron (SANS) and small-angle X-ray (SAXS) scattering from aqueous solutions, as well as by atomic force microscopy with the

adsorption of fibrils on a mica surface [3]. It has been shown that the obtained small-angle scattering curves (**Fig. 6**) are consistent with the helical structure of protofilaments forming amyloidal fibrils. For the analysis a simple approximation has been proposed, which makes it possible to find out the period of repetition (pitch) and the mean diameter of the helix, as well as the effective radius of their basic structural units. Some kind of 'isotope effect' on the helical structure was observed when using a heavy component in the solvent (H_2O/D_2O mixtures), which showed a significant increase in the helix diameter for the solutions with the dominant fraction of D_2O.

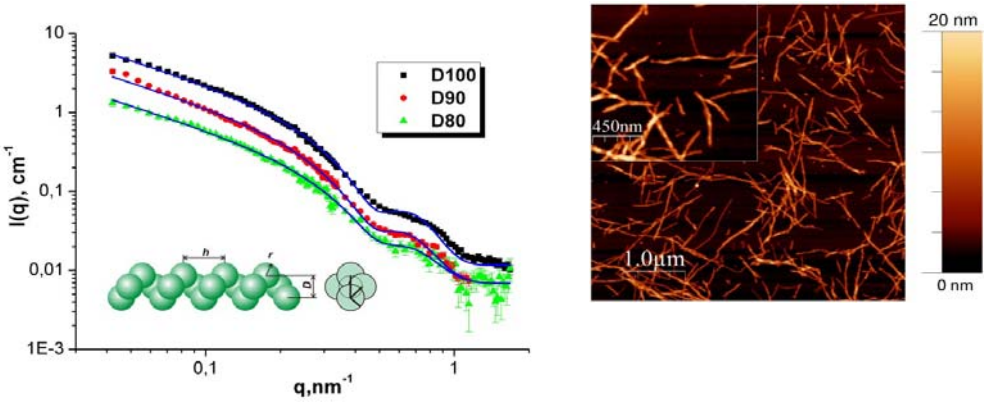

Fig. 6. Small-angle neutron scattering curves (SANS-II, PSI) from fibril amyloidal aggregates of hen egg white lyzosyme at different content of D_2O in solution. The curves are approached by the model 'helix from homogeneous spheres' whose parameters are illustrated in the inset. At the right the AFM image (IEP SAS) is shown for analogous aggregates adsorbed on the mica surface from D_2O.

Investigation of carbon nanomaterials.

The theoretical description of the kinetic growth of clusters in C_{60}/NMP and other polar solutions continued [4]. For the two models of fullerene aggregation proposed previously the time extrapolation of numerical solutions for kinetic equations has been performed. This has made it possible for the first time to obtain stationary size distribution functions of the clusters, *f(n)*, for the final stages of the cluster growth (**Fig. 7**). For one of the two models the stationary functions are well described by the so-called Slezov's functions for the classical coalescence. For another model it has been shown that among simple distribution functions the lognormal distribution gives the best fits. The calculations of *f(n)* have been made for different model parameters τ and τ_c corresponding to characteristic relaxation times in the solution.

The calculations of the evolution of the SANS curves have been made for different models of the cluster growth in C_{60}/NMP solution (**Fig. 7**). In the case of the model where the C_{60}-NMP complex formation is considered as a transition of fullerene molecules into the state of an oversaturated solution one can see that the shape of the SANS curves is inconsistent with the experimental data. This result is determined by the low polydispersity of *f(n)*, which can be explained by the error in the extrapolation (in the case of the second model this error is significant, since even the lognormal distribution poorly describes the distribution functions). The work has been done in cooperation with the University of Ulan-Bator (Mongolia).

1. SCIENTIFIC RESEARCH

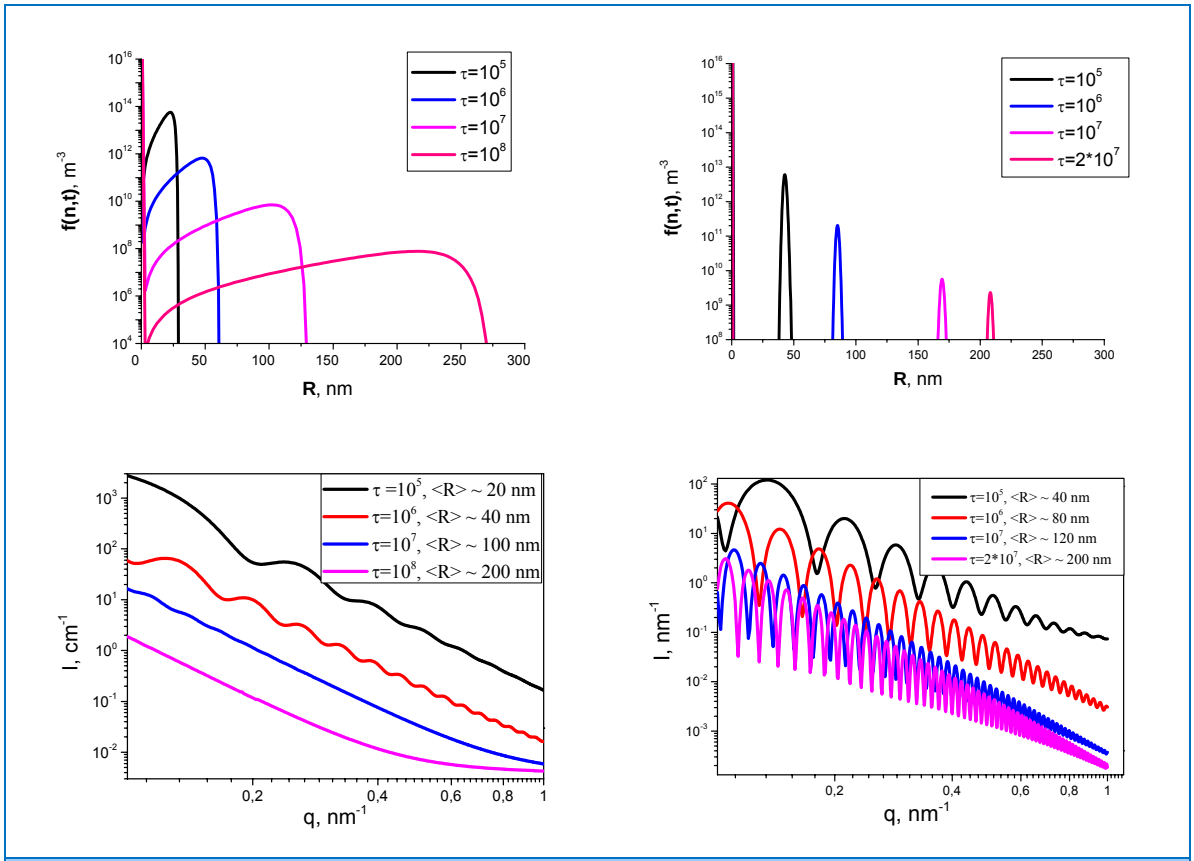

Fig. 7. At the top: stationary size distribution functions for fullerene clusters in solution C_{60}/NMP obtained by the extrapolation method for kinetic equations for two different models and various values of parameters τ and τ_c. The order of magnitude of τ-values corresponds to real times of the cluster growth. At the bottom: SANS curves calculated for the model stationary functions f(n) of the C_{60}/NMP solution at various parameters τ and τ_c.

Also, the experimental investigations of the properties of C_{60} solutions in mixed solvents continued. Thus, for the mixed solution C_{60}/NMP/toluene a non-reversible solvatochromic effect has been observed. It manifested a significant difference in the behavior of the absorption spectra of visible and ultraviolet range depending on the relative composition of the solvent for different ways of the solution preparation. If on addition of NMP into the initial solution C_{60}/toluene one can speak about classical solvatochromism (proportional shift of characteristic absorption peaks), in the reverse case, when toluene is added into the initial solution C_{60}/NMP, the selective solvatochromism is observed; toluene starts to penetrate the solvate shell only at its very high (> 95%) content in the solvent bulk. This behavior is related to a strong difference in the dielectric properties of the two types of the solvent molecules. An important observation of the research was that the found effect depends on the age of the initial solution and is influenced by the cluster state in C_{60}/NMP.

Investigation of magnetic nanostructures.

The transmission of non-polarized neutrons through a non-complanar structure has been investigated to reveal its dependence on the sequence order of magnetization components in the path of neutron wave propagation. Neutrons were reflected from two mirrors with the magnetizations

perpendicular to each other and lying in the reflection plane of the mirrors. The magnetic field was directed perpendicular to magnetization vectors. The coefficients of successive neutron reflections from the two mirrors in two cases of the opposite directions of the magnetic field are shown in **Fig. 8** together with their relative difference. The amplitude of the oscillations of this difference corresponds to the neutron polarization of 0.2-0.25 in the reflected beam. The period of oscillations of 0.7 Å corresponds to the period of Larmor precession in a magnetic field of 27 Oe. Thus, it has been experimentally shown that the polarized neutron beam transmission for non-complanar structures depends on the mutual orientation of three magnetic moments.

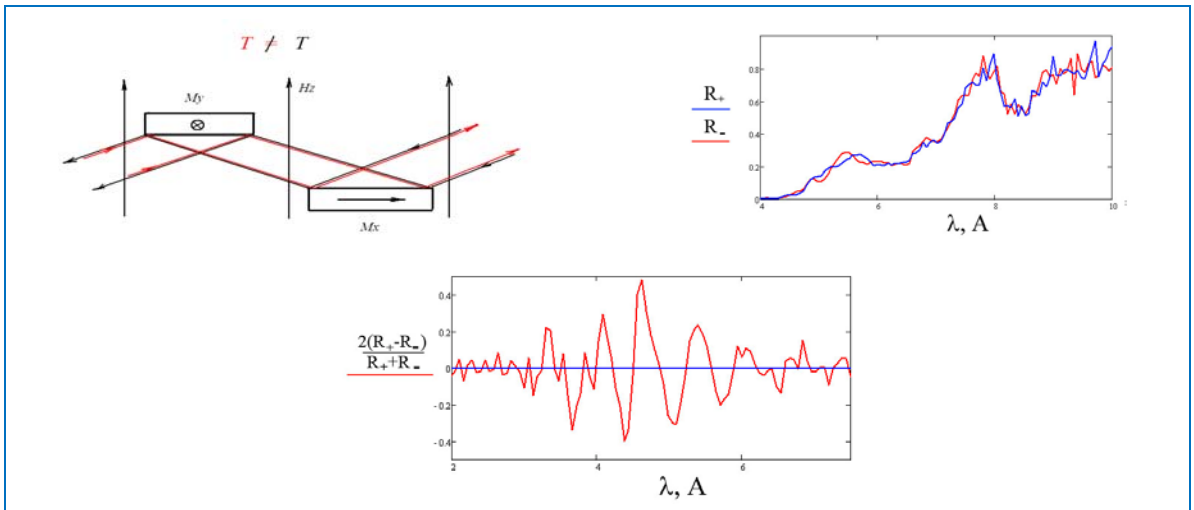

Fig. 8 Scheme of the experiment (upper panel). The coefficient of reflection from two neutron mirrors polarized perpendicular to the planes of the mirrors in a magnetic field of 27.5 Oe (blue line) and -27.5 Oe (red line) and relative difference of the coefficients of double reflection depending on the neutron wavelength (middle and lower panels).

Investigation of biological nanosystems, lipid membranes and lipid complexes.

The formation of micelles of photosensitive surfactant azobenzene trimethylammonium bromide (AzoTAB) has been studied by means of small-angle neutron scattering. In the trans-conformation the AzoTAB molecule forms charged ellipsoidal micelles. The micelle size and aggregation number increase with growing AzoTAB concentration. The temperature increase results in a decrease in these parameters. In contrast, the degree of dissociation of bromine ξ drops when the AzoTAB concentration increases and rises with increasing temperature. Under the ultraviolet irradiation the shape of the scattering curves changes sharply in the covered range of the momentum transfer q, which is indicative of reorganization of AzoTAB aggregates. It is possible that in this case AzoTAB forms strongly anisotropic objects. It has been shown that the addition of the photosensitive surfactant to nucleic acids causes their compaction. Along with this the compaction effect is also photosensitive. It is explained by the change in the surfactant conformation depending on the irradiation wavelength. Thus, the irradiation of the system by ultraviolet light causes the transition of the AzoTAB molecule from trans- to cys-conformation, which promotes the isolation of AzoTAB from RNA/DNA and decompaction of polynucleotide chains.

1. SCIENTIFIC RESEARCH

The investigations of the phase transition from the liquid crystal phase to the ripple-phase in aqueous solutions of lipid membranes DPPC/D_2O have been carried out using small-angle neutron scattering and simultaneous volumetric P-V-T measurements (**Fig. 9**). The thickness of the lipid bilayer (using SANS data) and changes in its volume (using volumetric data) have been determined. The achieved high precision in the determination of the volume changes made it possible to estimate the changes in the lipid molecule area as a result of the phase transition, which was found to be 6 $Å^2$ in agreement with the results of other works.

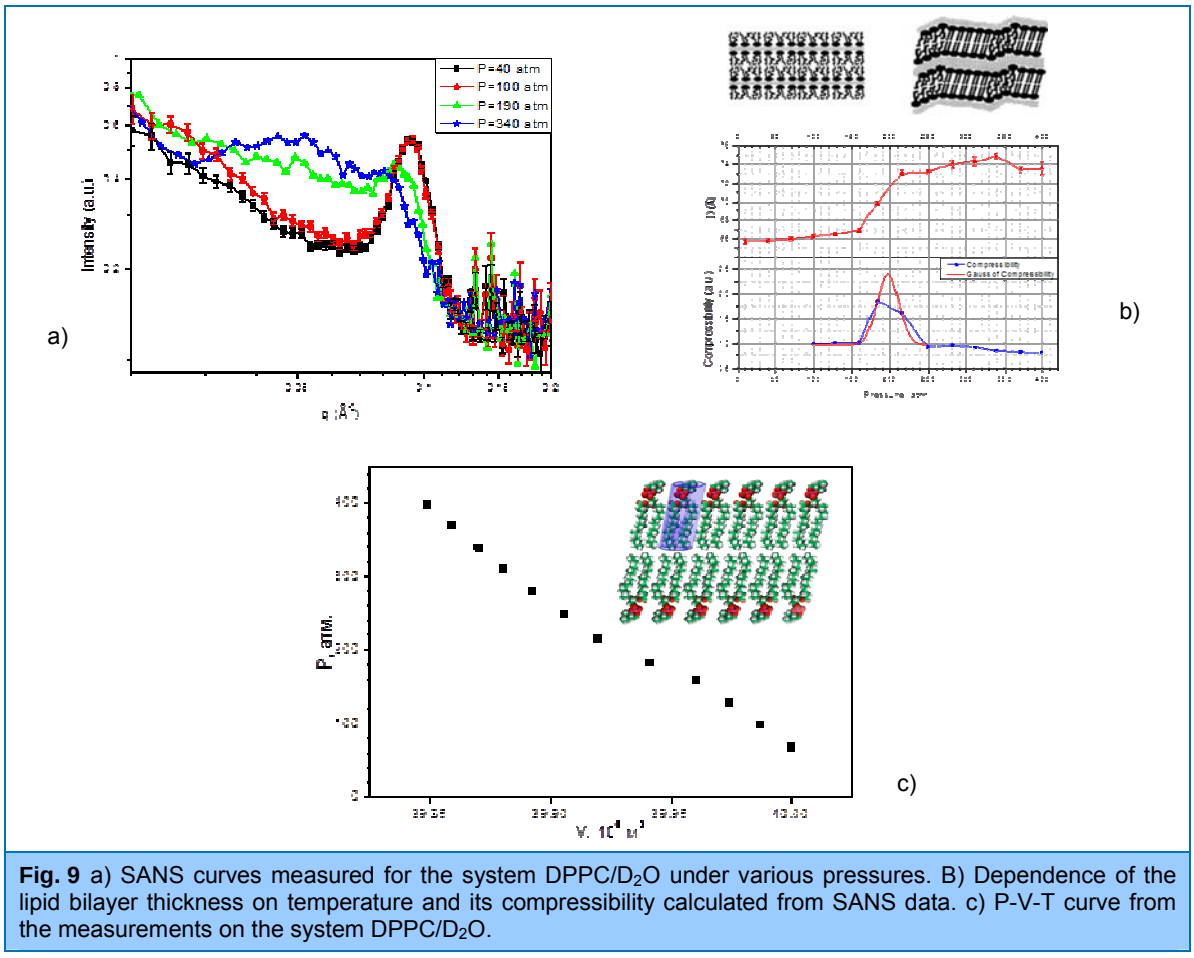

Fig. 9 a) SANS curves measured for the system DPPC/D_2O under various pressures. B) Dependence of the lipid bilayer thickness on temperature and its compressibility calculated from SANS data. c) P-V-T curve from the measurements on the system DPPC/D_2O.

The effect of salt on the structure of lipid membranes has been studied using the DMPC/H_2O/CaCl system as an example. It has been shown that with increasing concentration of calcium ions the multilamellar membranes undergo a transition to an unbound state in both gel and liquid-crystal phases. The obtained results are indicative of continuous (non-abrupt) character of the transition. The rise of the small-angle part of the curves with increasing concentration is also evidence in favor of this hypothesis. The analysis of small-angle scattering curves for multilamellar DMPC membranes has demonstrated that the destruction of the lamellar structure and the formation of single-layer vesicles occur at C_{Ca2+} ~ 0.3 mM in $L_{\beta'}$ phase and at C_{Ca2+} ~ 0.4 mM in L_{α} phase. The C_{Ca2+} values depend on both the phase state of the system and the concentration of the lipid. The detailed analysis of the diffraction peaks has made it possible to refine the numerical values for the

concentration of Ca2+ ions necessary for the bound-to-unbound transition of the system under study. It has been shown that in the pre-transition region the reduction of the lipid concentration does not affect the repeat distance in lipid membranes. The thicknesses of lipid bilayers formed spontaneously of multilamellar membranes in the region of the system transition to an unbound state correspond to the thicknesses of single-layer vesicles prepared by the extrusion method. This is direct evidence that single-layer vesicles are formed following the collapse of the lamellar phase of multilamellar DMPC membranes in both gel and liquid-crystal phases. Further addition of calcium ions results in partial adhesion of single vesicles.

Multilamellar membranes of DPPC (1,2-dipalmitoyl-sn-glycero-3-phosphatidylcholine) and mixture DPPC/POPC (1-palmitoyl-2-oleylphosphatidylcholine) in excess of water have been investigated by small-angle X-ray scattering and neutron small-angle scattering. The structural parameters of lipid bilayers have been determined in a temperature range of 3-60°C. It has been shown that the addition of POPC to DPPC/H_2O does not change the temperature of the DPPC main phase transition within the limits of experimental error. The observed phase separation occurs for the system DPPC/POPC/H_2O up to the pre-transition temperature (gel phase - ripple phase) of the DPPC multilamellar membranes. It has been found that the repeat distance of the gel phase for the DPPC/POPC mixture is smaller than that for DPPC. This effect is more pronounced for the samples measured by SAXS.

Model lipid membranes modeling the lipid component in the mucous membranes of the oral cavity of mammals based on ceramide-6 have been investigated by means of neutron diffraction (**Fig. 10**).

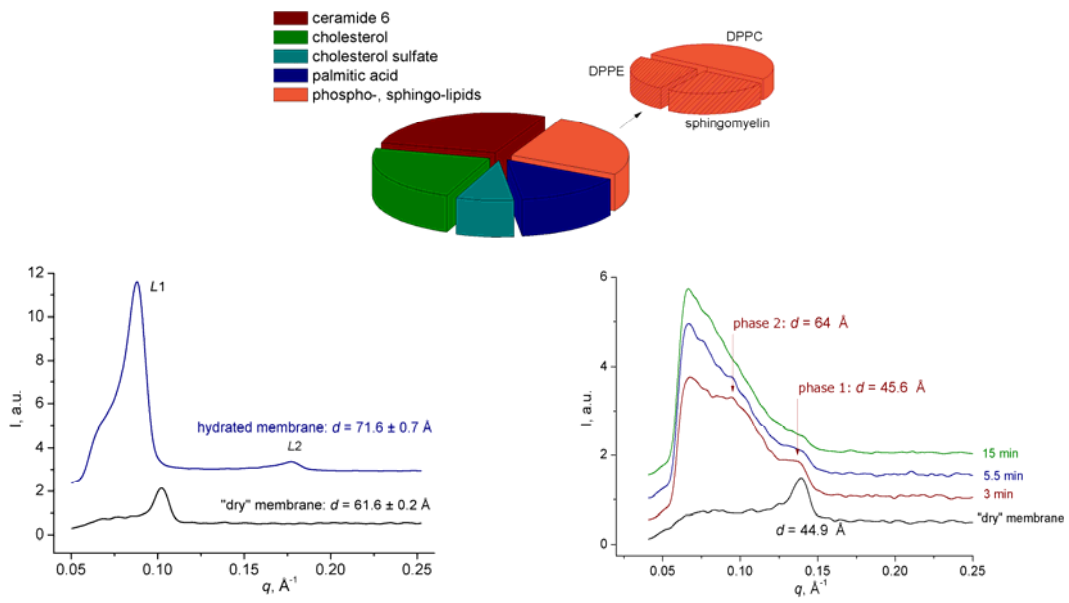

Fig. 10. At the top: composition of model OSC lipid membranes. At the bottom: diffraction spectra from model membrane DPPE/DPPC/SM in dry and hydrated states. The membrane is fully hydrated within 2 minutes after it is placed in the cell with water (at the left). Diffraction spectra from model OSC membrane = cer6/chol/PA/cholS/PL = 28/23/15/8/26 (PL= DPPE/DPPC/SM) in the process of hydration (at the right).

It has previously been shown that the model oral stratum corneum (OSC) membrane composed of ceramide-6/cholesterol/cholesterol sulphate/palmitic acid/DPPC/DPPE/ sphingomyelin at 37°C and a relative humidity of 99 % is characterized by the co-existence of several structural phases with repeat distances of 55, 46 and 58 Å. The experiments performed with oriented samples in excess of water have revealed that one of the structural phases shows the behavior similar to that of the model stratum corneum membrane with a slight increase in the repeat distance during the first several minutes of hydration from 44.9 to 45.6 Å. Since it is generally recognized that low hydration in SC is mainly due to ceramides, the data allow us to suggest that there are ceramide-richdomains in the lipid component of the natural mucous membrane, which are responsible for permeability control.

The morphology of the mixed double systems of DPPC/sodium cholate (basis of transdermal vesicular drug carriers) has been studied by the small-angle neutron scattering technique. It has been shown that in a temperature range of 10-60°C a lamellar-to-micellar phase transition occurs at 15°C, in a temperature range of 15-25°C the system exists in the micellar phase and at a temperature of 25°C undergoes a transition to the lamellar phase It has been suggested that the reason for this unusual temperature dependence of the double system of DPPC/sodium cholate is the existence of a minimum in the critical micelle concentration of sodium cholate in a temperature range of 15-25°C.

Atomic and molecular dynamics.

The quantum-chemical calculations of the lattice dynamics of vanadium oxide in polymorphic phases α-V_2O_5 and β-V_2O_5 have been performed [5]. Vanadium oxides are widely used in thin film electrochemical devices and as cathodes of lithium batteries due to their high energy density and retention capacity upon cycling. The model vibrational spectra showed satisfactory agreement with the experimental Raman spectra. Their analysis permitted a reliable description of all observed spectral features, and made it possible for the first time to establish 'structure-spectra' relationship for the two polymorphs of vanadium pentoxides. The activation energy of the phase transition α-$V_2O_5 \rightarrow \beta$-V_2O_5 has been estimated together with the additional calculations aimed at revealing possible mechanisms of the transition.

The neutron dynamic experiment on liquid sodium (T = 105-420°C) and sodium-hydrogen melt (T = 420°C, hydrogen concentration C ~ 0.04 % at.) has been carried out. It has been established that hydrogen is present and diffuses in the melt in the form of sodium hydride NaH. Basing on the analysis of the widths of the quasi-elastic scattering peaks (**Fig. 11**) the information on the diffusion properties of the matter has been obtained.

The temperature dependence of the phonon density of states has been studied for the most refractory metal – tungsten – which is of current interest for reactor applications. For the first time, the vibration spectrum of the crystalline lattice at temperatures of 293 and 2400 K has been obtained in the direct experiment. The vibration spectrum at a temperature of 2400 K is shifted towards lower frequencies because of the effect of the anharmonicity of vibrations. Along with this, the main peculiarities of the detailed structure characterizing BCC lattice remain unchanged.

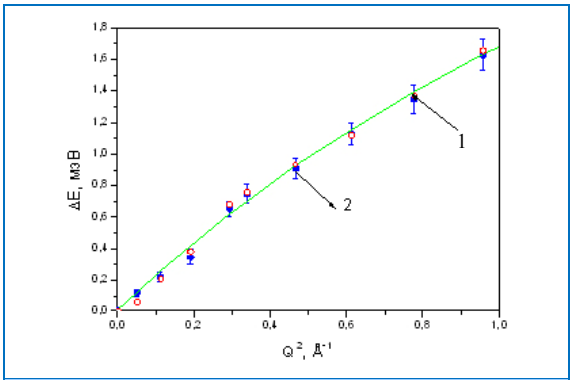

Fig. 11. FWHM of peaks of quasielastic neutron scattering from pure sodium (1) and sodium-hydrogen melt (2) for a temperature of 420°C. The curve corresponds to the model of mixed diffusion.

Applied research.

Among traditional applied investigations in the NICM Department are the experimental studies of internal stresses and texture of rocks and minerals, determination of internal stresses in bulk materials and products, including engineering materials and components of machines and devices. For the most part, these investigations are carried out using neutron diffraction.

A new comprehensive approach to the study of physical properties of layered textured rocks has been realized. It is based on the fabrication of model samples with specified characteristics, which are close in their internal structure and crystallographic texture to the real objects formed under natural conditions of the Earth's lithosphere. For this purpose the velocities of quasi-longitudinal elastic waves propagating through two-phase layered model samples in the shape of a ball made of mineral powder fillers (muscovite, quartz) and binding layered epoxide have been measured (**Fig. 12**). It has been revealed that samples with muscovite and quartz fillers have different relations between the layered structure and the spatial distribution of the velocities of quasi-longitudinal elastic waves, which is due to the process of fabrication of the models (deposition) [6].

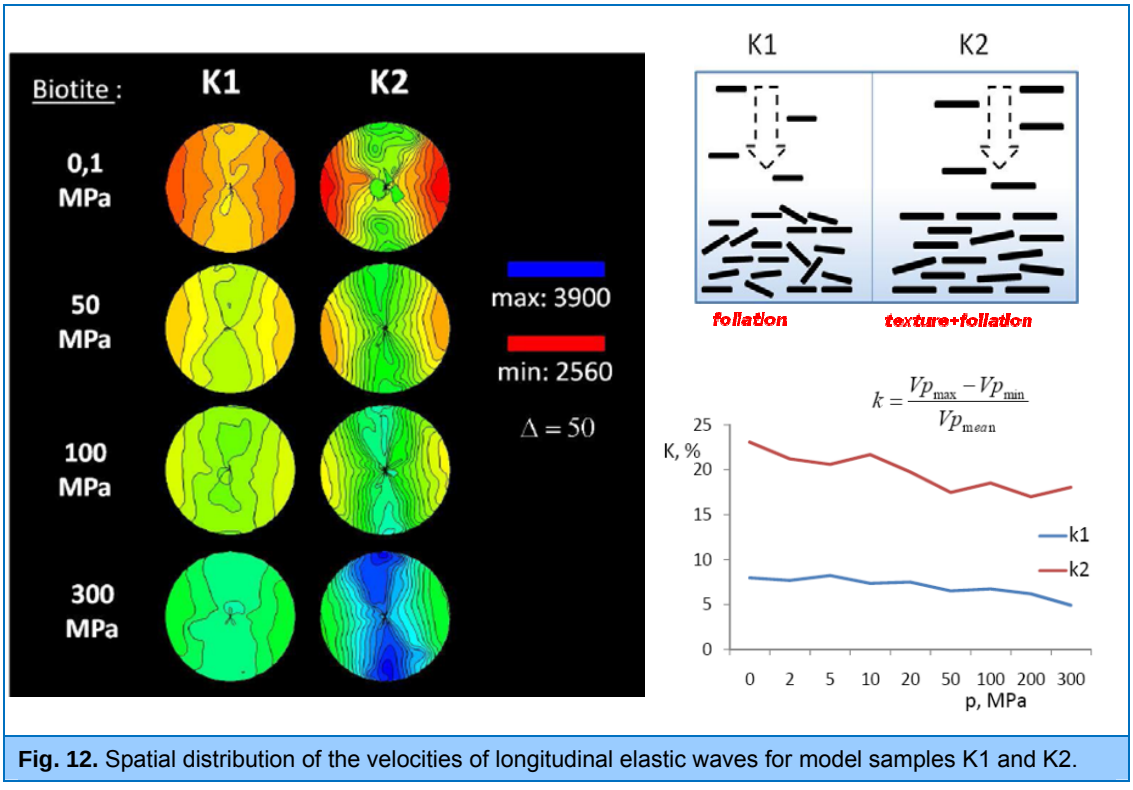

Fig. 12. Spatial distribution of the velocities of longitudinal elastic waves for model samples K1 and K2.

In collaboration with the State Center for Machine-Building Technology (TSNIITMASH) the processes of formation and decomposition of martensite after normalizing at 1050°C and further annealing in a temperature range of 500-840°C have been studied for heat-resistant ferritic-martensitic steels 10Х9К3В2МФБР and P91 (Russian notation). These steels are very promising materials for thermal and nuclear power engineering because they can be employed in power facilities at temperatures up to 650°C and vapor pressures up to 35 Pa, and their radiation resistance may amount to as much as 200 dpa.A strong anisotropy of the diffraction peak width (**Fig. 13**) caused by a

high dislocation density (as a result of martensite transition) was observed; the values of microdeformations and the dislocation density, as well as their decrease with increasing temperature and annealing time, were determined. The measured SANS spectra showed the strong surface fractal scattering in these martensites. At the annealing temperature of 600°C the intense precipitation of fractal particles of carbides and nitrides was observed during 1 hour. At further annealing the carbides were aggregated up to sizes out of the limits of the SANS method. At the same time the scattering from surface fractals reappeared up to the highest annealing temperatures.

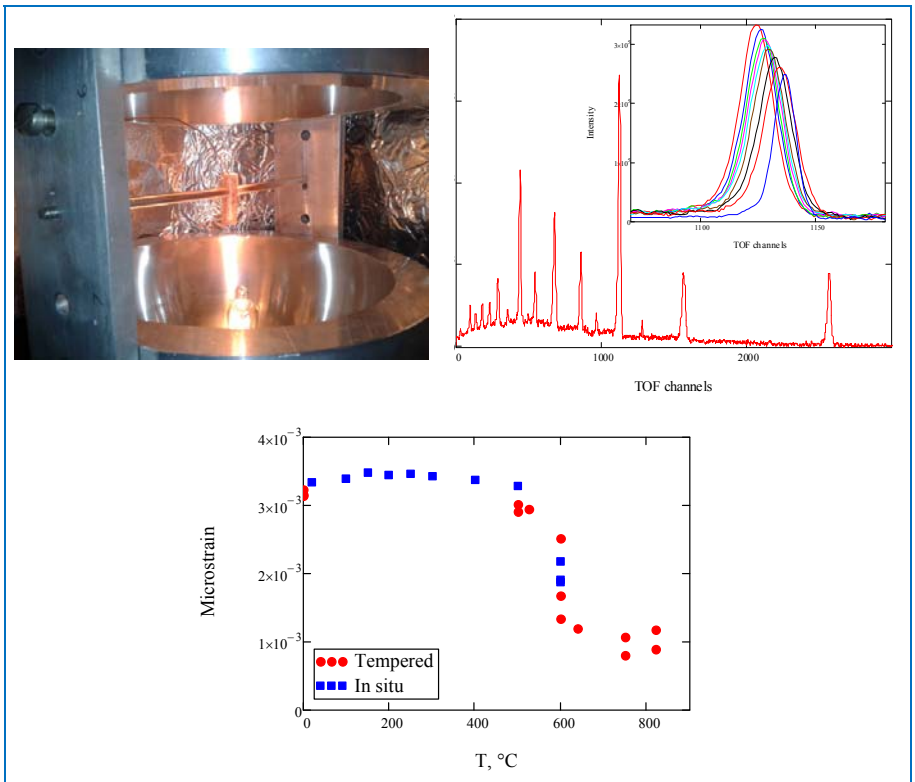

Fig. 13. At the top: sample of heat-resistant ferritic-martensitic steel 10Х9К3В2МФБР (Russian notation) at FSD at T=600 °C (at the left). Spectrum of steel 10Х9К3В2МФБР with characteristically widened diffraction peaks. The inset shows changes in the position and shape of the diffraction peak (211) with increasing temperature (at the right). At the bottom: Relaxation of microstrains in steel 10Х9К3В2МФБР with increasing annealing temperature.

The measurements of the local texture in a number of samples based on magnesium alloy MA21 (produced by intensive plastic deformation according to the technology of equal-channel angular pressing ECAP) have been carried out by means of synchrotron radiation diffraction. This deformation method is used for obtaining structures with submicron and nanometer crystallite grain sizes. It has been revealed that the texture of the initial sample after the application of the ECAP method is characterized by two strong components (basic and prismatic), which form as a result of extrusion with back pressure. Under the deformation by the ECAP technology the basic component shifts by 45° relatively to the direction of the extrusion, which can be explained by the realization of the simple shear deformation mechanism.

II. Instrument development.

The work on the basic configuration of the new DN-6 diffractometer for studying microsamples on beam 6b of the IBR-2 reactor has been completed. The main elements of the diffractometer (mirror vacuum neutron guide, mechanical part, detector system) have been installed at beam 6b. First scientific and methodological experiments have been carried out and demonstrated a one-order increase in the neutron counting rate compared to that of the analogous DN-12 diffractometer.

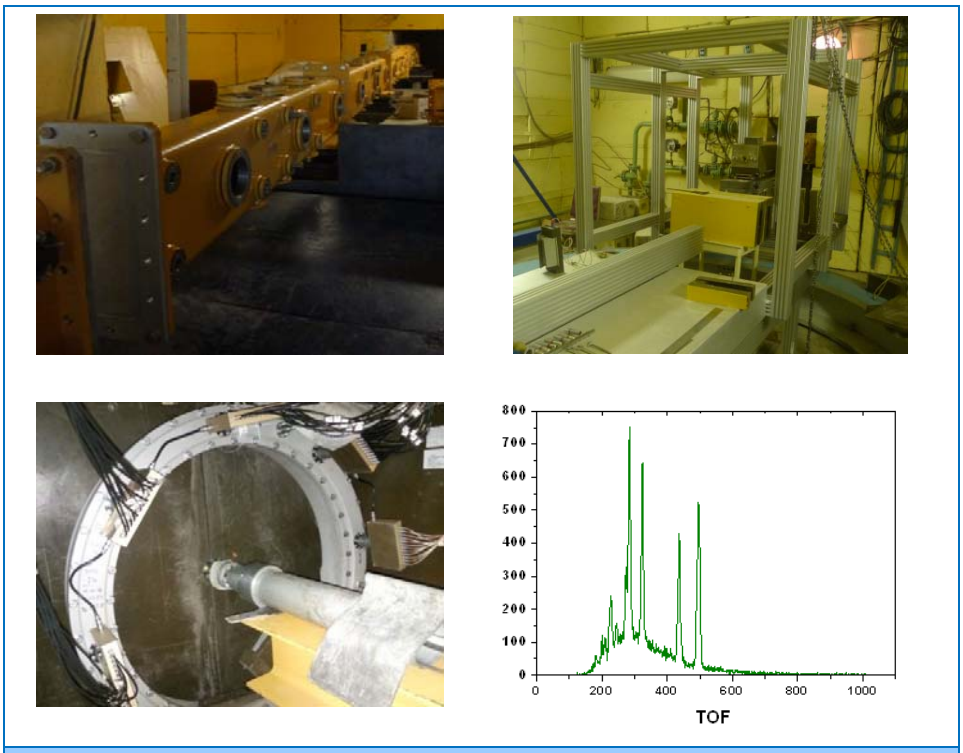

Fig. 14. Elements of the basic configuration of the DN-6 diffractometer: mirror vacuum neutron guide (top left), mechanical part (top right), detector system (bottom left), spectrum of a standard Ni sample (bottom right).

A large-scale modernization of the SKAT/Epsilon and NERA-PR diffractometers on beams 7a-1, 7a-2, 7-b (**Fig. 15**) aimed at the replacement of mirror neutron guides, installation of beam choppers and λ-choppers, modernization of the detector system, accumulation and sample environment electronics has been completed. On the NERA-PR spectrometer the integrated neutron flux at a sample position has approximately doubled and in the cold neutron range it has increased 4 times (in the operation mode with a cryogenic moderator). The analogous data for the SKAT/Epsilon are to be obtained. The instruments have been put into operation. A high pressure cell (Paris-Edinburgh type) has been purchased to extend experimental capabilities of the Epsilon diffractometer.

The work continued to construct a new multifunctional reflectometer GRAINS on beam 10 of the IBR-2M reactor. The improvement of the beam-forming system units has been carried out in order to eliminate the revealed design flaws. The final stage of the work on the design and construction of the reflectometer biological shielding has been completed. The electrical work necessary to prepare the spectrometer for commissioning is underway.

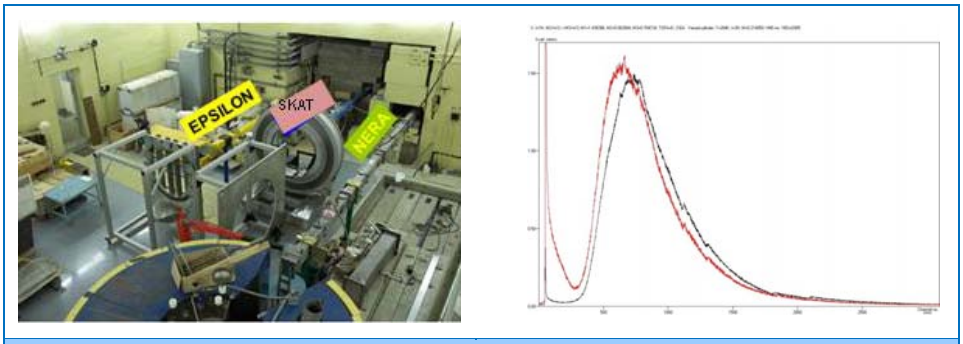

Fig. 15. Spectrometers SKAT, EPSILON and NERA on beams 7a-1, 7a-2 and 7b of the IBR-2M reactor (at the left). Incident neutron spectrum measured for a vanadium sample at the NERA-PR spectrometer before (black line) and after (red line) modernization – at the right.

The reconstruction of the DN-2 diffractometer into a diffractemeter for real-time measurements continued. A beam chopper, mirror neutron guide, 2D PSD with an active area of 200×200 mm^2 have been installed. First test measurements were started.

The final stage of the reconstruction of the head part of a neutron guide system for HRFD has been completed. A high vacuum in the new collimator-concentrator has been obtained. The development of algorithms and creation of the RTOF analyzer of a new type for registration of all events ("list mode") continued. A pilot prototype of the analyzer has been installed at FSD and the first experiments have been performed to compare the diffraction spectra obtained simultaneously using the existing DSP-based analyzer and the new "list mode" analyzer.

The re-adjustment of the elements of the REFLEX reflectometer has been carried out with due consideration for absolute measurements of neutron fluxes on beam 9 in 2011. The measurements have shown that the thermal neutron flux on beam 9 dropped significantly as compared with the parameters of 2006. The decrease in the neutron flux was induced by the change in the dimensions of the reactor core and the shift in the location of moderators relative to the axis of beam 9. To remedy the situation, all collimators of beam 9 were readjusted. The measurements of direct beam spectra conducted in May-June, 2012 showed the thermal neutron fluxes to be the same as it had been before the reactor shutdown in 2006. The adjustment and debugging of the electronics and software installed at the reflectometer at the end of 2011 went on through the year.

The creation of neutron beam infrastructure for the FSS diffractometer (moved from GKSS) and a prototype of a neutron radiography facility has started at beams 13 and 14 of IBR-2M. A biological shield has been built; the electrical work is nearing completion.

The measurements of the working parameters of the DIN-2PI spectrometer after the installation of a supermirror neutron concentrator have been completed. The gain factor estimated on the basis of the obtained results was found to be G (3 meV) ≈ 8.

A significant progress has been made in the development of neutron probe microscopy. The experiment was performed with a polarized neutron (4 Å) beam 2 μm wide formed by a layered waveguide, which was directed to an amorphous magnetic wire $(Co_{0.94}Fe_{0.06})_{72.5}Si_{12.5}B_{15}$ 190 μm in diameter with two types of magnetic domains (**Fig. 16**). As a result of scanning in the direction perpendicular to the neutron beam a cross sectional profile of a neutron spin precession angle was measured for the wire, thus making it possible to analyze its magnetic microstructure (distribution of magnetic induction). It has been experimentally demonstrated that statistically sufficient data on the

magnetic microstructure can be obtained for a reasonable measurement time (of the order of 10 hours).

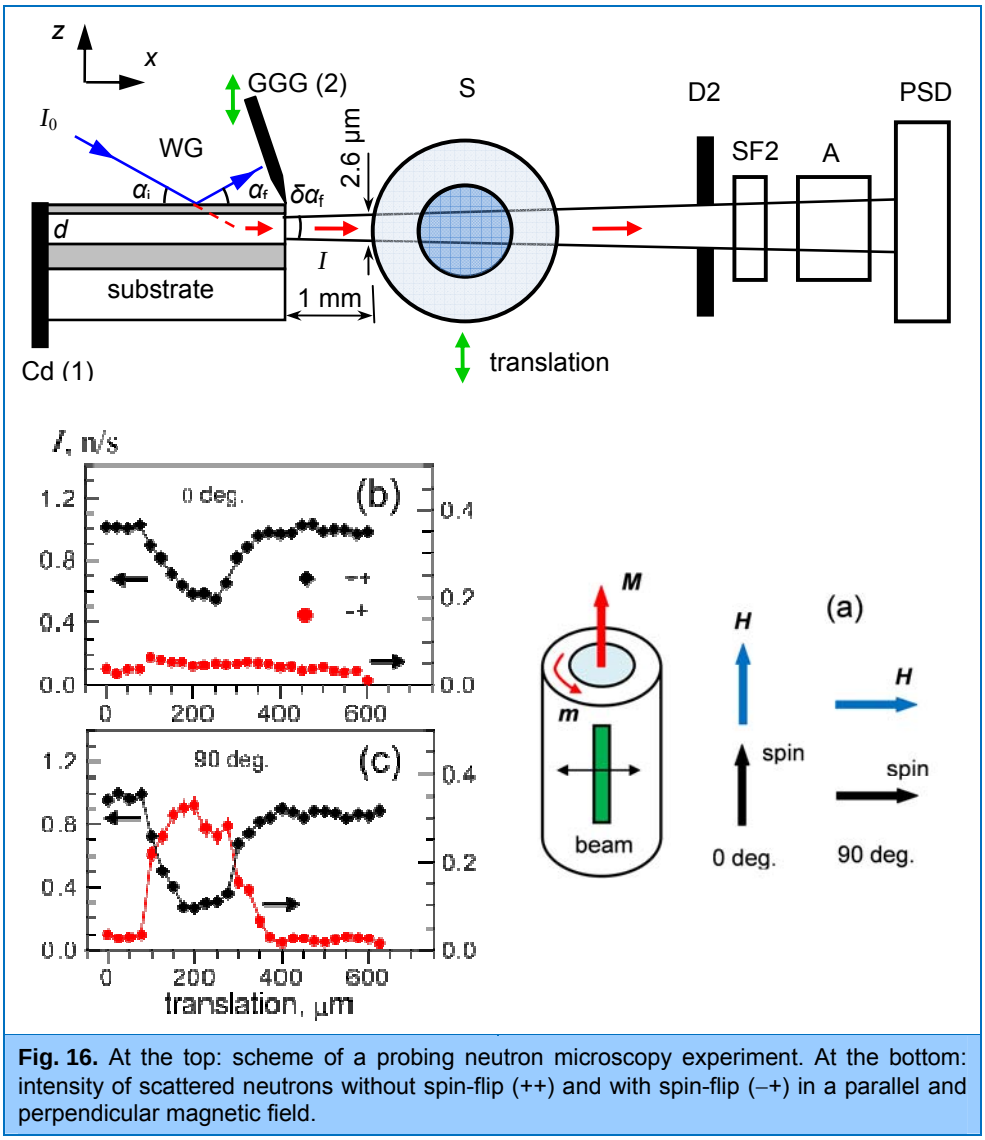

Fig. 16. At the top: scheme of a probing neutron microscopy experiment. At the bottom: intensity of scattered neutrons without spin-flip (++) and with spin-flip (–+) in a parallel and perpendicular magnetic field.

A theoretical problem of estimating the cross-section for thermal neutrons scattered by magnetic excitations in ferromagnetic layers several tens of nanometers thick has been considered. A method has been proposed to increase the cross-section by means of the resonant amplification of the neutron wave-function in a layered system with the optical potential of a special form. The scattering cross-section of neutrons with magnon absorption has been calculated taking into account the summation over all possible energy transfers depending on the scattering angle θ_S. It has been shown that at the sufficient neutron flux at the sample in the reflectometry experiment the observation of these processes is possible provided statistics are gathered during several days.

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NEUTRON NUCLEAR PHYSICS

In 2012, the instrument development activities on the preparation of experiments at the pulsed resonance neutron source IREN continued. The multi-detector system «ROMASHKA»-1 intended for neutron cross-section measurements and the AURA facility for (n,e)-scattering investigations were tested on the extracted neutron beams. The applied research activities using the neutron spectroscopy techniques were actively carried out.

The greater part of the fundamental investigations in the field of neutron nuclear physics was carried out on the neutron beams of nuclear research centers in Russia, Germany, Republic of Korea, China and France. The studies were conducted in the following traditional directions: investigations of time and space parity violation processes in neutron-nuclear interactions; studies of the fission process; experimental and theoretical investigations of electromagnetic properties of the neutron and of its beta-decay; gamma-spectroscopy of neutron-nuclear interactions, atomic nuclear structure, obtaining of new data for reactor applications and for nuclear astrophysics; experiments with ultracold neutrons; applied research.

I. Experimental and instrument development activities.

Development and improvement of multipurpose detector systems for neutron cross-section measurements at the IREN facility.

In the framework of cooperation between JINR and the Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences (BAS) the development and modernization of the NaI-crystal-based detector systems “Romashka-1” and “Romashka-2” are in progress. These systems are planned to be used in experiments on beams of the IREN facility.

“Romashka-1” is a movable, easy-adjustable, multidetector system for registering γ-rays, which consists of 24 scintillation cells (hexahedral NaI(Tl) crystals Amcrys + photomultiplier R1306 with a divider and high-voltage generator Hamamatsu) (**Fig. 17**).

Fig. 17. “Romashka-1” on channel №3 of the IREN facility.

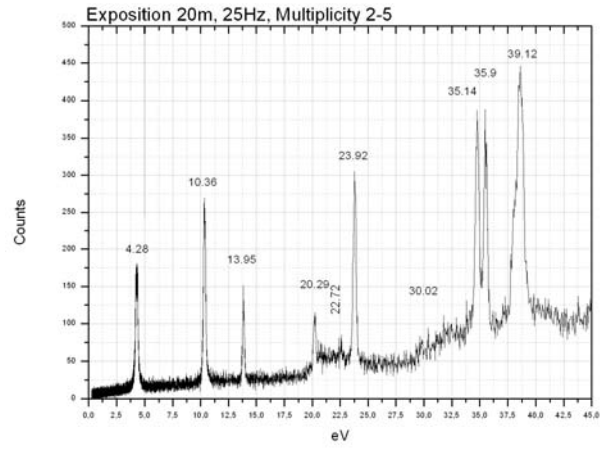

Рис. 18. **Зависимость выхода реакции Ta(n,γ) от энергии нейтронов, полученная в измерениях на пролетной базе 30 м.**

The energy and time calibration of the crystals has been made. The data acquisition system based on two 16-channel digitizers (AFI Electronics) combined in one 32-channel module has been produced. The system makes it possible to save on a hard disk all information registered by each of 24 crystals with the following analysis in the off-line mode. This allows one to register both time-of-flight and energy spectra, as well as to analyze overlappings, coincidence multiplicity, dead time and other parameters required for correct determination of neutron cross-sections and parameters of neutron resonances. At present, the system is being tested on beam №3 of the IREN facility (**Fig. 18**).

"Romashka-2" consists of two sets of 6 NaI(Tl) monocrystals of trapezoidal cross section (in the shape of a daisy) that are placed in metal cylindrical containers 30 cm in diameter. A photoelectronic multiplier PEM-110 is optically connected to the butt end of each crystal. The system is intended for the determination of the concentration of radioactive elements in the environment and for investigations of the radioactive neutron capture in experiments at the IREN facility by measuring gamma-ray multiplicity in the decay of radioactive nuclei.

Activities on the preparation of the (n,e) scattering experiment.

The installation of the AURA instrument on beam 2 of IREN has been completed. The software of the measuring module with a new 8-channel time encoder has been adjusted. During the tests of the AURA instrument on beam 2 of IREN, the spectra of the neutron beam passing through an Ag filter have been obtained using a ^{3}He-counter (diameter 30 mm, pressure 8 at). The beam was formed by a paraffin-boron collimator with an aperture 80 mm in diameter. The counter was placed vertically along the beam axis. The neutron beam area at the counter was ~ 22 cm^2. The neutron beam spectrum is given in **Fig. 19**.

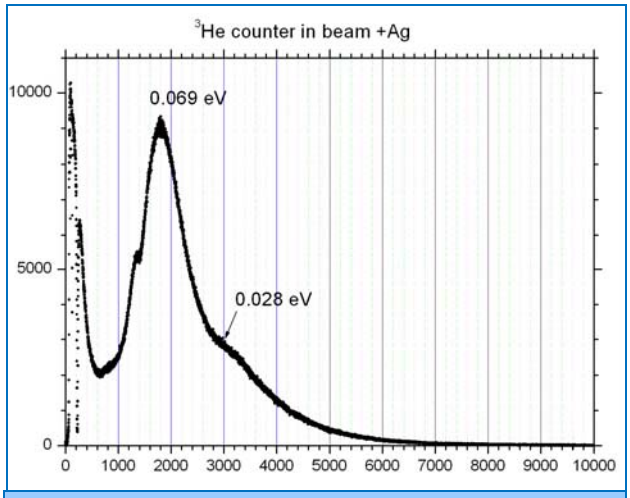

Fig. 19. Neutron spectrum on beam 2 of IREN, time channel width is 2 μs.

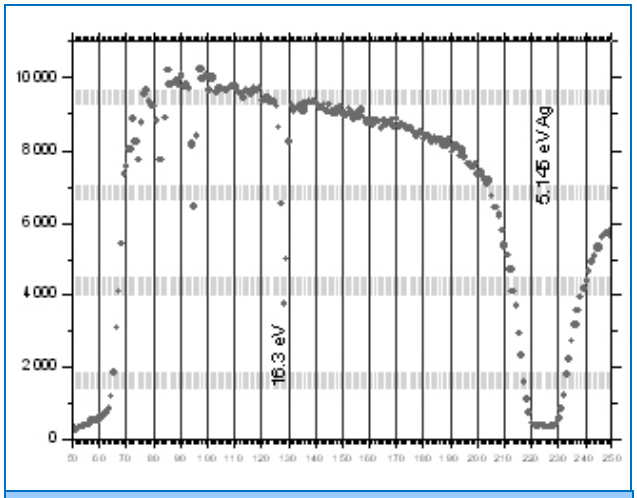

Fig. 20. Part of the neutron spectrum with resonance dips from Ag; time channel width is 2 μs.

Figure 20 shows a part of the spectrum with resonance dips from Ag, which was used for determining the flight path – distance between the IREN neutron source and the location of the helium counter.

The flight path was determined to be 13.75 m and the time between the start pulse and the burst – 7 μs. The estimated integrated neutron intensity of the IREN facility during its operation at a pulse repetition rate of 25 Hz was 1.2·10^{11} 1/s. The calculations aimed at refining the corrections for

the experiment on the determination of the n,e-scattering length from the angular anisotropy of slow neutrons scattered by argon (accuracy of corrections should be no worse than 10^{-4}) are in progress. The corrections for efficiency variation of detectors registering slow neutrons scattered forward or backward taking into account the thermal motion of argon atoms are calculated in the real geometry (at the LIT cluster). The required accuracy has been already obtained for 20 energy points in the neutron energy range from 0.0065 to 0.8 eV. The estimates of neutron scattering and transmission by cadmium covering the walls of collimators have been made in order to take into account the corresponding errors associated with the reflection of neutrons into detectors from “their own” collimators and from the collimators opposite to them.

Measurement of angular correlation between the spins of fission fragments and the direction of prompt fission neutron emission.

It is well-known that in the laboratory coordinate system prompt fission neutrons are emitted with a strong anisotropy, which is mainly determined by neutron focusing with respect to the direction of fission fragment emission. However, various attempts to analyze the experimental data on the anisotropy of neutron radiation have led to the conclusion that the anisotropy cannot be fully described by kinematic focusing of neutrons emitted by a moving fragment. Possible reasons which could explain the observed deviations in the experimental data are either the existence of the so-called «scission» neutrons or the presence of an anisotropic component in the neutron emission in the center-of-mass system of the fragments. The latter hypothesis is tested in the present study.

The first exploratory experiment using the CODIS detector system for registering fission fragments and a set of neutron detectors DEMON was performed in 2003 in Strasbourg to check out the possibility of running such kind of experiments. The analysis of this test measurement has shown that the anisotropy of neutron emission relative to the fragment spin can be effectively measured using triple neutron-neutron-fragment correlations. However, no conclusions about the presence of this effect have been drawn because of the poor statistics in this experiment. The main experiments with sufficient statistics were carried out in Strasbourg in 2009-2011. In 2012, the analysis of the experiments were performed. The data treatment was based on the determination of emission angles of fission fragments forming the fission axis and on the following projection of the directions of emission of two or more fission neutrons on the plane perpendicular to the fission axis. The theoretical calculations predict that there should be an angular anisotropy in this plane described by the formula W=1+a2*cos(2ϕ) (**see Fig. 21a**).

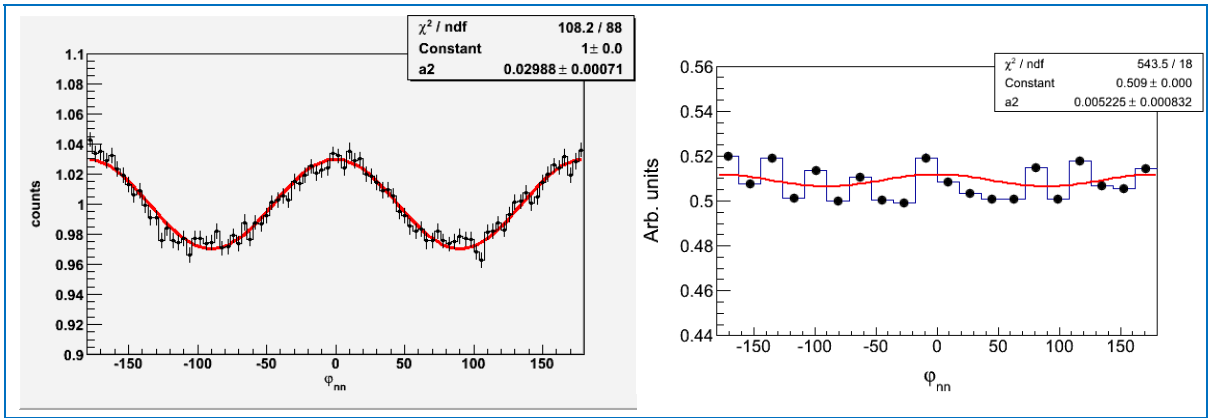

Fig. 21. a) calculated curve of the angular anisotropy of emission of two neutrons in a plane perpendicular to the fission axis; b) experimental curve demonstrating the sought-for anisotropy.

The experimental curve was obtained only for a part of the accumulated data, which is explained by the complexity of the technique used for the data treatment. The curve demonstrates the existence of some anisotropy of an analogous kind (see **Fig. 21b**) with the coefficient a2 characterizing the effect to be $(6\pm3)\times10^{-3}$, which is in qualitative agreement with the theoretical calculations.

Development of research methods in fission physics.

A new method of determination of prompt fission neutron energy that is applicable to single events with measured neutron time of flight has been developed and applied to study spontaneous fission of ^{252}Cf. The experimental data were obtained using a twin Frisch-grid ionization chamber and a liquid-scintillator-(NE213)-based fast neutron detector. The electronic equipment comprised the system of eight synchronized 12-bit waveform digitizers with 100 MHz sampling frequency. Prompt neutron multiplicity and energy distributions were determined with the help of the analysis of the kinematics of the fission process using the measured values of kinetic energies of fission fragments, the angle between the fission fragments and the neutron and the measured neutron time of flight along a given flight path. The idea of the determination of neutron energy distributions is based on the fact that the measured value of the neutron time of flight in a single fission event was considered as an average value of the known time-of-flight distribution. On this basis, a set of other realizations of the given value with the corresponding probabilities was determined and used further in the calculations of the required kinematic characteristics of the fission event. As a result of the averaging over the formed sampling, we obtained the data free of systematic errors associated with a non-linear dependence between the measured and calculated values. In the course of the analysis of experimental data a new method of separation of prompt neutrons and γ-quanta has been developed. The method is based on correlation functions whose parameters are used for separation of γ-quanta from prompt fission neutrons. The maximum of the correlation function (between a detector signal and exponent with a fall time constant close to the similar parameter of the detector signal) is realized when an exponential signal is delayed for a time equal to the time of flight of a neutron over a given flight path. The digital realization of the correlation algorithm made it possible to enhance the suppression factor for prompt fission γ-quanta by more than an order of magnitude. An important advantage of the method is that it has only one parameter for the event selection criterion.

Investigations of (n,p), (n,α) reactions.

The experimental and theoretical investigations of the (n,p), (n,α) reactions induced by fast neutrons continued. The experiments are carried out at the Van de Graaf accelerators EG-5 in FLNP JINR (Dubna, Russia) and EG-4.5 of the Institute of Heavy Ion Physics of Peking University (Beijing, China). Data on the neutron reactions with the emission of charged particles induced by fast neutrons are of much interest for studying the mechanisms of nuclear reactions and atomic nuclear structure. In addition, these data are of importance in choosing engineering materials and in performing calculations in the development of new facilities for nuclear power engineering.

The measurements of the parameters of the ^{57}Fe(n,α)^{54}Cr and ^{63}Cu(n,α)^{60}Co reactions at E_n ~ 4.0-6.5 MeV have been carried out; the data processing has started. The data treatment for the measurements of the ^{35}Cl(n,α)^{32}P and ^{40}Ca(n,α)^{37}Ar reactions conducted in a neutron energy range of 4.5-6.5 MeV has been completed.

Within the framework of the statistical model the systematic analysis of the (n,α) reaction cross-sections in an energy range from 6 to 20 MeV has been performed. The α-particle clustering factor has been determined from the comparison of experimental and theoretical cross-section values. It has been shown that this factor depends on the energy of neutrons.

Investigations of nuclear structure.

The analysis of the experimental data on the intensities of two-quantum cascades in ~40 nuclei in a mass range of 39<A<201 is in progress. We have tested several well-known and proposed phenomenological energy dependences of level density and radiative strength functions of cascade gamma transitions and found the most appropriate to provide the maximally accurate approximation of experimental data.

The development of radically new models of level density and γ-quantum emission widths is necessary first of all to assess the need for new experimental data and to determine parameters of the superfluid phase of nuclear matter, the threshold for Cooper pair breakup with an accuracy of no worse than several tens of percent in the first place. This would make it possible to thoroughly study the process of changing superfluid properties of such specific object as a heated atomic nucleus.

The information available now is insufficient for a full-scale solution of this problem. But the development of further experimental investigations in this direction presents no major difficulties and may well be realized on the experimental basis used in the low-energy physics.

Investigations of a possibility to search for space parity violation effects in neutron diffraction at IBR-2.

A prototype of the instrument for experimental determination of spatial parity violation in neutron diffraction has been tested at a 30-m flight path of beam 1 of the IBR-2 reactor. Testing of the data acquisition and accumulation system has been performed. The parameters of the neutron beam have been determined. The tests have given some indication of a pendulum-like behavior of the reflected neutron beam in the diffraction experiment, which is evidence of a high quality of a potassium bromide single crystal and the neutron beam. On the basis of the obtained results an estimate of time necessary for detecting the spatial parity violation effect in diffraction with a statistical accuracy of $3 \cdot 10^{-4}$ has been made.

Investigations of the interaction of a relativistic deuteron beam with a massive multiplying target of natural uranium.

In March and December of 2012 in the framework of the research project «Energy and Transmutation of Radioactive Wastes» («E&T RAW») a massive (500 kg) natural uranium (∅ 30 × 65 cm) target assembly QUINTA with a 10-cm lead blanket was irradiated at JINR NUCLOTRON by accelerated deuterons with energies from 1 to 8 GeV. The characteristics of energy spectra of prompt neutrons and time spectra of fission delayed neutrons (DN) between accelerator pulses have been obtained using the detectors DEMON and IZOMER-M. The optimization of the detector shielding has been successfully performed to reduce the background from various sources. The treatment of the results from the measurements conducted in December, 2012 is in progress. The dependence of the incident deuteron energy, E_d, on the relative total yield of DN, Y_{DN}, measured in March, 2012, is in agreement (up to $E_d = 8$ GeV) with the corresponding dependence of the total number of fission events, N_f, obtained by the integration of the spatial distributions of natural uranium fission rates over the QUINTA volume. The above-mentioned distributions were measured using solid-state track detectors and independently by the activation method. The values of Y_{DN} and N_f (normalized to one incident deuteron and one GeV) were found to be constant within the limits of experimental errors (10-15%) for the whole deuteron energy range under study. The group analysis of

DN time spectra indicates a growth of the average energy of the neutrons initiating fission of target nuclei with an increase in the energy of incident deuterons. The group analysis of DN time spectra indicates a growth in the average energy of the neutrons initiating fission of target nuclei from 15 to ~ 45 MeV with an increase in energy of the incident deuterons from 1 to 8 GeV. This result will be refined by further analysis of the data from the measurements of December 2012 conducted with minimum incident deuteron pulse duration.

Development of a facility to study the possibility of cold neutron accumulation at the end of a neutron beam line.

Earlier we have proposed a project of a new high-intensity UCN source capable of producing ~10^8 UCN/s with the UCN density in the storage volume reaching 10^5 n/cm^3, which is 3 orders of magnitude higher than that of the available 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. This layout of the source makes it possible to position it on extracted thermal neutron beams, which reduces many fold the heat load on the source and, accordingly, its cost. This allows the range of application of UCN to be extended many times and to use them not only for scientific research but for applied and educational purposes as well.

In the framework of the study of the possibility to create a new helium UCN source, work has been conducted to develop and construct an experimental facility for carrying out test measurements. Test measurements should show what gain in cold neutron flux may be expected in a cavity at the end of a neutron guide surrounded by a solid methane moderator/reflector. The main parts of the facility have been developed and manufactured:

- cryostat for creating a methane cavity and cooling methane down to the helium temperature, which includes the system for feeding and evaporating methane from the cryostat (**Fig. 22**);
- neutron flux chopper (**Fig. 23**).

Fig. 22. Cryostat (exploded view).

Fig. 23. Neutron flux chopper.

The measurements are scheduled for 2013. They can be performed on both the IBR-2 reactor (beam 2) and on the IR-8 reactor (KI, Moscow). In the first case the spectrum of neutrons leaving the cavity can be obtained for different energies ('monolines') of incident neutrons. In the latter case the time-of-flight method is used to get spectra at the inlet and outlet of the cavity. For these measurements a chopper has been designed and constructed.

Cooperation in the framework of the GRANIT project in ILL (France).

The GRANIT project aimed at designing and building a second-generation gravitational neutron spectrometer with ultra-high energy resolution GRANIT (**GRA**vitational **N**eutron **I**nduced **T**ransitions). This spectrometer will make it possible to observe resonance transitions between neutron quantum states in the Earth's gravitational field. It is planned for the first time to directly measure the energy of quantum states. The storage time of UCN in quantum states for this spectrometer is expected to reach values of the order of a second.

The GRANIT spectrometer will become a unique tool for carrying out a wide range of investigations in the field of physics of elementary particles and fundamental interactions, quantum mechanics, surface physics and applied research. In the framework of the GRANIT collaboration the FLNP specialists took part in the activities on the adjustment of detectors for the spectrometer and in the commissioning and adjustment of its UCN source.

In 2012 the collaboration was engaged in the commissioning of various parts of the GRANIT spectrometer. The first important step is to ensure reliable operation of the UCN source of the GRANIT facility and its effective interfacing with the spectrometer. Work on the optimization and adjustment of operation of a helium source was carried out.

Experiment on the direct measurement of the n-n scattering.

In cooperation with Gettysburg College (Gettysburg, Pennsylvania, USA) the final stage of the analysis of data from the first experiment on the direct measurement of the n-n scattering cross section at the YAGUAR pulsed reactor (Snezhinsk, Russia) aimed at studying the charge symmetry of nuclear forces has been performed. It has been shown that the observed abnormally strong effect of an increase in the scattering intensity with increasing JAGUAR pulse energy can be explained by radiation desorption of hydrogen from the surface of the aluminum channel of the facility induced by a powerful dose of gamma radiation during the reactor pulse. The obtained value of the desorption coefficient, $\eta(\gamma) = 0.02$, is in agreement with the data from other experiments. The performed analysis of literature on metal surface treatment methods suggests that $\eta(\gamma)$ can be reduced down to the value that would be acceptable for n-n scattering cross-section measurements.

Investigation of time variation of the fine structure constant.

In collaboration with the North Carolina State University (NCSU, Raleigh, North Carolina, USA) research work has been conducted on the application of isotope data from the Oklo natural nuclear reactor zones for studying time variation of the fine structure constant α. The results for α depend on the poorly-known temperature of active zones during reactor operation (10^9 years ago). It has been shown that the applied Lutetium thermometry based on a strong temperature dependence of the burn-up cross section of ^{176}Lu and, respectively, on the change in the concentration of ^{176}Lu and ^{175}Lu isotopes, suffers from insufficient accuracy of neutron capture cross sections of lutetium-175 forming lutetium-176 in the ground and isomeric states. The modeling of gamma-ray fluxes in the Oklo reactor has been performed leading to the result that they are insufficient to influence the burn-up of ^{176}Lu by means of gamma quanta as it occurs in stars producing powerful bursts of gamma radiation.

1. SCIENTIFIC RESEARCH

II. Theoretical investigations.

Investigations of neutron fluxes generated by linear electron accelerator-based neutron sources.

In 2012, the investigations of the production of neutrons and radioisotopes on E-linac-driven neutron sources continued. The basic physical characteristics of the production of neutrons from high-atomic-number materials irradiated by electron beams have been studied. The bremsstrahlung of incident electrons inducing photonuclear reactions has been considered. The experimental data on photonuclear reactions are used to describe the generation of neutrons caused by gamma radiation absorption by nuclei. The available theoretical approaches are applied to study the energy distribution of photo-neutrons. The neutrons statistically distributed over the energy are considered as the main part of all produced neutrons; the share of direct neutrons is taken into account as well. The neutron spectrum, mean neutron energy and total neutron yield are calculated in relation to the energy and current of the electron beam, as well as to the characteristics of irradiated samples. No numerical Monte-Carlo simulations were applied in the study. The results of the calculations are in satisfactory agreement with those of the experimental measurements.

On the possibility to increase the IREN neutron flux.

The neutron yields from tungsten and uranium targets of different configurations have been calculated using the FLUKA program. The results for a tungsten target have made it possible to compare them with the experimental data obtained on the IBR-30 booster using the EKON program. The possibility to increase the neutron yield by a factor of 2-4 without using the second section of the accelerator has been demonstrated provided a bremsstrahlung target of tungsten or plutonium is surrounded by two layers of 18 plutonium rods.

Wave optics research.

A new effective analytical approach to describe electromagnetic waves in anisotropic media has been proposed. An analytical description of the refraction and reflection at an interface between isotropic and anisotropic media has been demonstrated. Beam splitting upon reflection and refraction as well as surface wave generation have been studied. D'yakonov surface waves and methods of their observation are under discussion. Analytical and numerical calculations of the reflection and transmission of plane-parallel uniaxial plates have been demonstrated.

III. Methodical and applied research.

Investigations of properties of semiconductor detectors and scintillators.

In 2012, alpha and gamma detectors were manufactured from fast inorganic scintillators LFS based on micropixel avalanche photodiodes with high pixel density (15000 pixel/mm^2).

The registration of alpha particles has been investigated using fast inorganic scintillators LFS-3 ($2 \times 2 \times 10$ mm) based on micropixel avalanche photodiodes at room temperature. The energy resolution for 5.5 MeV alpha particles from radioactive ^{241}Am source was 9%. The amplitude spectrum is given in **Fig. 24** (at the left). The gamma-radiation was registered using scintillator LFS-8 ($3 \times 3 \times 0.5$ mm^3) based on micropixel avalanche photodiodes in a wide energy range (59.6-662 keV) at room temperature. The energy resolution is 11.5% for 662 keV gamma quanta from ^{137}Cs radioactive source. The amplitude spectrum is given in **Fig. 24** (at the right).

The results have demonstrated that these detectors can be used in positron emission scanners for controlling radioactive contamination in various media and public safety (Associated Particle Imaging for the detection of explosives and drugs).

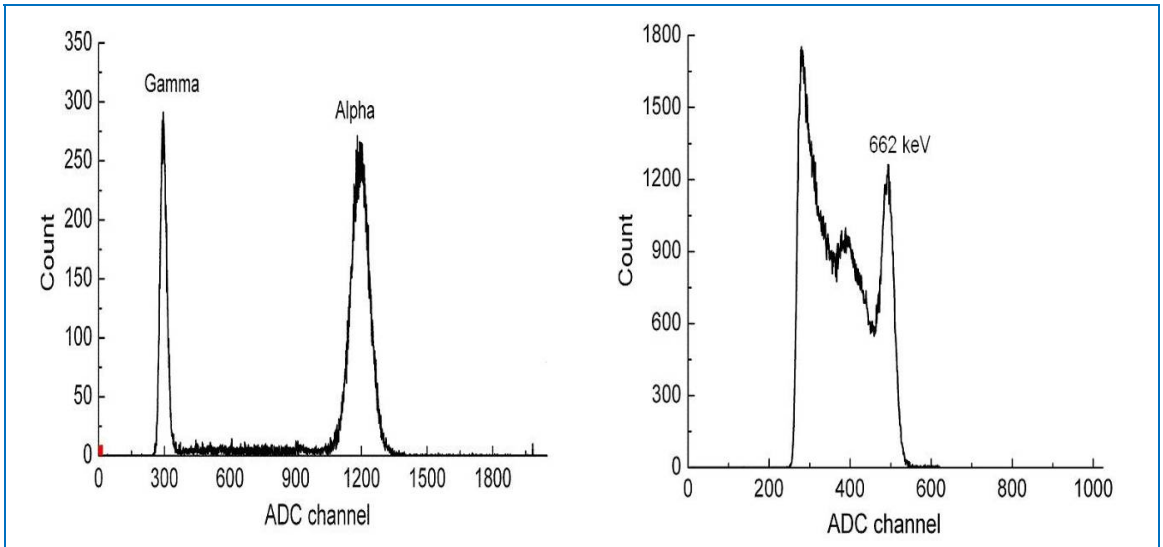

Fig. 24. Amplitude spectra of ^{241}Am alpha- (left) and ^{137}Cs gamma- (right) sources.

In addition, to detect fission fragments and light charged particles emitted in fission, a stand consisting of a thin silicon ΔE-detector about 12 μm thick and 600-μm silicon detector Timepix (E) with full absorption of the particle energy has been constructed (**Fig. 25**).

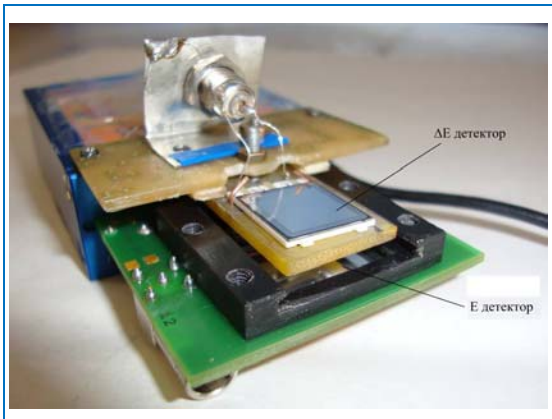

Fig. 25. Half-part of the stand.

This stand is intended for studying the possibility to apply the E-ΔE method in combination with a high-resolution position-sensitive detector Timepix for investigating the fission process. This method allows one to identify light charged particles by their charge and mass, as well as to separate them from background events related to the scattering of the fragments by the substrate. One of the most complicated problems in the design of the given stand was the organization of the coincidence scheme for simultaneous registration of ΔE and E signals. The detector E (Timepix) has its own readout system, which makes it possible to register the time of each event but does not allow the integration with external electronic modules. A signal from the ΔE detector is read out by a desk-top digitizer CAEN (12 bit, 250 MHz), which can also register the arrival time of events. At this stage the coincidences are organized by means of the analysis of the time labels of two event types saved on the computer in the off-line mode. The time resolution of this method is not enough for the efficient organization of coincidences. The development of a more efficient coincidence scheme is in progress.

1. SCIENTIFIC RESEARCH

Development of analytical techniques using neutron spectrometry.

At the IREN pulsed resonance neutron source the activities have been carried out on the development and application of the methods of elemental and isotope analysis using neutron spectrometry. The analysis of the boron content in ceramics of nanocomposite materials prepared in the Belorussian State University (Minsk) has been performed by measuring neutron transmission. These new multifunctional materials combine efficient neutron shielding properties with high heat resistance and mechanical strength.

In cooperation with the Sternberg Astronomical Institute, MSU, the investigations of the samples (presumably cosmic dust) from an Altai mountain glacier by means of the resonance spectrometry method continued.

At the request of the Central Geological Laboratory of the Mongolian Ministry of Natural Resources and Energy the analysis of the content of rare-earth elements in ore samples has been made.

Nuclear analytical techniques using charged particle beams.

Non-destructive nuclear analytical techniques based on low-energy charged particle beams are widely used for the analysis of elemental depth profiles in various kinds of technical and research problems. Their analytical possibilities have been investigated using specially selected samples. The method of Rutherford back-scattering of helium ions allows one to determine depth profiles of almost all elements with rather high depth resolution.

As one can see in **Table 1**, the treatment of one spectrum of the scattered helium ions gave the information about depth profiles of 7 elements from carbon to bismuth with atomic concentrations within an interval of 1-100 at.%. Two layers (140-nm-thick titanium oxide and 100-nm-thick cobalt on a silicon substrate) are observed in the sample. An intermediate 20-nm-thick layer consisting of all three elements is observed in-between.

Table 1.

Layer thickness 10^{15} at./cm^2	Depth, nm	Element concentration, at.%						
		C	O	Si	Ti	Co	Br	Bi
50	5,5	8,0				89,3	1,0	1,7
100	16,6	5,0				94	1,0	
760	101,2					100		
100	117,5		40		30	30		
650	255,3		70		30			
5000	10301,5			100				

A thin layer on the sample surface contains some amount of impurities including carbon (9×10^{15} at./cm^2), bromine (1.5×10^{15} at./cm^2) and bismuth (8.5×10^{14} at./cm^2). The analysis of this layer demonstrates both the advantages and disadvantages of the Rutherford back-scattering technique.

The amount of bismuth atoms observed in the experiment shows that the method is sensitive to the amount of atoms of a heavy element, which is below their amount in a monolayer. On the other hand, a rather significant amount (~10^{16} at./cm^2) of carbon atoms does not provide a noticeable yield of scattered helium ions.

The analytical possibilities of the Rutherford back-scattering technique can be improved by increasing the initial energy of helium ions. Thus, for example, the sensitivity to oxygen atoms can be enhanced by increasing the initial energy of helium ions up to above 3.045 MeV. The energy dependence of the scattering cross section shows a narrow resonance with the maximum cross section higher than the Rutherford scattering by a factor of 17. For the electrostatic generator EG-5 this energy is quite achievable. Measurements at several energies, which exceed the resonance one make it possible to investigate in details the oxygen depth profile in the near-surface layer of samples.

An oxygen depth profile of a TiO\Pt\Si sample has been studied by employing a resonance in the elastic scattering of helium ions with the energy of 3.045 MeV from oxygen atoms. Three 10-30 nm-thick layers with an oxygen content of 50-60-67 at. % and one layer with an oxygen concentration of 10 at. % were detected by scanning over the energy range near the resonance. The oxygen content was measured with an accuracy of 2 at. %.

A sequential analysis of samples using a proton and helium ion beam makes it possible to improve the precision in the determination of concentrations for light elements and to increase the covered depth. A sample composed of two layers (Ag and $LiNbO_3$ on silicon substrate) was used to demonstrate these possibilities. The mentioned analysis gave the information not only about the elemental composition of the two layers with the total thickness of 2.5 μm but also about the element distribution over the sample depth up to 20 μm. The treatment of two spectra showed the presence of a noticeable concentration of silicon in both Ag and $LiNbO_3$ layers. An in-between 100-nm-thick layer is of intermediate composition with Si inclusions.

The effect of irradiation with fast neutrons at a dose rate of $1.4 \cdot 10^{14}$ n/cm^2 on the properties of SiC and SiC(N) films has been studied using nuclear analytical RBS and ERD techniques. A 100-fold change in the conductivity of layers was found while the element content and layer thickness in the samples experienced no noticeable changes.

Deuterium concentration depth profiles in the samples intended for investigations of the astrophysical S-factor and the screened electron potential in the $d(d, n)^3$He reaction on targets of deuterides of titanium, tantalum and zirconium have been studied using nuclear analytical methods.

Analytical investigations at the IBR-2 reactor.

In the reported period the software package has been developed for complex automation of the neutron activation analysis on the IBR-2 reactor, which includes a database, database management programs, programs for registering the weight of samples, for obtaining spectra and for calculating the concentration of elements. While running the software, the programs underwent development and upgrade. Various nonstandard cases arising in the process of treating gamma-spectra by the Genie 2000 (Canberra) software were studied. The development of the mechanical part of a sample-changing device on the detectors started and the modernization of the pneumatic transport facility continued.

The measurements of thermal and resonance neutron flux densities have been carried out in the irradiation channels of the REGATA pneumatic transport facility and on some other neutron beams in new experimental conditions after the completion of the IBR-2 modernization.

1. SCIENTIFIC RESEARCH

In 2012, in the framework of the international program “Heavy metal atmospheric deposition in Europe – estimations based on moss analysis” the data analysis was completed and a number of papers, which reflect the contribution of the NAA Sector to the European Atlas of Heavy Metal Atmospheric Deposition for Macedonia, Bulgaria, Croatia and Serbia were published. The data on some regions of the Russian Federation (Tikhvin; Kostroma, Ivanova, Moscow) were submitted to the European Atlas as well.

In 2012, the mass multielement analysis of soils and bottom sediments from various regions of the Nile delta and its near-shore area was performed in the framework of the joint JINR-Egypt project «Assessment of the environmental situation in the delta of the Nile River using nuclear and related analytical techniques». The soil samples from the Siwa Oasis in the Sahara desert have been studied as well. The obtained results are of interest to the geologists and ecologists of Egypt from the viewpoint of new information on the elements whose concentrations have been determined for the first time.

Within the framework of the Cooperation Agreement with the Institute of Biology of the Southern Seas (Sevastopol, Ukraine) the analysis of macroalgae-biomonitor samples in the coastal zone of the Black Sea from the Tarkhankut peninsula to the Kerch Peninsula has been performed to assess the state of the coastal ecosystem of the Crimea.

For the first time the results of the multielement analysis of moss-biomonitors and lichens from the area of Stellenbosch and Cape Town (South Africa) have been obtained for the evaluation of atmospheric pollution in this region. To assess the state of water ecosystem of this region, the analysis of samples of mollusks and oysters from two gulfs of the Indian Ocean has been made. The preliminary results have demonstrated the efficiency of the chosen objects for the development of the biomonitoring system under conditions of a growing port in Cape Town.

A review on the results of more than 20 years of cooperation between the Sector of Neutron Activation Analysis and Applied Research (SNAA&AR) and the Analytical Center of the Geological Institute RAS in the field of research of food quality by nuclear and related analytical techniques has been prepared and published. Similar studies have started in cooperation with I.Javakhishvili Tbilisi State University (Tbilisi, Georgia).

In cooperation with the specialists from the University of Bucharest, Romania, the samples of poorly studied loess deposits (up to 20 m deep) in the southeast Dobruja have been analyzed to assess the changes in the elemental composition of this kind of soils for the last 1.2 million years. The results of INAA performed on the IBR-2 reactor in 2012 along with the data of electron paramagnetic resonance (EPR), x-ray phase analysis (XPA), scanning electron microscopy (SEM), radiometric and thermoluminescence analysis have allowed us to make a number of conclusions reflected in *Duliu et al. 2012a*. It has been found that the samples from different time periods have similar elemental composition, which suggests that the wind-blown dust originated from the same most likely source – the Măcin Mountains located in the north of the Dobruja Massif.

The results of the study of bottom sediments and rocks of two semiclosed ecosystems of the glacial lake Balea (Fagaras mountains) and the crater lake St. Ana (Harghita mountains) have been presented at the International Seminar ISINN-20 (Duliu et al., 2012b).

In 2012 on the REGATA facility the neutron activation analysis was conducted to search for cosmic dust in two peat columns (natural slabs) collected in Western Siberia. These studies along with the results of scanning electron microscopy suggest the possible presence of particles of

extraterrestrial origin. The material collected using magnetic traps from a melting high-mountain glacier in Altai with traces of the substance of extraterrestrial origin has been analyzed as well.

In the framework of the RFBR project in cooperation with the Moscow State University (D.N.Anuchin Research Institute and Museum of Anthropology) the NAA of hair samples of a representative group of children from the Ongudaysky District of the Altai Republic as well as soil samples from the places of their residence has been conducted to find possible correlations between their elemental composition and to reveal the endemic features of the effect of the geochemical environment on the human body.

In 2012, in collaboration with the E.Andronikashvili Institute of Physics, I.Javakhishvili Tbilisi State University and I.Chavchavadze State University (Tbilisi, Georgia) the studies continued on the development of methods for synthesis of silver and gold nanoparticles by certain new kinds of bacteria – extremophilic bacteria and blue-green algae *Spirulina platensis*. In combination with a number of optic and analytical methods the neutron activation analysis was used to develop the technology for the synthesis of nanoparticles by the bacteria under study. On the IBR-2 reactor using the NAA method the elemental composition of the microbiological samples containing gold and silver nanoparticles has been investigated to assess the possibility of application of the obtained nanomaterials for medical and pharmaceutical purposes.

The research work to study the changes in the characteristics of nitrides in the Li-N system at different pressures of synthesis has been carried out in cooperation with the Scientific and Practical Materials Research Center of the National Academy of Sciences of Belarus and the specialists in x-ray diffraction and scanning electron microscopy from the University of Galați, Romania. It has been shown that an increase in the nitrogen pressure during the formation of nitrides results in the synthesis of structures with a higher nitrogen content in the bulk and a smaller crystallite size.

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

Development of the complex of neutron moderators.

In the first quarter of 2012 in the framework of the project aimed at the development of a complex of cold moderators the experiments on the simulation of loading mesitylene beads into a moderator chamber were carried out at various operating modes at a full-scale test stand. The automated system of acquisition and registration of data from sensors of the cold moderator monitoring system was modernized. In addition, the main technological systems and units of the cold moderator were upgraded.

The cold moderator operating mode, which determines the key maximum permissible physical parameters during its operation has been developed on the basis of the obtained results, and the start-up of the first cold aromatic hydrocarbon-based moderator CM-202 (**Fig. 26**) has been carried out on the modernized IBR-2M reactor.

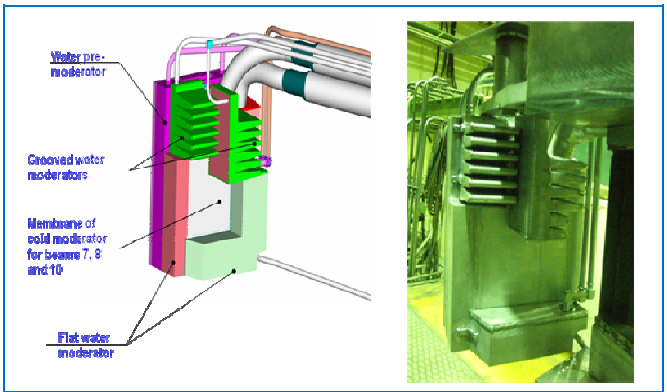

Fig. 26. A photo of the complex of neutron moderators CM-202 for beams № 7, 8, 10 and 11.

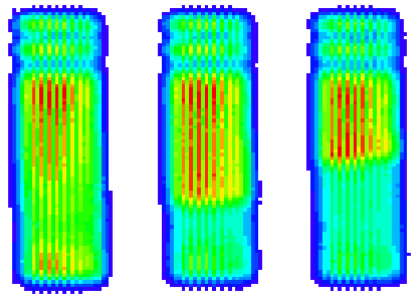

Fig. 27. Neutron images of a part of the complex of moderators CM-202 with a cryogenic moderator located in the bottom half at different bead filling levels: empty chamber (at the left), 2/3-filled (at the centre) and full chamber (at the right).

The key physical parameters of the CM-202 cold moderator while being loaded with frozen mesitylene beads were: 1) helium mass flow in the transport pipeline – 1.5 g/s, temperature – no less than 80 K; 2) maximum bead feed rate from the charging device to the transport pipeline did not exceed 8 pieces/s. The movement of beads through the pipeline was controlled by differential pressure sensors. A "pinhole-camera" method was used for monitoring the charging process by taking 2D neutron images of the moderator chamber (**Fig. 27**) by a two-coordinate PSD.

Upon filling the moderator chamber the reactor was brought to a power of 2 MW. The average temperature in the moderator chamber was 30 K. The measurements of neutron spectra have demonstrated that the long-wavelength neutron flux from the surface of the cold moderator has increased by a factor of up to 13 as compared to that from the surface of a water moderator (**Fig. 28**). Work is underway to determine the maximum operating time with one loading of the cold moderator.

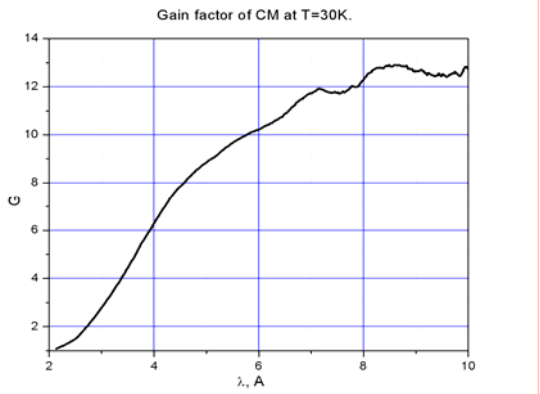

Fig. 28. The measured gain in the cold neutron flux when using the cold moderator.

Calculations and simulation of spectrometers.

In 2012, special VITESS modules that allow the simulation of the neutron spin behavior in arbitrary magnetic fields continued to be improved. Time dependences of magnetic fields for simulating spin-echo spectrometers with time-dependent (pulsed) magnetic fields (stationary fields are calculated by an external program) were added to the modules. A large number of simulations of parts of a new spin-echo spectrometer with rotating magnetic fields for the REFLEX beam of the IBR-2M reactor (in cooperation with V.Bodnarchuk and A.Rubtsov, FLNP NICM Department) were done in real magnetic fields calculated by the external program. A comparison with the first experiments (one spin-echo spectrometer arm) revealed good agreement between the experimental data and the data calculated using new VITESS modules. Further recommendations on engineering of units of a spin-echo spectrometer with rotating magnetic fields were developed on the basis of the performed simulations and calculations.

The first stage of a novel project – the immersion of VITESS modules in a magnetic field – has been fulfilled. A special library of VITESS subroutines that makes it possible to realize this task has been developed. At present, the module “polarizing mirror in a magnetic field” (**Fig. 29**) has been developed and tested, and is planned to be included into the next VITESS version. All the above-mentioned activities were carried out in collaboration with Prof. A.Ioffe (JCNS-Munich).

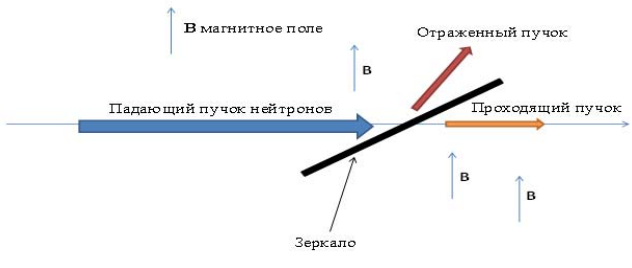

Fig. 29. Polarizing mirror in a magnetic field.

Four new VITESS modules have been developed for simulation and calculation of neutron time focusing for time-of-flight spectrometers on pulsed neutron sources. One of the modules makes it possible to calculate the time focusing surface for a given configuration of a time-of-flight spectrometer

in a rectangular or polar coordinate system. Using other modules one can calculate approximating surfaces for the time focusing surface. An option is available to approximate by a plane/planes, cylinder/cylinders and sphere/spheres. These modules are in the testing stage. An example of building an ideal time-focusing surface is given in **Fig. 30**. In 2012, a module from the MCSTAS program for simulating a gas PSD was introduced and adapted for the VITESS package.

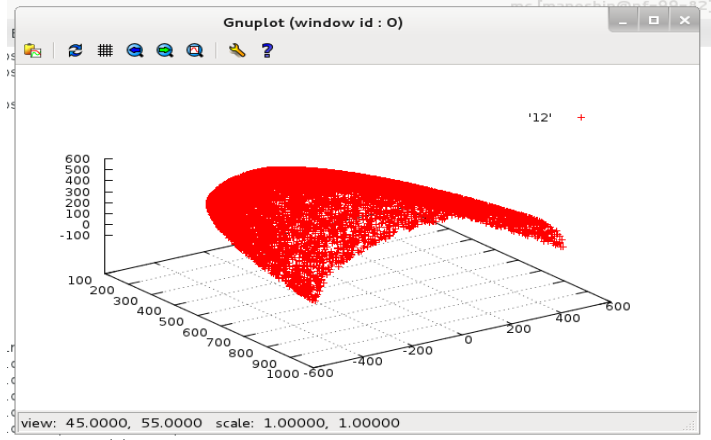

Fig. 30. An example of building an ideal time-focusing surface for a simple ideal instrument with a Bragg scatterer for one fixed interplanar spacing.

Test beam and new Fourier diffractometer.

The work continued on the construction of a new high-resolution Fourier diffractometer on the basis of the units of the FSS spectrometer (GKSS, Geesthacht, Germany) on beam 13 of the IBR-2M reactor. In connection with the decision to create a new NIS spectrometer on beam 14 a draft layout of the instruments was corrected and a new arrangement of biological shielding of beams 13 and 14 was developed, drawings were made, shield elements were manufactured and assembled. Unfortunately, the problems connected with the transportation of the FSS equipment from St. Petersburg to Dubna have not been solved yet.

Cryogenics.

The work to design and construct a helium-3 purification facility (**Fig. 31**) has been completed. The facility is intended for purification and preparation of He^3 for re-use in neutron detectors. A gas He^3-containing mixture from the detectors is stored in the tanks of the facility, and then helium is separated from other gases using cryogenic and pumping-over systems. Next by means of a special cryogenic pump He^3 is compressed to a pressure of 80 bar, which is sufficient to fill new detectors. The facility has undergone pre-commissioning tests and has been put into operation.

Fig. 31. Helium-3 purification facility.

A feasibility study has been conducted to develop a pulse tube cold head under laboratory conditions. As a result a single-stage cold head connected to a Leybold RW4000 compressor has been made. The lowest temperature that can be reached at the cold head is 48 K. The cold head is used at the Department cryogenic stand.

The development of a horizontal cryostat for cooling high pressure cells with sapphire anvils (DN-6 diffractometer) has started.

Reconstruction of a neutron guide and modernization of the automation system of spectrometers on beam 7 of the IBR-2M reactor.

In 2012 on beam 7 of the IBR-2M reactor the construction and installation of an 80-m neutron guide for the NERA-PR spectrometer were completed **(Fig. 32**). The adjustment of optical elements was performed.

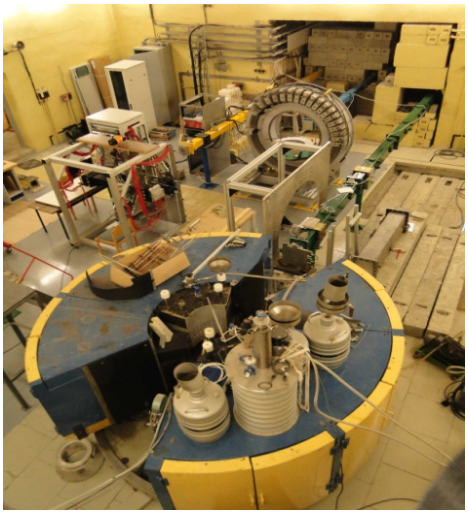

Fig. 32. Beam 7 in the IBR-2M experimental hall after reconstruction (EPSILON – yellow, SKAT – blue and NERA-PR – green; the detector system of NERA-PR is in the foreground).

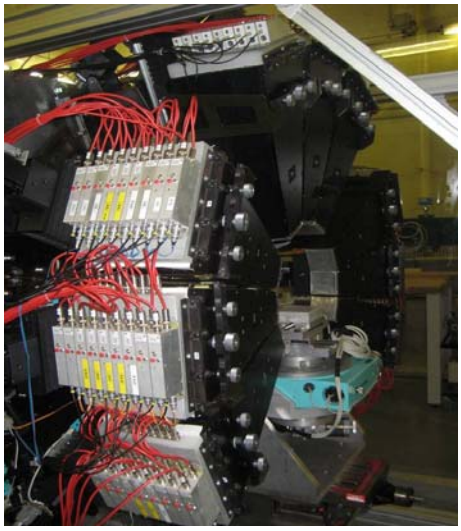

Fig. 33. Photo of detector collimators and goniometer (Huber) at the EPSILON spectrometer.

An adjustable diaphragm for neutron beam focusing has been manufactured. The diaphragm is controlled by stepper motors connected to PC via CAN/USB controller and converter. The modernization of a multi-counter detector for NERA-PR has been carried out as well. Amplitude spectra and counting characteristics of helium counters of the detector (36 rectangular counters, 24 SNM-17 and 4 monitor counters) have been obtained. On the basis of the characteristics measurement results the counters were grouped according to the gas amplification and working voltage, and the discriminating thresholds were determined for each counter.

A control system of detector collimators and goniometer (Huber) has been put into operation at the EPSILON spectrometer (**Fig. 33**). For the first time ball screws (BS) and stepper motors with controlled electromagnetic brakes were used in actuators of the FLNP spectrometers. Ball screws consist of a screw shaft, ball nut and a ball return mechanism and are usually used in situations in which high precision is necessary. They translate rotational motion to linear motion or vice versa with high accuracy and efficiency. A hardware-software system has been developed, which makes it possible to control the brakes using stepper motor controllers already employed at the IBR-2M spectrometers.

The total number of control channels for driving the actuators of the spectrometers on beam 7 has reached 72 (EPSILON – 32, SKAT – 4 and NERA-PR – 36 channels).The automation system of these instruments on beam 7 also monitors the status of choppers, shutters, and the readings of vacuum sensors and other elements of the spectrometers. At present, at the EPSILON and NERA-PR

spectrometers new DAQ systems for point detectors have been installed; the adjustment work is nearing completion and test measurements are being made.

Sets of equipment for automation systems and data acquisition systems have been adjusted at a test-stand and are ready to be installed at the SKAT, GRAINS and DN-2 (RTD) spectrometers. Two polarizers and two diaphragms have been assembled and tested for GRAINS, and drawings of a beam collimation system for DN-2 have been developed. Among the actuators of the RTD spectrometer are:

- platform with a detector with a rotation angle varying from 0° to 180°. (1 control channel and 1 angular position sensor);
- goniometer Huber (1 control channel);
- goniometer GKS-100 (10 control channels including spare channels for connecting a neutron beam diaphragm and point detector collimators).

Detectors.

The project of creation of a gas ring-shaped multi-section detector for the DN-6 diffractometer has been completed. In 2012, the following main activities were conducted within the framework of the project:

– mechanical units for fastening and adjustment of the detector were developed and manufactured, and its background shield was mounted;

– 96-channel data acquisition and accumulation electronics were checked out and debugged;

– programs for testing the detector were written, data accumulation software was upgraded and a new program interface was developed;

– test trials of the detector were conducted on beam 6b with working gas mixtures at different pressures of He^3.

In November the measurements were conducted with the ring-shaped detector with background shielding with a working gas mixture (4.0 bar ^3He + 500 mbar of Ar + 30 mbar of CO_2). **Figure 34** illustrates the spectra of the samples under study. At present, the detector has been handed over to the physicists for further testing and working measurements.

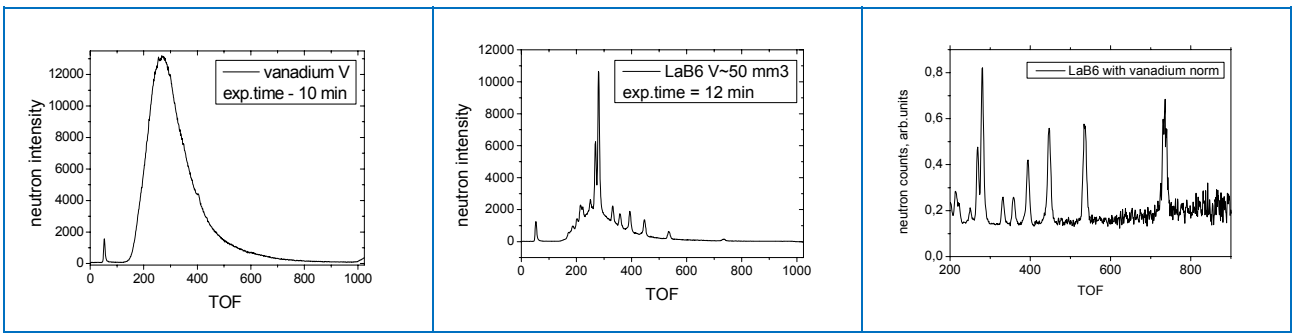

Fig. 34. Spectra of samples under study a) V, b) LaB_6, c) LaB_6 normalized to vanadium.

Inoperative position-sensitive detectors on HRFD and REFLEX have been replaced. Two detector systems that comprise 2D PSD, detector electronics, data acquisition and accumulation electronics as well as software have been made and transferred to the Nuclear Research Institute (NRI) in Řež (Czech Republic).

On the DN-2 (RTD) diffractometer a detector system with 2D PSD (active area of 225×225 mm^2) has been put into operation and a ring-shaped helium back-scattering detector (**Fig. 35**) has been manufactured, assembled, and tested on a test stand.

An ND-screen-based scintillation counter with light collection using wavelength shifting fibers has been made and tested The preparation for production of scintillation counters for the “Astra” detector has begun.

Fig. 35. Ring detector for DN-2.

A number of measures to upgrade the clean room have been taken; its area has increased to 10 m^2.

Neutron beam profiles have been measured on beams 2, 4, 6a, 6b, 7, 9, 11, 12 of the modernized IBR-2M reactor. The measurements were carried out in the beam extraction areas using a 2D thermal neutron PSD-monitor. An average intensity, coordinate and time distributions of neutron fluxes were measured for each beam.

Data acquisition systems.

In 2012, the introduction of a new generation of data acquisition and accumulation systems at the IBR-2M spectrometers continued. In accordance with the time schedule of this project approved at a joint meeting of the Scientific and Technical Councils of the SC and NICM departments, the major part of this work for all spectrometers should be completed in 2012-2013. This means that within the specified period either the DAQ systems will be put into operation or all electronic units, firmware and running-in test software will be manufactured and debugged, and the work on the Sonix+ software for particular spectrometers will be completed within the time limits agreed with the physicists.

In 2012, DAQ systems for point detectors were put into operation at the spectrometers NERA-PR, RTD (DN-2), EPSILON, SKAT, DN-6, REFLEX and FSD (for the development and debugging of the correlation analysis programs and for carrying out the instrument development studies). All the above-mentioned systems except for those of REFLEX and FSD consist of two types of units ─ one digital unit capable of registering and accumulating data from 1 to 240 point detector elements and several 32-channel analog units in which data acquisition, discrimination, transformation and transfer are performed using low-voltage differential signals (LVDS) from the detectors’ preamplifiers to the digital unit MPD-32. In the analog unit the transition from LEMO connectors to a flat cable is done as well. As an example, a block diagram of a 96-channel DAQ system for the ring detector of the DN-6 diffractometer is shown in **Fig. 36** and a photo of electronic modules of this system in a NIM crate is given in **Fig. 37**.

The MPD-16 modules, which combine printed-circuit boards with analog and digital electronics within a single frame, are installed at the REFLEX and FSD spectrometers. An MPD-16 module is intended for spectrometers with the number of detector elements being no more than 16. MPD-32 and MPD-16 modules are software compatible.

A test generator simulating the operation of data accumulation system is built in the MPD modules. This makes it possible to perform a quick test of the operability of the equipment before a reactor cycle as well as its independent adjustment without involving detector elements.

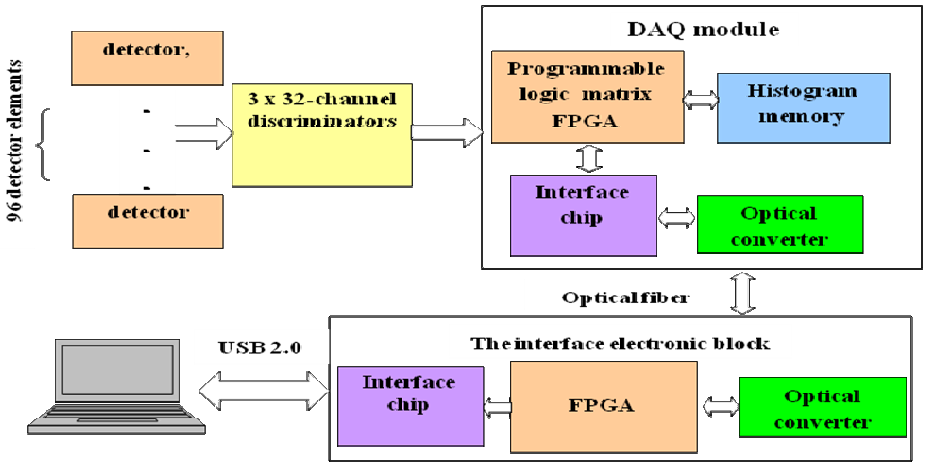

Fig. 36. Block diagram of the DAQ-system of the ring detector for DN-6.

Data transmission between DAQ electronics and USB 2.0 port is carried out via an interface unit using a serial fiber-optic communication line. Data transmission rate is 1.25 Gb/s, maximum distance from a computer – up to 100 m.

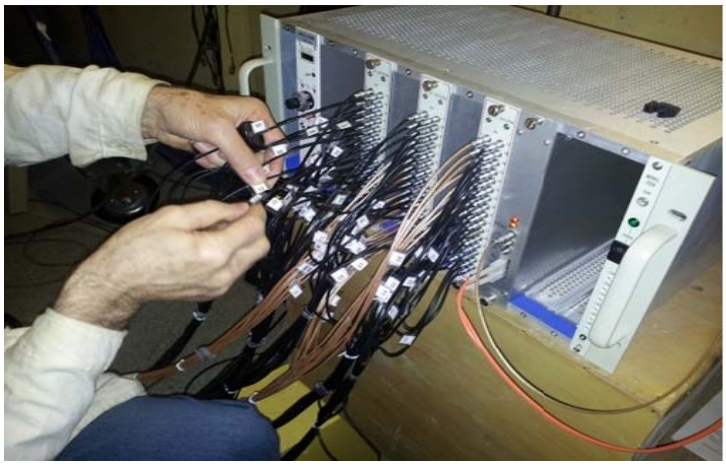

Fig. 37. Photo of MPD-32 electronic modules.

The electronics of the MPD modules are unified, and specific features of each spectrometer are considered when programming FPGA. The key parameters of MPD modules are as follows:

- time discretization frequency of all signals (detectors, reactor start, pick-up, etc.) – programmable (maximum of 62.5 MHz);
- maximum number of detector elements – 240;
- maximum count rate – $8 \cdot 10^6$ events/s;
- internal histogram memory – 64 Mbyte;
- maximum delay of registration start relative to a reactor burst – 0.268 s (programmable, time step – 16 ns); with the same accuracy the channel width for histogram memory and the width of a time window within which neutrons are registered, can be programmed.

On the FSD diffractometer the tests of a MPD-16-module-based "List Mode"-analyzer for accumulation of "raw" data in the list mode and the debugging of processing programs are in progress. It is expected that in the near future MPD electronics will replace the existing DSP electronics on all IBR-2M Fourier-diffractometers. **Figure 38** illustrates good agreement between the low-resolution spectra obtained using DSP- and MPD-analyzers.

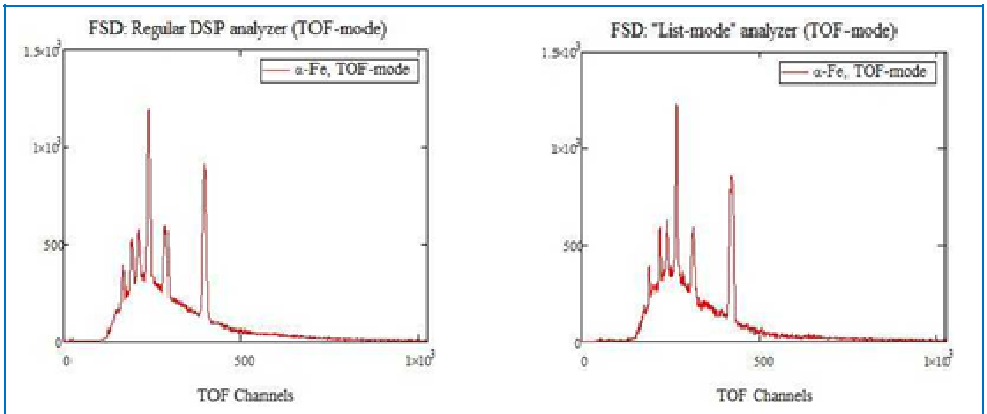

Fig. 38. Low-resolution spectra obtained with the FSD spectrometer.

Development of the Sonix+ software.

Sonix+ versions have been developed and put into trial operation on the spectrometers where new DAQ systems are installed. The complexity of this work lies in the fact that on many spectrometers the replacement of the detecting and data accumulation electronics proceeds along with the replacement of the control equipment of actuators of the spectrometers and of sample environment systems as well as along with the change-over from OS-9 to Windows. This demands certain efforts both from the physicists and engineers and eventually requires their joint work in testing the electronics and software during one-two reactor cycles.

Among other software-design activities the following should be mentioned:

- test program was prepared for testing a ring detector on the DN-6 spectrometer (the tests were successful and the detector with the DAQ system was put into operation).
- technology of designing program components and the technique of their use for creating systems of adjustment of the IBR-2M spectrometers were developed. Versions of adjustment programs were written for the YuMO, REMUR, REFLEX spectrometers. The adjustment program for YuMO was used to adjust a new drive of the ring-shaped collimator.
- work to improve the data visualization program continued. A new version of the SpectraViewer program for point detectors and PSD was developed on the basis of PyQT and Matplotlib. The program was implemented on the YuMO, REFLEX, NERA-PR, EPSILON, DIN-2PI spectrometers. The examples of the use of the SpectraViewer program are shown in **Figs. 39, 40** and **41**.
- initial version of the Journal program for automatic registration of measurements on spectrometers was developed. The program is being tested on the YuMO spectrometer.

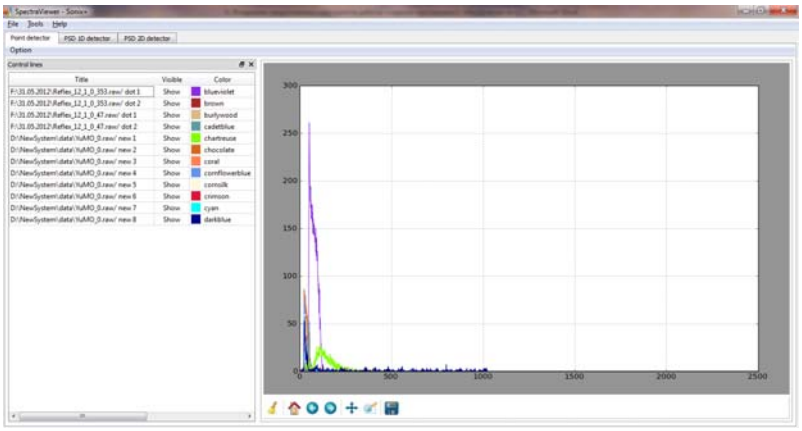

Fig. 39. Visualization of spectra from point detectors (YuMO spectrometer).

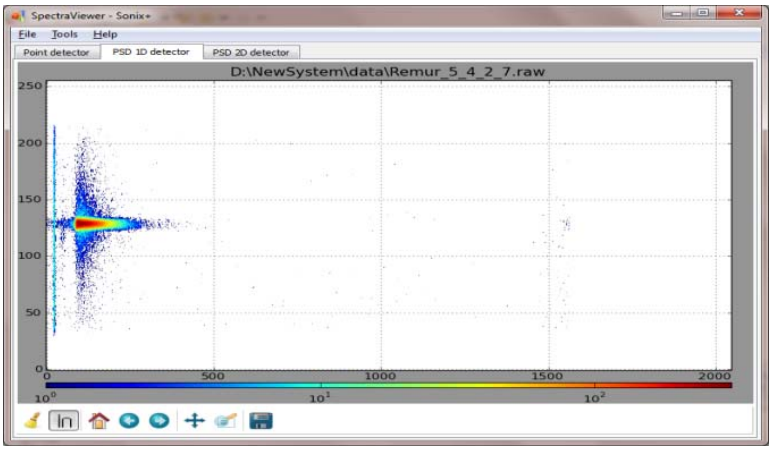

Fig. 40. Visualization of data from 1D PSD (REMUR spectrometer).

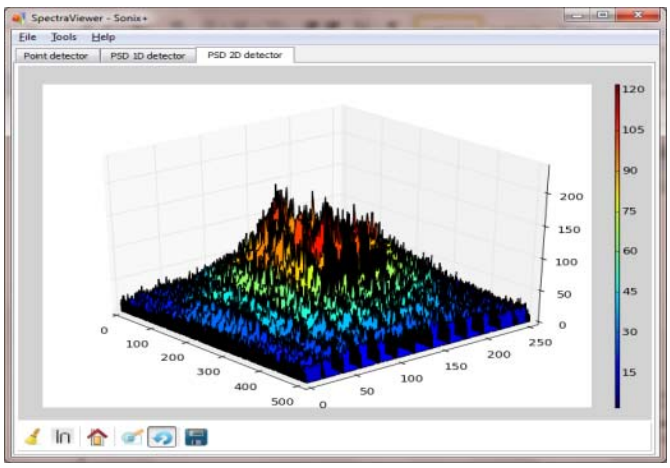

Fig. 41. Visualization of data from 2D PSD (YuMO).

Local area network.

The main task of the current year in the development of LAN ─ to provide the end-user with the rate of up to 1 Gb/s in the main network segments (bldg. 42, 42a, 43 (IREN), 44, 117, 119) ─ has been successfully fulfilled. A trouble-free operation of all network equipment has been maintained both on the IBR-2M spectrometers and in the offices of the Laboratory.

The work on the FLNP LAN modernization started in 2011, continued. The main reasons for the network modernization are:

- Change-over of the JINR Backbone to 10 Gbit/s.
- Modernization of the IBR-2 reactor and its spectrometers; construction of new instruments; tendency to the accumulation of raw data.
- Rapid increase in the efficiency and possibilities of personal computers.
- Higher requirements for information provision for users.
- Provision of access and shared use of network devices, data archives and software packages.
- Mass use of Internet.

The main objectives of the FLNP LAN modernization: **a)** localization of data flows and allocation of segments in a subnetwork to provide the maximum possible throughput of the communication equipment; **b)** to provide data transfer rates of up to 10 Gbit/s. Modernization stages:

- Replacement of the control switching equipment of level 3 and 2 in the main laboratory network segments (bldg. 42, bldg. 42a, IBR-2M, bldg. 119).
- Replacement of the server equipment and further network extension.

At present, the first stage has been mainly completed. A logic diagram of the modernized network as of December 1, 2012, is shown in **Fig. 42**. The following features of the new configuration of LAN should be mentioned:

- An increase in the amount of data coming from the IBR-2M reactor required to connect the IBR-2M segment directly to the FLNP switch to provide a throughput of up to 10 Gbit/s.
- An increase in the throughput by an order of magnitude for all segments of the network (from 100 Mbit/s to 1 Gbit/s and from 1 Gbit/s to 10 Gbit/s, respectively).
- A new SuperMicro 6047 server intended, first of all, for data storage was purchased and installed. The server disk memory capacity is 72 TB.

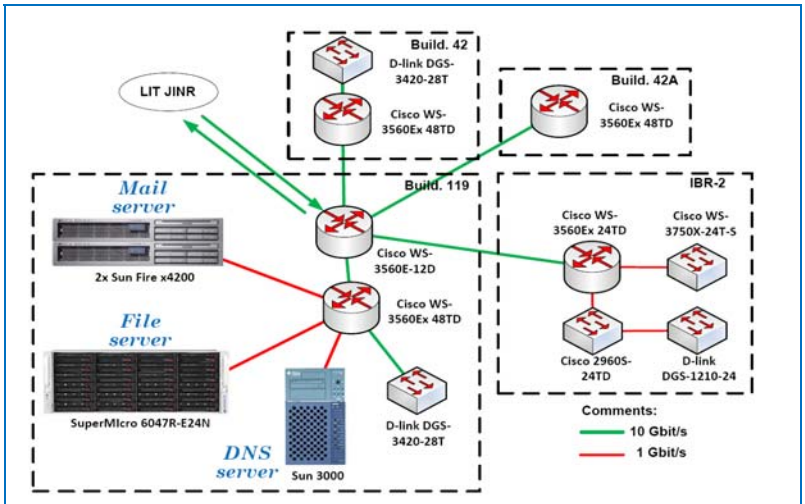

Fig. 42. Logic diagram of FLNP LAN (2012).

2. NEUTRON SOURCES

THE IBR-2 PULSED REACTOR

1. Rostechnadzor license №GN-03-108-2614 of 27.04.2012 has been obtained for the regular operation of the IBR-2 reactor.

2. In accordance with the license requirements during the year the specialized organizations together with the IBR-2 personnel have been performing the scheduled work on the technical evaluation and assessment of the remaining life of the technological reactor equipment.

3. The modernization of the cooling system of the movable reflector MR-3 jacket has been carried out: The scheme of pump unloading has been changed over to partial discharge of water directly to a distillate tank and the pumps of the cooling system of the movable reflector MR-3 jacket have been replaced.

4. Since May 2012 regular IBR-2 cycles of physics experiments have been carried out at a power of 2 MW with the CM-202 moderator operating either in a water or cryogenic mode depending on the schedule of the physical start up of the cold moderator.

The working parameters of the reactor during the cycles are presented in **Table 2**.

Table 2. Data on the IBR-2 operation for physics experiments.

№ cycle	Period	Moderator mode	Reactor power, MW	Reactor operation at power, h	Reactor operation for physics experiments, h
1	May, 21 - June, 1	water	2	247	241
2	June, 18 - June, 29	water	2	272	264
3	September, 24 - September, 28 October, 3 - October, 9	cryogenic cryogenic	2	244	201
4	October, 22 - November, 1	water	2	179	171
5	November, 12 - November, 24	water	2	290	281
6	November, 28 - December, 4	cryogenic	2	171	131
7	December, 13 - December, 21	cryogenic	2	189	182
			Total:	**1592**	**1471**

An additional one-day run of the reactor at a low power was performed on July 10 in order to test the cryogenic system.

THE IREN FACILITY

During 2012 the IREN facility provided more than 1500 h for experiments. the instrument development activities on the preparation of experiments at the pulsed resonance neutron source IREN continued. The multi-detector system «ROMASHKA»-1 intended for neutron cross-section measurements and the AURA facility for (n,e)-scattering investigations were tested on the extracted neutron beams. The applied research activities using the neutron spectroscopy techniques were actively carried out. The collaboration with a number of scientific centers from Russia and the JINR Member States in the field of physics experiments and development of new equipment for nuclear data experiments continued.

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3. PUBLICATIONS

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4. PRIZES AND AWARDS

MISCELLANEOUS

Anghel L.

The EuNPC 2012 Poster Prize was awarded to L. Anghel (Institute of Chemistry of ASM, Chisinau, Moldova) for the best poster presentation in Applications of Nuclear Physics entitled "Molecular Dynamics Simulation of Diferric Human Lactoferrin" co-Author **R. Erhan** (Horia Hulubei National Institute of Physics and Nuclear Engineering - IFIN HH, Bucharest, Romania)

At every session of the Programme Advisory Committees for Condensed Matter Physics and Nuclear Physics a competition is organized for the best poster presented in the poster session for young scientists. The poster "Moss biomonitoring in Albania using GIS technologies" presented by Z. Goryainova was selected as one of three best posters by the 36th session of the PAC for Nuclear Physics and recommended for oral presentation at the JINR Scientific Council.

JINR AND FLNP FELLOWSHIPS

Since 2010, the Association of Young Scientists and Specialists of JINR has been annually organizing a competition for scholarships in four categories. In 2012 the scholarships were awarded to:

1. grant for young PhD researchers
   - R.N. Vasin
   - A.I. Ivankov

2. grant for young researchers
   - Yu.V. Alekseenok
   - A.E. Verkhoglyadov
   - I.I. Zinicovscaia
   - G.V. Kulin

3. grant for young specialists
   - A.V. Kutergin
   - M.V. Bulavin
   - E.V. Lukin
   - K.A. Mukhin

4. grant for young workers
   - D.V. Kokunov
   - D.A. Korovin

Since 2002, in FLNP a scholarship named after Academician of the USSR Academy of Sciences and first Director of the Laboratory of Neutron Physics **I.M. Frank** has been established in order to stimulate scientific and methodical research of young scientists.
In 2012 I.M. Frank scholarships were awarded to:

- In Neutron Nuclear Physics
  S.V. Goryunov
- In Condensed Matter Physics
  S.E. Kichanov
- In Methodical Investigations
  I.V. Bazhazhina

4. PRIZES AND AWARDS

Since 2006, a scholarship has been founded to immortalize the memory of outstanding scientist, Corresponding Member of the USSR Academy of Sciences **F.L. Shapiro**. The scholarship is awarded annually to two young FLNP employees in the following research directions: UCN physics; polarized neutrons; neutron spectroscopy.

In 2012 F.L. Shapiro scholarships were awarded to:

- In «Polarized Neutrons»
  A.I. Ivankov
- In «Neutron Spectroscopy»
  Z.I. Goryainova

FLNP PRIZES

Nuclear Physics:

Second Prize

«Quantum aspects of binary and ternary fission»
Authors: W.I. Furman, A.L. Barabanov

Third Prizes

«Possible neutron experiments to search for new spin-dependent forces»
Authors: Yu.N. Pokotilovski.

«A New Design of Fission Detector for Prompt Fission Neutron Investigation »
Authors: Sh. Zeynalov, O. Zeynalova, M.A. Nazarenko, F.-J. Hambsch, S. Obersted

Applied and methodical research:

First Prize

«The world's first pelletized cold neutron moderator»
Authors: V.D. Ananiev, A.A. Belyakov, A.A. Bogdzel, M.V. Bulavin, A.E. Verhoglyadov, E.N. Kulagin, S.A. Kulikov, A.A. Kustov, K.A. Mukhin, T.B. Petukhova, A.P. Sirotin, A.N. Fedorov, E.P. Shabalin, D.E. Shabalin, V.K. Shirokov

Second Prize

«Neutron spectrometer based on a proton telescope with electronic collimation of recoil protons»
Authors: V.M. Milkov, Ts.Ts. Panteleev, A.A. Bogdzel, V.N. Shvetsov, S. Kutuzov, S.B. Borzakov, P.V. Sedyshev

Encouraging prizes

«Data representation of off-specular scattering and spatial neutron beam-splitting»
Authors: S.V. Kozhevnikov, F. Ott, F. Radu

«Correlation Time-of-Flight Spectrometry of Ultracold Neutrons»
Authors: M.I. Novopol'tsev, Yu.N. Pokotilovski

Condensed matter physics:

First Prize

«Theoretical and experimental investigations of neutron waveguides and their application for the development of probe neutron microscopy».
Authors: V.K. Ignatovich, S.V. Kozhevnikov, Yu.V. Nikitenko

Second Prizes

«High pressure effect on the structure and atomic dynamics of molecular and ionic ferroelectrics»
Authors: D.P. Kozlenko, S.Ye. Kichanov, A.V. Belushkin, S.G. Dzhabarov, B.N. Savenko, Ye.V. Lukin

Third Prize

«Complementary studies of mesomorphic and physicochemical properties of a novel antiferroelectric (S)-1-methylheptyl-4-(4'-decyloxybiphenylthiocarboxy)-benzoate (MHPSBO10)»
Authors: K. Druzbicki, E. Mikuli

4. PRIZES AND AWARDS

JINR PRIZES

JINR Prizes are awarded annually for the best scientific, technical, methodical and applied research studies. In 2012, the following studies performed by the FLNP specialists or in collaboration with the employees from other JINR Laboratories or scientific institutions were awarded with the prizes of various degrees:

Scientific and technical applied research:

First prize

«Physical and power start-up of the modernized IBR-2M research reactor»
Authors: V. D. Ananiev, A.V. Vinogradov, A.V. Dolgikh, L.V. Edunov, Yu.N. Pepelyshev, A.D. Rogov, S.A. Tsarenkov, A.A. Zaikin, I.T. Tretiyakov, N.V. Romanova

Second prize

«The multimeter method of promissory functional materials investigation: quantum chemistry, neutron scattering and optical spectroscopy»
Authors: V.Yu. Kazimirov, M.B. Smirnov, A.M. Balagurov, I.V. Natkaniec

Experimental physics research:

Second Prize

«Refraction and reflection of polarized neutrons from non-collinear and non-coplanar magnetic systems»
Authors: V.L. Aksenov, V.I. Bodnarchuk, V.K. Ignatovich, S.V. Kozhevnikov, D.A. Korneev, Yu.V. Nikitenko, A.V. Petrenko, F. Radu, A.A. Fraerman

FLNP SEMINARS

L. Cser (BNC, Hungary)

- **Belushkin A.V.** (FLNP, JINR) *(18.01.2012)*
  Modernized IBR-2 high flux pulsed reactor: current state and future prospects.
- **Kozlenko D.P.** (FLNP, JINR) *(18.01.2012)*
  Spectrometers complex of the IBR-2M reactor: current state and directions of development.
- **Podurets K.M.** (NRC "Kurchatov Institute) *(18.01.2012)*
  Neutron and complementary imaging: methods and applications.
- **Strobl M.** (ESS) *(18.01.2012)*
  Potential of neutron imaging at a (long) pulse source.
- **Nikitin V.A.** (LHEP, JINR) *(25.01.2012)*
  Fundamental particle physics – a bird's-eye view.
- **Khiem L.H. (**Vietnam Institute of Physics) *(05.04.2012)*
  Introduction to Vietnam Academy for Science and Technology. Present status of nuclear research in Vietnam.
- **Cser L.** (BNC, Hungary) *(18.02.2012)*
  Overview on the scientific activity at the Budapest Neutron Center.
- **Harrison A.** (ILL, France) *(09.10.2012)*
  Recent developments and new opportunities for science at ILL.
- **Maksimenko S.A.** (RINP of BSU, Belarus) *(07.12.2012)*
  Nanocarbon based applied nanoelectromagnetics.

COMMEMORATION

In September 2012 one of the JINR' alleys was named after Polish Professor Jerzy Antoni Janik. Since the establishment of the Laboratory of Neutron Physics he directly participated in the creation of first experimental facilities for neutron spectroscopy investigations and organized a Polish neutron group in LNP. Being an outstanding scientist and organizer of scientific research, for many years Prof. J. Janik was the Chairman of the Neutron Committee and the Member of the JINR Scientific Council.

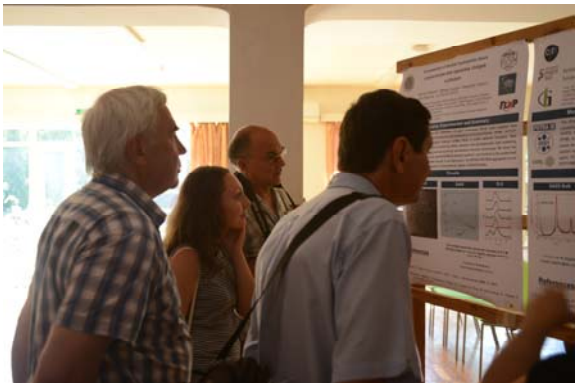
Prof. J. Janik trained and inspired several generations of scientists who continue their research in JINR and on other neutron sources in the world.

5. EVENTS

CONFERENCES AND MEETINGS

The 20th edition of the traditional **International Seminar on Interaction of Neutrons with Nuclei**: "Fundamental Interactions & Neutrons, Nuclear Structure, Ultracold Neutrons, Related Topics" took place in Alushta, Ukraine on May 21-26. The papers presented covered a wide range of issues of fundamental and applied nuclear physics and ecology studied with neutrons.

From left to right: V.V. Nesvizhevsky (ILL France), L. Cser (Hungary), A.V. Strelkov (JINR) at ISINN-20.



CMSMS'12. Poster session.

The **International Summer School and Workshop "Complex and Magnetic Soft Matter Systems**: Physico-Mechanical Properties and Structure" (CMSMS'12) was held in Alushta, Ukraine on September 3-7. The School-Workshop was organized by FLNP JINR together with the West University of Timisoara, Institute of Continuous Media Mechanics of Ural branch of Russian Academy of Sciences (Perm), Institute of Physics and Nuclear Engineering "Horia Hulubei" (Bucharest) and Romanian Society of Physics.

On the initiative of the Romanian representative in ENSA the International Neutron Center FLNP JINR (Dubna) was chosen to be the venue for the **39th European Neutron Scattering Association Meeting** (October 8-9, 2012).

EDUCATIONAL PROGRAM

The objective of the FLNP educational program is the training of specialists in the field of neutron methods for condensed matter and nuclear physics research and in the field of electronics and automatics of experimental installations. More than twenty students from different Russian universities performed their term and diploma theses in FLNP during 2012.

Three scientific schools for advanced training of young scientists were organized by or in collaboration with the Frank Laboratory of Neutron Physics in 2012.

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 in order to attract young scientists to the further development and exploitation of the FLNP facilities.

V Higher Courses of CIS Countries for young scientists, postgraduates and students in modern methods of research of nanosystems and materials "**Synchrotron and Neutron Investigation of Nanosystems**" (SYN-nano-2012) (June 17 – July 5, Moscow – Dubna) were organized together with the National Research Centre "Kurchatov Institute" and the RAS Institute of Crystallography (with the financial support of the Intergovernmental Foundation for Education, Scientific and Cultural Cooperation of the CIS Member States (IFESCCO) and the Ministry of Education and Science of the Russian Federation).

SYN-nano-2012. Poster session.

IV International Neutron School for Young Scientists and Students "**Modern Neutron Diffraction Studies: Interdisciplinary Research of Nanosystems and Materials**" (September 24-28, Dubna) About eighty students, PhD students and young scientists under the age of 35 from Russia, Ukraine, Belarus, Armenia, Poland, Slovakia and other countries took part in the work of the School (with the financial support of the Ministry of Education and Science of the Russian Federation).

A group of students at the DN-12 spectrometer of the IBR-2 reactor.

III International Scientific School for Young Scientists and Students "**Instruments and Methods of Experimental Nuclear Physics. Electronics and Automatics of Experimental Facilities**" (September 08-12, Dubna). Fifty-three students and young scientists from seven European and Asian countries took part in the third School (with the financial support of the Ministry of Education and Science of the Russian Federation).

The student practical laboratory work in the Department of the IBR-2 spectrometers' complex.

Participants of the Schools had ample opportunity to establish new scientific contacts with other researchers to enrich their experimental ideas with new research methods. During the guided excursion to the IBR-2 high-flux pulsed reactor and IREN neutron source, the participants familiarized themselves with these unique facilities. The Schools were not confined only to the lectures and practical laboratory work. The participants were encouraged to present their own investigations in poster sessions and short oral presentations.

5. EVENTS

The FLNP successfully collaborates with the JINR University Centre in the organization of summer practical work for students from the JINR Member States (Belarus, Czech Republic, Poland, Romania, Slovakia,) and Associated countries (Egypt, South Africa). Lectures and excursions to the FLNP facilities for teachers of physics from Russia and the JINR Member States were organized as well.

Students from Poland during their summer practice at the NERA spectrometer of the IBR-2 reactor.

FLNP is always a partner of the JINR University Centre in organizing visits to the Laboratory neutron sources for participants of the Scientific School for school teachers from the Russian Federation and other JINR Member States and scientific excursions for pupils from high schools.

Pupils of high school N18 of Novocheboksarsk, Russian Federation in the IREN control room.

The FLNP leading scientists give lectures in the Dubna University and the Dubna branch of D.V. Skobeltsyn Institute of Nuclear Physics (*SINP*) of the Moscow State University.

VISITS AT OUR FACILITIES

The delegation of the Vietnam Academy of Science and Technology (VAST) headed by Prof. Chau Van Minh, VAST president, visited the FLNP facilities during the working visit to the JINR in July, 2012.

The members of the Innovation Working Group of the U.S.-Russia Bilateral Presidential Commission visited JINR in October, 2012. The potential use of the FLNP research facilities in innovation programs was discussed during their visit to the IBR-2 reactor.

Visit of the EU delegation of businessmen in the framework of the Presidential Program of Management Training in October, 2012.

Visit to JINR of the representatives of the Polish industry in November, 2012.

American delegation in the experimental hall of the IBR-2 rector.

6. ORGANIZATION

STRUCTURE OF LABORATORY AND SCIENTIFIC DEPARTMENTS

Directorate:	
Director	*A.V. Belushkin*
Deputy Director	*V.N. Shvetsov*
Deputy Director	*Deleg Sangaa*
Deputy Director	*S.V. Kozenkov*
Chief engineer:	*A.V. Vinogradov*
Scientific Secretary	*O.A. Culicov*
Laboratory Scientific Leader	*V.L. Aksenov*
Advisor to Directorate	*V.D. Ananiev*

Reactor and Technical Departments	Head
IBR-2 reactor	Chief engineer: *A.V. Dolgikh*
Mechanical maintenance division	*A.A. Belyakov*
Electrical engineering department	*V.A. Trepalin*
Design bureau	*A.A. Kustov*
Experimental workshops	*A.N. Kuznetsov*

Scientific Departments and Sectors	Head
Department of neutron investigation of condensed matter	*D.P. Kozlenko*
Nuclear physics department	*V.N. Shvetsov*
Department of IBR-2 spectrometers complex	*S.A. Kulikov*

Administrative Services
Secretariat
Finances
Personnel

Scientific Secretary Group
Secretariat
Translation
Graphics

6. ORGANIZATION

DEPARTMENT OF NEUTRON INVESTIGATION OF CONDENSED MATTER

Sub-Division	Title	Head
Sector 1: Neutron Diffraction. Head: *A.M. Balagurov*		
Group No.1	HRFD	*A.M. Balagurov*
Group No.2	DN-2	*A.I. Beskrovnyi*
Group No.3	DN-12	*B.N. Savenko*
Group No.4	Geomaterials	*A.N. Nikitin*
Group No.5	SKAT /Epsilon	*Ch. Scheffzük*
Sector 2: Neutron Optics. Head: *M.V. Avdeev*		
Group No.1	Physics of Surfaces	*Yu.V. Nikitenko*
Group No.2	Physics of Nanostructures	*M.V. Avdeev*
Small angle scattering group		*A.I. Kuklin*
Inelastic scattering group		*D. Chudoba*

NUCLEAR PHYSICS DEPARTMENT

Sub-Division	Title	Head
Sector 1. Correlation γ-spectroscopy and development of experimental installations. Head: *N.A. Gundorin*		
Sector 2. Investigation of neutron properties. Head: *Ye.V. Lychagin*		
Sector 3. Neutron activation analysis. Head: *M.V. Frontasyeva*		
Group No.1	Analytical	*M.V. Frontasyeva*
Group No.2	Experimental	*S.S. Pavlov*
IREN facility		*V.G. Pytaev*

DEPARTMENT OF IBR-2 SPECTROMETERS COMPLEX

Sub-Division	Title	Head
Group No.1	Detectors	*A.V. Churakov*
Group No.2	Electronics	*A.A. Bogdzel*
Group No.3	Information technologies	*A.S. Kirilov*
Group No.4	Sample environment and choppers	*A.P. Sirotin*
Group No.5	Cryogenic investigations	*A.N. Chernikov*
Group No.6	Cold moderators	*S.A. Kulikov*

PERSONNEL

Distribution of the Personnel per Department as of 31.12.2012

Theme	Departments	People
-1104-	Nuclear Physics Department	87
-1069-	Department of neutron investigation of condensed matter	89
-1075-	Department of IBR-2 spectrometers complex	42
-1105-	IBR-2 reactor Mechanical and Technical Department Electric and Technical Department Central Experimental Workshops Nuclear Safety Group Design Bureau	46 47 31 38 7 6
	FLNP infrastructure: Directorate Services and Management Department Scientific Secretary Group Supplies Group	 9 24 3 4
Total		**433**

Personnel from the JINR Member States (besides the RF) as of 31.12.2012

Country	People	of which young specialists (≤35 years)
Azerbaijan	9	8
Belarus	1	1
Bulgaria	5	3
Georgia	2	
Germany	3	1
Kazakhstan	7	7
Moldova	3	3
Mongolia	10	7
Poland	9	3
Romania	7	2
Ukraine	14	13
TOTAL	**70**	**48**

6. ORGANIZATION

Our PhD students

In 2012 23 PhD students from 11 countries conducted their experimental research at the FLNP facilities.

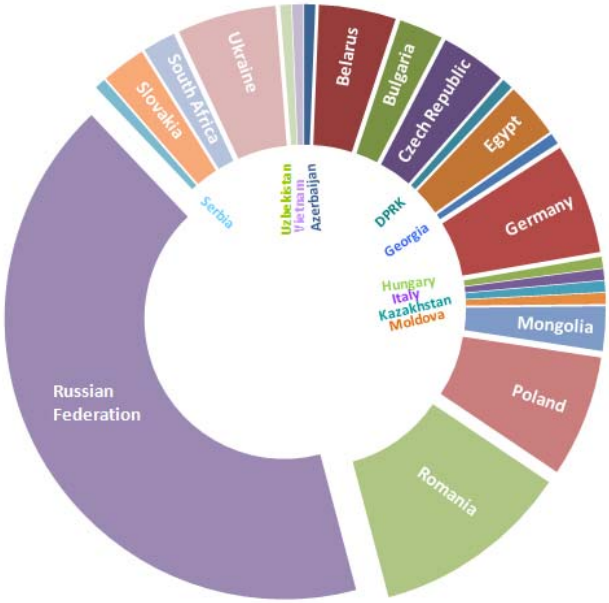
Name	Country	PhD student of
Djabarov S.G.	Azerbaijan	Institute of physics of the Azerbaijan Academy of Sciences
Taibov L.	Azerbaijan	Institute of radiation problems Azerbaijan Academy of Sciences
Alekseenok Yu.V.	Belarus	International Sakharov Environmental University
Milkov V.M.	Bulgaria	University of Sofia
Barandovsky L.	Macedonia	Ss. Cyril and Methodius University in Skopje
Anghel L.	Moldavia	Institute of chemistry of the Moldavian Academy of Sciences
Zinikovscaia I.	Moldavia	University of the Moldavian Academy of Sciences
Neamsuren B.	Mongolia	National University of Mongolia
Erhan R.V.	Romania	University of Bucharest
Bulavin V.V.	Russia	Tula National University
Goriunov S.V.	Russia	JINR University centre
Goriainova Z.I.	Russia	Institute of ecology and evolution of the Russian Academy of Sciences
Mukhin K.A.	Russia	JINR University centre
Verhogleadov A.E.	Russia	JINR University centre
Zontikov A.O.	Russia	Dubna International University for nature, Society and Man
Ntombizikhona Beaulah Ndlovu	South Africa	Stellenbosch University
Kravtsova A.V.	Ukraine	A.O. Kovalevsky Institute of biology of the Southern Seas
Nagornyi A.V.	Ukraine	National University of Kyiv
Solovev D.V.	Ukraine	National University of Kyiv
To Than Loan	Vietnam	Tula National University
Fan Thi Ngok Loan	Vietnam	Tula National University
Chan Tuan An	Vietnam	Tula National University
Dang Ngok Toan	Vietnam	Tula National University

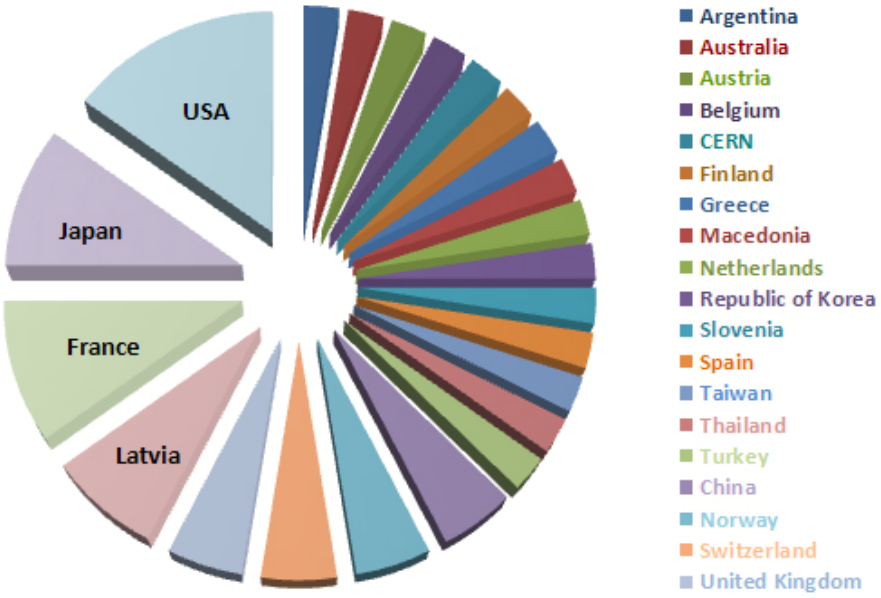
In 2012, 12 BSc and 6 MSc theses were defended using the experimental material obtained in FLNP. Eight of our employees were conferred a Doctor of Science degree and one of them a Doctor Habilitatus degree.

7. INTERNATIONAL COOPERATION AND USER INTERACTION

INTERNATIONAL COOPERATION

In 2012 the Frank Laboratory of Neutron Physics collaborated with 148 institutions from 20 JINR Member States or Associated Members of JINR and 29 institutions from 19 Non-Member States of JINR. The distribution of the institutions by country is presented below.

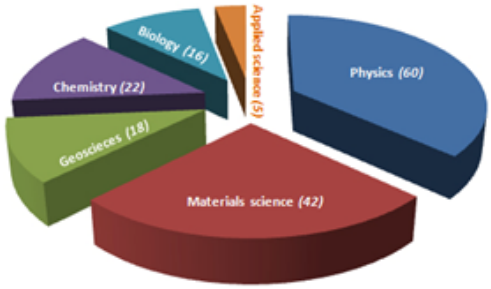




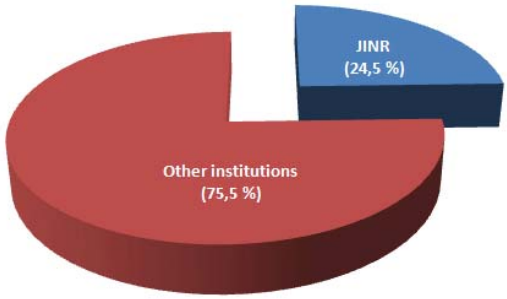
7. INTERNATIONAL COOPERATION AND USER INTERACTION

USER INTERACTION

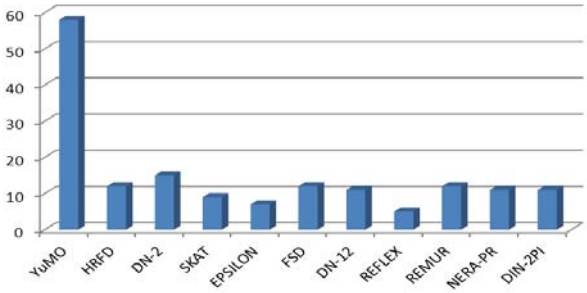
The first call for proposals for experiments at the modernized IBR-2 reactor was open from November 15 to January 31 and extended to February 15. A total of 163 proposals from 17 countries were submitted. 119 experimental proposals have been accepted to be conducted at the IBR-2M spectrometers with 93 of them realized in 2012.



Proposal distribution by science



Proposal distribution by applicant's affiliation



Proposal distribution by facilities

List of Visitors from the JINR Member States or Associated Members of JINR in 2012

Country	Nr of visitors
Azerbaijan	1
Belarus	4
Bulgaria	2
Hungary	2
Vietnam	1
Germany	9
Egypt	4
Mongolia	5
Poland	5
Romania	16
Ukraine	5
Czech Republic	8
South Africa	4

List of Visitors from Non-Member States of JINR in 2012

Country	Nr of visitors
United Kingdom	1
Indonezia	1
China	5
Latvia	1
Republic of Korea	2
Sweden	1
Japan	1

8. FLNP AND MASS-MEDIA

The most significant FLNP events in 2012 – the start of regular operation of the modernized IBR-2 reactor, resumption of the user program at IBR-2 spectrometers and successful start-up of the cold neutron moderator at the IBR-2 reactor – were covered by:

- **television channels** national (like Russia Cultural) or regional (like TV Podmoskovie and Dubna TV) audience

14.03.2012. TV Podmoskovie-“Innovation+”
http://rutube.ru/tracks/5431453.html#cutid1-

29.11.2012. TV Russia Cultural - “Black hole-white spots”
http://tvkultura.ru/video/show/brand_id/20863/video_id/177442

- leading Russian **popular science journals**

Science and Life № 4/2012
http://www.nkj.ru/archive/articles/20608/

ПОИСК

Poisk № 26/2012
http://www.poisknews.ru/theme/international/3745/?print

- and in **electronic publications**:
  http://www.i-mash.ru/news/nov_otrasl/19615-modernizirovannyjj-reaktor-ibr-2-vyveden-na.html
  http://www.nanonewsnet.ru/news/2012/reaktor-nachal-regulyarnuyu-rabotu-na-eksperiment

The world wide distributed bilingual bulletin *News of the Joint Institute for Nuclear Research* and the weekly newspaper *"DUBNA: Science, Cooperation, Progress"* published by JINR also regularly include reports on the FLNP events and achievements.

9. ANNIVERSARIES

V.K. IGNATOVICH

To the 75th birthday jubilee of, a leading scientist of the Frank Laboratory of Neutron Physics.
Fragment from the article by A.V. Strelkov

V.K. Ignatovich, a PhD student of the Laboratory of Theoretical Physics, joined our Laboratory in the mid-sixties. It happened largely due to the LNP Deputy Director F.L. Shapiro who immediately appreciated the abilities and knowledge of the young theoretician and offered him a position in LNP. At that time the research focus of the Laboratory was mainly on the investigations in the field of nuclear physics, and F.L. Shapiro got him involved in the discussion of a possible experiment on the search for the existence of an electric dipole moment (EDM) of the neutron. Having tackled the problem, V.K. Ignatovich unexpectedly suggested that one should search not for a neutron EDM but for an electron EDM in an alternative experiment, which was soon carried out using a high-precision magnetometer in LNP in the group of B.V. Vasilyev.

Later on V.K. Ignatovich got absorbed in ultracold neutrons (UCN), which F.L. Shapiro proposed to use in the neutron EDM experiment. And literally right in front of his eyes these very UCN were first observed in the experiment conducted on the IBR reactor. Afterwards, the young theoretician took an active part in all UCN experiments carried out in LNP and on the reactors of other institutes. He was particularly attracted by an intriguing problem of UCN leakage from closed vessels caused by anomalously high UCN losses after hitting the vessel walls. To explain the reasons for this phenomenon, V.K. Ignatovich put forward a number of hypotheses starting with the assumption of some imperfection of quantum mechanics itself and ending with an idea about surface contamination by hydrogen atoms. Having summed up his knowledge on the subject of UCN, Ignatovich defended his PhD thesis and wrote a monograph “The Physics of Ultracold Neutrons”, which was published in 1986 and later translated and printed abroad. It was the first book on UCN and it still remains a valuable reference material. V.K. Ignatovich found himself increasingly attracted to the wave nature of the neutron. He devoted a number of his studies to the behavior of the neutron as a wave packet and made a series of surprising assumptions regarding the imperfection of the scattering theory. His scientific reputation grew rapidly and he was invited to work in Japan, where he conducted theoretical and experimental investigations in neutron optics.

In 2007 V.K. Ignatovich received D.Sc. degree and the following year his second monograph “Neutron Optics” was published. But it should be mentioned that his passion for neutron optics extends to research in the field of ordinary light optics as well. He has come up with a bold theory to explain the generation mechanism of a mysterious natural phenomenon – ball lightning – considering it as a trap for light photons. V.K. Ignatovich has an excellent command of English and more than once he had to work as a simultaneous interpreter at various workshops and conferences.

V.K. Ignatovich has turned 75. He has three sons, two of whom have graduated from the Moscow State University and work in the USA. Of course, age is beginning to tell on: it takes somewhat longer to get home from work and perhaps he is not so quick to go up the stairs, but it has not dampened his lifelong infatuation with physics in the slightest. He is open to his colleagues and students at all times, always willing to share his knowledge and experience with others. He really enjoys helping to train the next generation of scientists and finds true delight in teaching and inspiring his students. And speakers at seminars always expect his “tricky” questions and principal remarks that are bound to help to get to the core of the problem discussed.

A.V. STRELKOV

To the 75th birthday jubilee of, a leading scientist of the Frank Laboratory of Neutron Physics.
Fragment from the article by E.P. Shabalin

Alexander V. Strelkov came to the Laboratory of Neutron Physics (JINR) in 1960 after graduation from Gorky University, – a young man with tousled hair in a frayed sweater. He already knew a lot, but did not have much experience and skills yet. But now… Now each time when I enter Sasha's office (his lifestyle, his unique manner of interacting with people leave no choice but to call him this way), a book about Robert Wood, "a wizard of a physical laboratory", comes to my mind. The same overwhelming thirst and incredible liking for physical experiments… The same ingenuity and complete mastery in performing them… This is not Harry Potter's sorcery; this is true magic of a talented physicist.

When you write or tell about an extraordinary person, it is difficult to decide where to begin. The name of Sasha Strelkov immediately brings to your mind a wide variety of events, phenomena, episodes, activities. But probably in a scientific journal first of all it should be noted that Alexander Vladimirovich is a brilliant physicist-experimenter, the best expert in neutron detection. With the help of his wonderful detectors he can do anything you like: at a distance of kilometers find out whether this or that JINR accelerator is in operation, sober up enthusiastic supporters of sensational discoveries of cold fusion, measure gravitational levels of ultracold neutrons and many other things.

For colleagues who happen to drop into his office he always has in store a few enthusiastic words about this or that remarkable person and a physicist with whom he has recently talked (it must be added that Sasha is very lucky to encounter and become friends with wonderful people), some physical riddles and brain-teasers (his most favorite problems are about half-full bottles in the ocean, though he is a teetotaler himself), or interesting stories and recollections of some past events that others have forgotten long ago, and which probably were not so impressive and heroic as he depicts them in his story, but as the Russian saying goes «what is a song without a bayan*?» And Sasha Strelkov like legendary Pushkin's Boyan* from "Ruslan and Ludmila" is a keeper and narrator of folk tales, myths, and legends of our Laboratory.

And all these are not an "epatage" or a show meant to draw attention to himself. These are the joy of life, these are his emotions and love, his interest to people… To give life to four children, to teach physics to a blind young man – if this is not love, tell me what it is?

And I forgot to mention three magic letters - UCN. They are a part and parcel of A.V. Strelkov's work all his life. If you hear the words «ultracold neutrons», it means that Alexander Vladimirovich and his «Dunya» (not a girl-friend, but a UCN counter) is sure to be somewhere around. Since 1968 when he together with Yu.N. Pokotilovski and V.I. Lushchikov under the supervision of F.L. Shapiro was the first in the world to prove the existence of these marvelous particles (registered as a discovery), he has always been faithful to them and still continues to surprise the world with unique possibilities of their application for solving the riddles of the Universe in Grenoble (unfortunately, our reactor cannot produce enough UCN). However, the word "to surprise" is not quite correct. Sasha mostly follows the motto "What one should do is not to surprise the world, but to live in it". And he lives his life to the fullest, generously and honestly…

Wishing you lifelong health and many happy returns of the day, Alexander Vladimirovich… Sasha!

**Russian button accordion "bayan" was named after the 11th-century bard Boyan.*

9. ANNIVERSARIES

S. MATHIES

To the 75th birthday jubilee of, a leading scientist of the Frank Laboratory of Neutron Physics.
Fragment from the article by T.I. Ivankina

It is rather difficult and challenging for me to write about Siegfried Matthies. First, we belong to two different generations, and second, he is more like a teacher to me, therefore pupil's respect and deference to a teacher makes me restrain from too emotional and frivolous statements.

Once I heard a phrase from my physics teacher at the Tula University “He is an excellent physicist and has mathematics at his fingertips”. These words fit perfectly to describe Siegfried’s professional qualities. There seems to be no problems in physics too intricate for him to solve using sophisticated mathematical tools.

I first heard about Siegfried Matthies in the eighties. Being a graduate student of the O.Y. Schmidt Institute of Physics of the Earth of AS USSR in Moscow at that time, I was concerned with mastering a new research technique – mathematical texture analysis. I was interested in the possibility of quantitative description of crystallographic textures (preferred orientations of minerals) of quartz-containing rocks with piezoelectric properties. At that time a number of papers appeared by an unknown-to-me author [S. Matthies // Phys. Stat. Sol. (b), 1979] who had long been openly writing about the existence of “ghosts”, negative ODF values, and explained them (impossible!!!) by the limitations of the Bunge's method itself. The Bunge's method was considered to be a basic one. His conclusions were astonishing. I was faced with the prospect of searching for other ways to quantitatively describe textured polycrystalline materials on the basis of experimental data. But soon S. Matthies himself proposed such a method.

So, the life history of the theoretician S. Matthies began … (All the details of his biography were written by me as told by the scientist himself).

Siegfried R. Matthies was in 1937 near Dresden (Germany) in the family of a whitesmith. Having graduated from the elementary school in 1955 was sent to study at the Physics Department of the Leningrad State University. In 1963 S. Matthies defended his PhD thesis on nucleon associations in light nuclei (area that has again become “fashionable” in recent years), having gained a solid background in quantum mechanics and group theory. In 1971 S. Matthies joined the Laboratory of Neutron Physics, where he worked until 1977. At that time at the suggestion of F.L. Shapiro and under the supervision of K. Hennig a German research group was created to study the energy levels of 4f-electrons in an electric crystal field. Soon he was invited to work at the Paul Scherrer Institute (PSI) in Switzerland, which was almost unheard of at that time. Having summed up his research work in Dubna, he defended his Sc.D. thesis at the Technical University of Dresden (1978). In 2007, having formally retired, S. Matthies willingly accepted the invitation of the FLNP Directorate to work several months a year as a leading researcher in the group of the late Prof. A.N. Nikitin. Siegfried Matthies is the author of about 130 publications and monographs. His algorithms, especially the WIMV-method to determine ODF, the method of standard functions and the method of geometrical averaging of elastic properties are important elements of the popLA (Los Alamos, USA), BEARTEX (Berkeley, USA) and MAUD (Trento, Italy) texture analysis software packages and are widely used all over the world. In 1983 S. Matthies received the Gustav Hertz Award of the German Physical Society and in 1984 he was conferred with the title of Professor of AS GDR.

That is what Siegfried Matthies is: a versatile scientist, a superb teacher and a man who excels in almost everything he puts his mind to.

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