ОБЪЕДИНЕННЫЙ
ИНСТИТУТ
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

Дубна

D3-2000-300

V.L.Aksenov

40 YEARS OF NEUTRON PHYSICS IN DUBNA

Submitted to «Вестник РАН»

2000

Historically, the first intense neutron sources were nuclear reactors with a continuous flux where in the process of spontaneous fission of uranium the thermal power and consequently, the neutron flux are kept constant over time. On June 23, 1960 in Dubna of Moscow Region in the Joint Institute for Nuclear Research (JINR), a research reactor of the new type, the pulsed reactor of periodic operation (a shorter name is IBR, the first letters for the Russian "impulsnyi bystryi reaktor" (pulsed fast reactor)). The idea of pulsed neutron generation by fast rotation of some part of the active zone in the reactor was suggested at the end of 1955 by D.I.Blokhintsev, who was at that time the director of the Institute of Physics and Power Engineering (IPPE, Obninsk), where as early as at the beginning of 1956, I.I. Bondarenko and Yu.Ya. Stavissky developed a mathematical substantiation of the project. The main advantage of such a reactor is the possibility of generating large pulsed neutron fluxes at quite high repetition rates, up to 50 pulses per second. At the same time, the reactor is very economical, sufficiently easy to operate, and relatively inexpensive thanks to its small average power, which results in lower activation of the equipment and slower burning of the fuel.

In March 1956 in Dubna, the international scientific center JINR was founded with Blokhintsev as a director elected by representatives of the member-states. The project of the new reactor moved to Dubna, where in 1957 its construction started in the Laboratory of Neutron Physics headed by I.M.Frank, the Nobel Prize Winner. D.I.Blokhintsev had been the scientific leader and active participant of all works related to pulsing reactors until his death in 1979.

Successful operation of the IBR reactor and its modifications [1] stimulated the appearance of several analogous projects in Europe and the USA in the mid-1960's. However, the project of the IBR-2 reactor was only realized in Dubna in 1984. This was possible due to experience in operation of such systems in Dubna and Obninsk and active participation of the USSR Ministry of Medium Machine Industry (today, the RF Ministry of Atomic Energy) and its research institutes and industrial plants. The principal distinguishing feature of IBR-2 from other reactors in the IBR series is the use of a high speed rotating device (up to 1500 rot/min) that reflects neutrons into the active zone (the movable reflector) to provide pulsed modulation of reactivity and as a result, of the reactor power and generated neutron flux (see [2,3] for a comparative analysis of the characteristics of pulsed reactors and other neutron sources).

Today, the IBR-2 reactor is the world highest flux pulsed neutron source for scientific research. Moreover, IBR-2 has no analogs in the world and it serves a testing ground for mastering experimental methods at high flux pulsed neutron sources with a long pulse, hence influencing the strategy of development of neutron sources for physical research. Figure 1 shows the general view of the experimental hall of the IBR-2 reactor.

In the past 40 years many investigations of principal importance for our understanding of the structure of matter and those opening new scientific directions were conducted at the JINR reactors. Initially the investigations were oriented to nuclear physics but gradually, work to study the condensed state of matter is being more and more developed with an increasing number of experiments in materials science, chemistry, biology, earth sciences, and engineering. Being interdisciplinary is a common feature of neutron investigations due to unique properties of the neutron demonstrating themselves in neutron – matter interactions.

NUCLEAR REACTIONS WITH NEUTRONS

Since the neutron does not have an electric charge ($Q_n \leq -0.4 \cdot 10^{-21} |Q_e|$), nuclear reactions with neutrons may occur at its smallest energies. The reaction cross sections have a resonance character and reach very high values at certain neutron energies. These are called the neutron resonances and they are analogous to spectral lines of atoms in optics. Each resonance corresponds to a certain level of the excited compound nucleus formed as a nucleus captures a neutron. The decay of the compound state may go through the different channels: emission of neutrons, protons, α-particles, γ-quanta, or through the fission of the nucleus. The channel determines the information on the processes in the atomic nucleus that can be obtained.

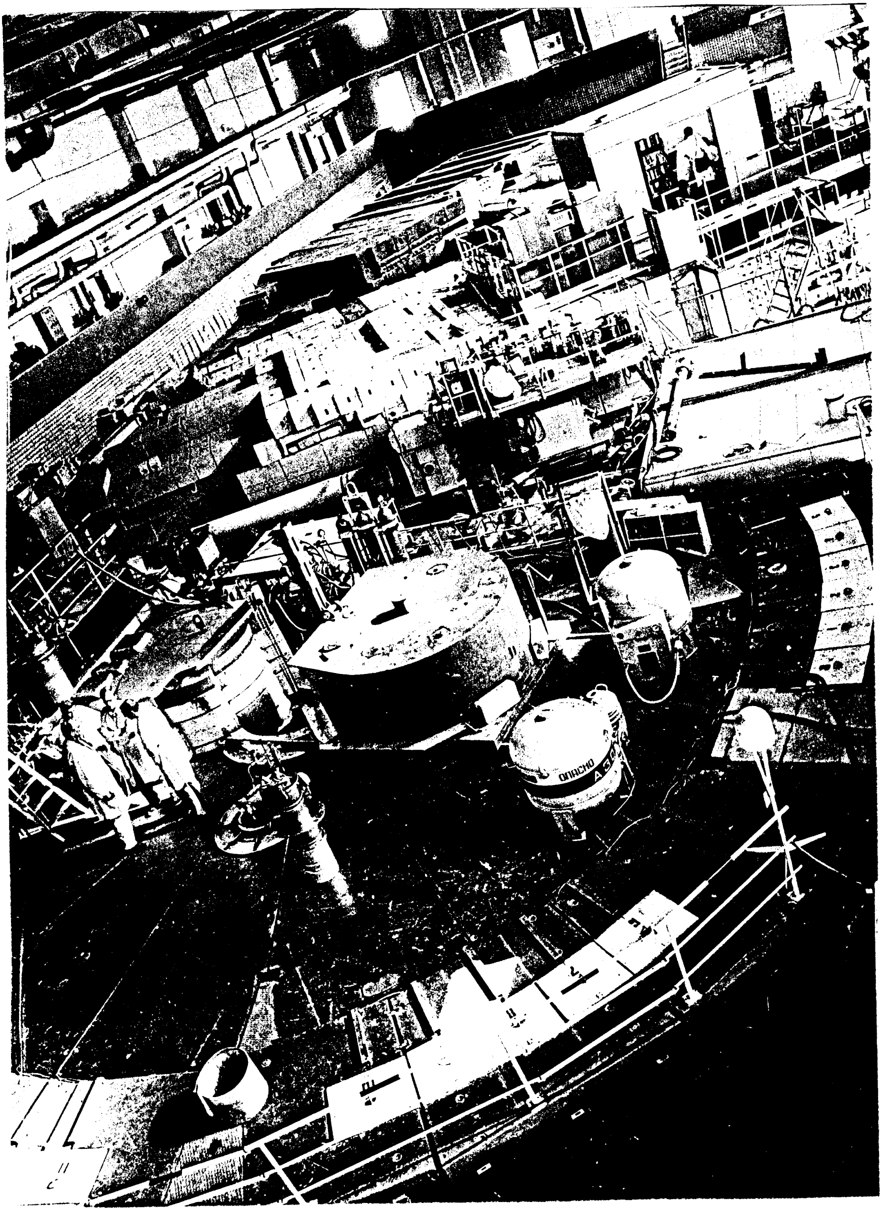

Fig. 1. A general view of the experimental hall of the IBR-2 reactor.

The specific feature of the JINR pulsed reactors is a high luminosity and a long pulse duration. This has stimulated staging of experiments that do not require a high energy resolution. As a result, an original scientific program of studies in high excited states of nuclei, super-fine interaction effects in compound states, spatial parity violation and time invariance in neutron resonances, interference phenomena in fission, nuclear synthesis, and similar processes occurring in the nuclei of red giants and in the explosion of super novas, has formed.

One of the brightest and most promising directions of neutron physics born in Dubna is the investigations with polarized neutrons and polarized nuclei. Beginning from 1961, on the initiative of F.L.Shapiro, there have been developed methods of neutron polarization using a dynamically polarized proton target, polarization of nuclei in the target by cooling it to a temperature of the order of 10^{-2} K in the refrigerator dissolving helium-3 in helium-4, and pioneer experiments to study super-fine interaction effects in the compound states of nuclei have been conducted [4]. At present, the methods are used to study the violation of fundamental symmetries in neutron resonances.

Interest to investigations of spatial parity violation effects (P-parity, symmetry relative to inversion of coordinates or mirror symmetry) in nuclear interactions is due to their possible enhancement because of the closeness in energy of the states with opposite parities. Experiments in the field were started by the group of Yu.G.Abov in the Institute of Theoretical and Experimental Physics (ITEP) in Moscow in 1964 after an asymmetry relative to the neutron polarization direction in γ-emission following radiative capture of polarized thermal neutrons by unpolarized ^{113}Cd nuclei had been observed. The effect was on the level of 10^{-4} in comparison with $10^{-7}\div10^{-8}$ for few-nucleon systems.

The understanding that the observed effects are related to particular neutron resonances has only become possible after elastic neutron scattering experiments, i.e. (n, n) reactions, were conducted in Dubna in 1981. It appears that in these reactions the total enhancement is 10^6 times the primary effect in the nucleon-nucleon interaction. Two mechanisms of the enhancement effect in complex nuclei were confirmed. The first is the dynamically enhanced mixing of levels because of their energy proximity and the second is the kinematic enhancement that may reach a value of $10^2\div10^3$.

Another possibility of the enhancement of P-odd effects follows from the Yu.M.Kagan and A.M.Afanasiev theory of the interaction of neutrons with nuclei in regular structures. In the conditions of dynamic diffraction an enhancement effect may arise due to coherent action of nuclei when the target crystal turns into a sort of single resonator. Preparations for the staging of the experiment that has been realized by nobody yet are under way at the IBR-2 reactor [5].

Study of enhanced P-odd effects is of much interest for nuclear physics as it allows a deeper insight into the structure of excited states. The aim of such studies is the measuring of the parameters of mixing resonances to determine matrix elements of the weak interaction in nuclei. It is necessary to note that the problem is quite difficult as modern theory does not provide means for reliable description of a complicated structure of compound states and exact calculation of enhancement coefficients. Today's goal of the direction is, therefore, the accumulation of information with an emphasis on increasing experimental precision and observation of weak effects, for which small matrix elements are responsible, and also, the use of not only polarized neutrons but also polarized nuclei.

Another interesting result of the investigation of the elastic channel of the interaction of polarized neutrons with polarized nuclei is the discovery of a new possibility for the investigation of symmetry violation relative to time inversion (time invariance).

In experiments to study P-odd effects there are investigated pair correlations between the neutron spin $\vec{s}_n$ and the moment of a γ-quantum $\vec{k}_\gamma$, of the neutron itself $\vec{k}_n$, or the spin of the target $\vec{I}_n$. To study time invariance violation, both polarized neutrons and polarized nuclei are used. In this case, in the amplitude of forward elastic neutron scattering the additional triple correlation $\vec{s}_n \cdot [\vec{k}_n \cdot \vec{I}_N]$ whose contribution is proportional to the matrix elements of both P- and T-odd interaction must be taken into account. The existence of this correlation results in a difference between the total cross sections of the transmission through a polarized neutron target of the neutrons polarized parallel and antiparallel to the axis $[k_n \cdot I_n]$. At the same time, there are present the enhancement factors similar to those in P-violation which may reach the value $10^5 - 10^6$.

Polarized proton targets are the most effective polarizers of intense resonance neutron beams. Today in the world there exist three such targets: in JINR, in the Institute of High Energies (KEK) in Tsukuba (Japan), and in the Neutron Scattering Center in Los Alamos (LANSCE). Recently, the beam in JINR was additionally equipped with another proton polarizer produced in ITEP. This has made it unique as the beam now has a polarizer and an analyzer. Another experimental facility with a polarizer and a ^{3}He-based analyzer is made in collaboration with physicists from the P.N.Lebedev Institute of Physics, RAS. This creates unique possibilities for investigations in the fundamental problem of time invariance violation.

ULTRACOLD NEUTRONS

Attempts to investigate time invariance with neutrons gave rise to a new field of neutron physics, the physics of ultracold neutrons (UCN), the neutrons with the energy less than 10^{-7} eV or the effective temperature below 10^{-3} K. In 1968, F.L.Shapiro suggested to use a UCN gas to measure the electric dipole moment (EDM) of the neutron [6]. Elementary particles possess EDM if only there is time invariance violation.

The specific feature of ultracold neutrons is their total reflection from the surface at any angle of incidence. This means that such neutrons must be stored in a closed vessel until they β-decay, which provides a unique possibility for carrying out experiments to study the properties of the neutron as an elementary particle. Theoretically, this UCN property was investigated by Ya.B.Zeldovich in 1959.

In 1968 the first successful experiments of the observation and storage of UCN were conducted at the IBR reactor in JINR. The experiments then continued in collaboration with physicists from the I.V.Kurchatov Institute of Atomic Energy (today, RRC "Kurchatov Institute) at the IRT reactor, where experiments of UCN storage in closed vessels were made for the first time in the world. The experiments continue at the reactors of the Scientific Research Institute of Atomic Reactors (NIIAR) in the town of Dimitrovgrad, Petersburg Institute of Nuclear Physics (PINP) RAS, Laue-Langevin Institute (ILL, Grenoble, France). Nowadays, all leading neutron centers in the world have or are building UCN channels, and UCN-aided investigations are intensely developing.

From the very start the problem arose of keeping UCN in vessels as their time of life in them is shorter than theoretically predicted due to different reasons. The problem is still under investigation. In parallel, the β-decay of the neutron itself is studied as its detail understanding is important for fundamental physics. Note that quite few parameters of β-decay are measured with the necessary precision. It is therefore can be expected that these experiments will be continuing for more than one dozen of years. The only exception is possibly the time of life of the neutron whose accuracy has been raised to 0.3%. The most reliable values are the ones obtained using UCN by several groups in FLNP JINR, PINP RAS, and RRC KI. A joint FLNP JINR and PINP group used the original facility KOVSH proposed and developed in FLNP to conduct the measurements at the VVR-M reactor in PINP. At present, experiments to study UCN properties with KOVSH continue at the ILL reactor.

The physics of UCN provides new possibilities for the study of problems in fundamental interactions, quantum mechanics, and neutron optics. For example, measuring of EDM of the neutron remains a topical problem. Its upper limit was established at $3 \cdot 10^{-26}$ e·cm in UCN storage experiments by ILL physicists in 1990 and PINP RAS physicists in 1992. In the course of neutron EDM measurements several theories of time inversion symmetry violation have already been rejected [7]. Presently, the left-right symmetry grand unification theories are under discussion. Of special interest is the verification of the hypothesis of A.D.Sakharov about prevalence of matter over antimatter in the Universe created after the Big Bang (the problem of barion asymmetry in cosmology). These models estimate EDM at 10^{-27} e·cm. In this case, the experiment to measure EDM of the neutron will be of a "yes-no" character.

For this type of experiments and further development of UCN physics UCN sources with a high density are needed. Recently, FLNP specialists suggested a new method of UCN generation using moving converters in combination with the powerful pulsed reactor BIGR of VNIIEF (Sarov) [8]. The expected UCN density is up to 10^5 n/cm^3, which will make it possible to not only increase statistics but also conduct new experiments yet not feasible with the existing sources. The maximum UCN density from the ILL reactor is no higher than 10^2 n/cm^3 at present. The first test experiments with the BIGR reactor proved that the method works, and having optimized the facility we will possibly obtain record UCN densities.

TIME-OF-FLIGHT NEUTRONOGRAPHY

Almost immediately after the creation of research nuclear reactors it was discovered that the neutron is an extremely powerful tool of investigation of matter in the condensed state. Neutrons have a number of advantages in comparison with other types of radiation used to obtain information about the structural organization and dynamics of atoms and molecules in condensed media - solids and liquids (e.g. see [3]). That is why neutronography, i.e. the use of different types of neutron scattering on condensed media to study their structure, has become an absolutely necessary instrument of natural science today.

There exist two possibilities of carrying out experiments of neutron scattering by condensed matter. At a neutron source with a continuous flux, changes in the neutron energy in inelastic scattering or changes in the neutron scattering angle in elastic scattering are measured after the scattering of a monocromatic neutron beam on the sample. At a pulsed neutron source, the time of neutron emission and the time of its arrival at the detector are registered. The measured source-to-detector time of flight of neutrons is then used to determine their characteristics after scattering on the sample.

The time-of-flight method was well known in neutron nuclear spectrometry. Therefore, work to develop experimental techniques of inelastic neutron scattering by condensed media started simultaneously with the beginning of the startup procedures at the IBR reactor in 1960, and no longer than in two years the first results on the dynamics of water and the dynamics of hydrogen in zirconium hydride were obtained [1]. In 1965, physicists from Krakow initiated the creation of the first variant of an inverted geometry spectrometer. Further modifications of the spectrometer resulted in a unique Krakow-Dubna instrument at the IBR-30, the KDSOG spectrometer, and later, in the KDSOG-M and NERA-PR spectrometers at the IBR-2 reactor [9].

On the KDSOG spectrometers a number of pioneer investigations in the dynamics of molecular crystals (together with the Institute of Solid State Physics RAS), crystalline electric field effects in rare earth intermetallic compounds (together with the A.A.Baikov Institute of Metallurgy RAS), and the dynamic properties of hydrogen in metals (together with RRC KI and IPPE), were conducted.

Another class of inelastic scattering spectrometers is the DIN type created by IPPE physicists. The brightest results obtained with these spectrometers are from the study of the spectrum of elementary excitations and search for Bose-condensate in superfluid helium [10].

Inelastic neutron scattering investigations at the IBR reactors are mainly oriented towards measurements of the density of states and are consequently only concerned with incoherent dynamics. To study the coherent dynamics of solids, continuous operation reactors (steady state or stationary reactors) are effectively used, and they supply unique information (e.g., see [11]). Of a most suitable character for the IBR-2 reactors and any other pulsed neutron sources there appear to be elastic neutron scattering investigations.

Neutron time-of-flight diffractometry experiments started at the IBR reactor in 1962 and in fact, they are the first real experiments in the field that demonstrated the serviceability of the method. The first publications appeared in 1963 (see review [12]). They fix the place and year of birth of the time-of-flight neutron diffractometry. At about the same time the possibility of staging a time-of-flight diffraction experiment at a steady state reactor was demonstrated by the B.Buras group in Swierk (Poland) but the reactor power was insufficient for a full value realization of the method.

Soon after the experiments were made in Dubna and Swierk time-of-flight diffractometry has spread fast over the world. In 1964 under the leadership of B.Buras a time-of flight diffractometer was installed at the reactor with a Fermi chopper in Riso, Denmark. Time-of-flight diffractometers started to be used at electron accelerator-based pulsed neutron sources: in 1966 in the USA, in 1968 in Japan, and in 1969 in Great Britain. Diffractometers at such pulsed sources as well as the first diffractometer at the pulsing IBR-2 reactor were a step forward in comparison with a combination of a steady state reactor and a Fermi chopper.

Even in the first experiments done in FLNP a lot of the predicted advantages of the time-of-flight diffractometers, including in the first place, fast data acquisition and the possibility of measuring three-dimensional diffraction spectra, were confirmed. An especially attractive feature is the pulsed manner of neutron irradiation of the sample as it allows involving of an external action on the sample and reach higher parameters of the action in the pulsed than in the stationary regime.

The history of the development of the method in FLNP in the 1960's-1970's has some very bright moments. In 1996 the principle of time focusing of neutrons that increases the luminosity and resolution of the diffractometers was simultaneously and independently discovered in Dubna and Argonne (USA). In 1967 scientists first managed to obtain data on changes in the magnetic structure of hematite in the fields up to 12 T using the diffractometer with a pulsed magnetic field created at the IBR-reactor. In the early 1970's a specialized diffractometer for the investigation of monocrystals which was equipped with a position sensitive detector for the first time in the world practice was constructed at IBR. On this diffractometer pioneer experiments to study the domain structure of ferroelectrics-ferroelastics making it possible to observe on the microscopic level the processes of polarization and repolarization of domains under the action of an external electric field were made in collaboration with the Institute of Crystallography RAS. The world's first refining of the structure of a monocrystal with the time-of-flight diffractometer was also done at the IBR reactor. Namely, in a molecule of lanthanum-magnesium dinitrate the situations of all the 48 hydrogen atoms entering the hydration water were determined.

The possibilities of time-of-flight diffractometery started to be realized in the whole volume in the early 1980's when the new generation of high flux pulsed neutron sources appeared.

The creation of powerful sources on the basis of proton accelerators in Japan (Tsukuba – 1980), in the USA (Argonne – 1981 and Los Alamos – 1985)), in Great Britain (Didcot – 1985), and of the pulsing reactor IBR-2 in Dubna (1984) gave a second birth to time-of-flight diffractometry. By now at each of these sources several time-of-flight diffractometers that exceed the diffractometers at stationary reactors in a whole number of parameters have been built.

A considerable increase of almost 100 times in the neutron flux from the IBR-2 reactor compared to the previous generation of sources has made it possible to go beyond traditional diffraction investigations concerned with solid state physics and materials science. Among other things, on the DN-2 diffractometer a program of neutron time-of-flight diffraction investigations of biological membranes using a position-sensitive detector that allows simultaneous measurements of diffraction reflections at different neutron wavelengths corresponding to different diffraction angles, which is not the case at steady state reactors, was launched in collaboration with the A.N.Belozersky Institute of Physico-Chemical Biology of Lomonosov MSU and the Institute of Biological Physics RAS [13].

For the illustration of the studied objects Fig. 2 shows a fragment of a multilayer structure consisting of lipid bilayers and water layers and how it changes as water is being added. Adding of water transforms the multilamelar phase into multilayer liposomes and excessive water turns it into monolamelar lipid vesicles. The lipid matrix is the main element of biological membranes that surround cells and enable their vital activity. To understand the working mechanisms of the membrane, it is necessary to know such parameters as the thickness of the water layer and of the hydrophobic part, the repetition period of lipid bilayers, the area per one lipid molecule, and the dependence of these parameters on the temperature and the presence of admixtures. The parameters were measured using neutron diffraction for the lipid structures of dipalmitoylecithin, egg lecithin, egg phosphatidylcholine, phospholipids. A meaningful result of the measurements is the determination of the binding energy of water molecules with the lipid head. For example, in the case of phospholipids it appears to be 30 J/mol.

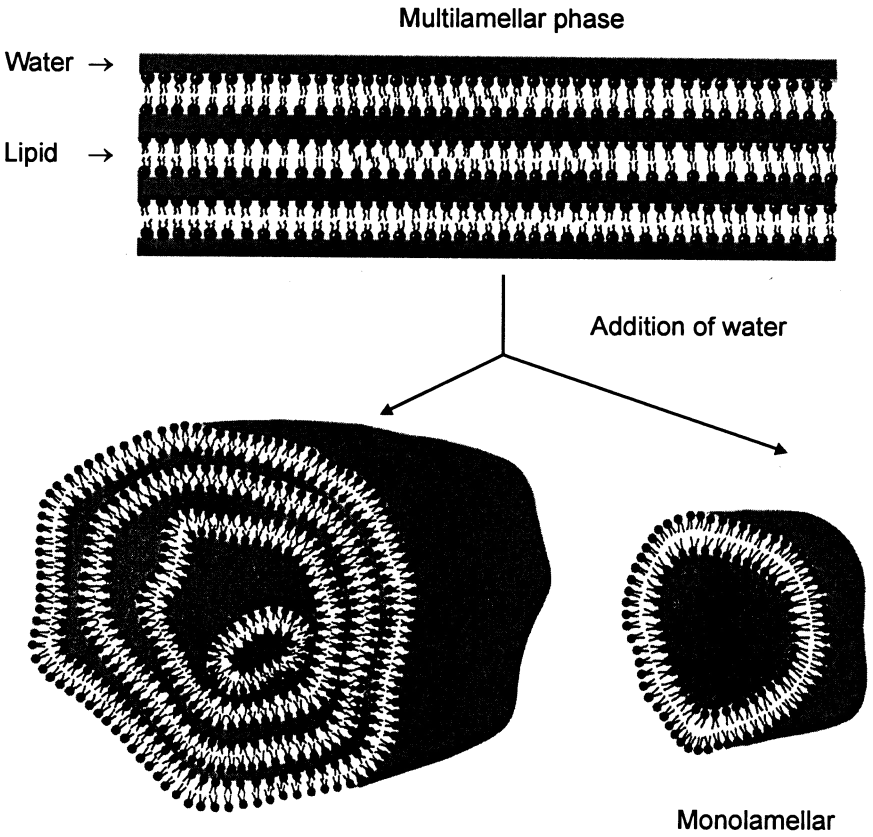

Fig 2. A schematical presentation of the evolution of the main element in biological membranes, the lipid bilayer, studied with neutron diffraction.

A large neutron flux from the IBR-2 reactor allows effective investigations of irreversible processes in crystals. The essence of the created method, which was named real-time neutronography, is that the diffraction spectra from the investigated sample are measured in the time noticeably shorter than the characteristic time of structural rearrangements caused by a diversity of processes. It is obvious that the possibilities of the method largely depend on how small the times of neutron spectra measurement are feasible in principle. At stationary neutron sources, including the most powerful reactor of its class in ILL, it is possible to acquire the necessary statistics during the measuring time from 5 to 10 min. Even the first IBR-2 experiments have shown that possibilities exist of improving the time resolution down to 1 minute and in some cases, to several seconds. A series of experiments conducted in a short period of time provided detail information about structural rearrangements in the process of the hydration of components of concrete, synthesis of high temperature superconductors from primary elements, phase transitions in heavy ice hardened under high pressure (in collaboration with the Institute of Solid State Physics RAS), and of many other processes.

Of the most important and perspective directions of neutron time-of-flight diffractometry is the use of high pressure for structural investigations. In cooperation with the world leading specialists in the field, physicists from the L.F.Vereschagin Institute of Physics of High Pressures RAS (IPHP) and RRC "Kurchatov Institute", methods for the investigation of matter at high pressure based on a complementary use of the technique of monocrystal anvils and high luminosity low-background systems of neutron registration were developed. Monocrystal anvils make it possible to investigate very small amounts of matter (down to 0.01 mm^3 in volume), which extends significantly the possibilities of studying monocrystals of new compounds and materials. A unique diffractometer, DN-12, for investigations at pressures up to 20 Gpa is created at the IBR-2 reactor in cooperation with RRC KI. At present, it is the highest luminosity diffractometer for investigations of microsamples in the world.

High pressure cells of IPHP RAS make operate successfully in the complex of texture diffractometers used to conduct investigations of rocks related to fundamental problems of geology and geophysics and also, to solve applied problems, e.g., siting of deep radioactive wastes storages. Figure 3 illustrates the scheme of rock studying experiments carried out in collaboration with the Geophysical Institute of Czeck Academy of Sciences, Institute of Geology and Dynamics of Lithosphere of Goettingen University, and the Institute of Mining Deposits Geology RAS. The samples were of the olivine xenolytes from the earth mantle carried out to the surface with a lava flow from the depths between 80 and 120 m in the Czeck Republic and from deep cores in the Kola Peninsula. One of these samples is shown in the upper part of Fig. 3. In the left side of Fig. 3 there are mapped the isolines of longitudinal elastic wave velocities measured at different bulk pressures, and in the right side of the figure there are neutronographic pole figures that visualize the nature of the dominating orientations of the olivine grains. A comparison of the measured data with the results of structure modeling shows that the behavior of elastic anisotropy changes strongly as the hydrostatic pressure grows and it only depends on the crystallographic texture at high pressure [14].

The next stage in the development of diffractometry was the creation of a high resolution Fourier diffractometer (HRFD) at the IBR-2 reactor in 1992. It has been the second time when Dubna became the place where a new method in neutron diffractometry, the neutron fourier-diffractometry method, was realized at a pulsed neutron source. In contrast to the conventional time-of-flight method the new one fixes the probability of time-of-flight distribution of the detected neutrons and not the time of flight of each registered neutron [12]. The technical problems of the restoration of the diffraction spectrum in the method with a fourier-chopper were solved by Finn physicists from the Center of Technical Research in Helsinki who developed the reverse time-of-flight method and realized it in a prototype variant in 1975. The first fourier-diffractometer for structural investigations at a stationary reactor was built in PINP RAS in 1984.

Soon it has become evident that most adequate for the efficient realization of the method is a pulsed neutron source with a long pulse, i.e. the IBR-2 type source. In 1989 the Frank Laboratory of Neutron Physics together with PINP RAS and the Center of Technical Research of Finland began the construction of the high resolution fourier-diffractometer at IBR-2. The experience earlier acquired in Helsinki and Gatchina helped successful completion of the project in mid-1992 – on June 11 there were obtained the first spectra.

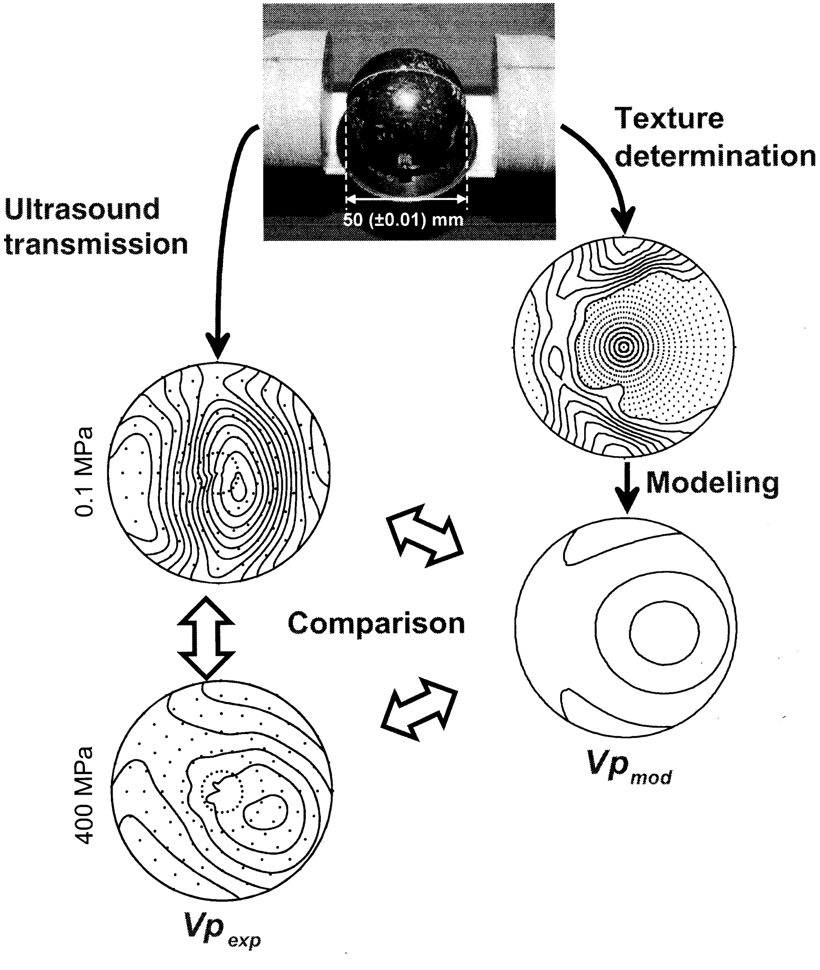

Fig. 3. The scheme illustrating the use of neutron diffraction in earth sciences. The data on the behavior of the anisotropy of the elastic compression rate, V_p, are obtained by neutron diffraction (determination of pole figures in the texture) and by spatial measurements of the propagation velocity of sound at different overall pressures (maps of isolines of elastic longitudinal wave velocities).

Today, HRFD is one of the world four best neutron diffractometers with the highest resolution, on the level of a tenth of percent, and a record neutron flux on the sample. HRFD opens wide perspectives in the field of physics, chemistry, biology, and materials science. The particular examples of HRFD-aided research are the precision investigations of the structure of polycrystals and analysis of the diffraction spectra of monocrystals, if it requires such a high resolution, as well as experiments to analyze internal stresses in massive industrial products.

HRFD is, due to its design, the only neutron diffractometer in the world that allows the measurement of spectra from monocrystals with a spatial resolution better than 0.1%. This advantage was made full use of in the study of the phase separation effect in superconductors which is presently the subject of keen attention of both theoreticians and experimentalists. Crystals of lanthanum cuprate were chosen to be studied with HRFD [15] and a series of experiments were conducted which revealed in the first place, the existence of crystals containing an about equal amount of superstoichiometric oxygen whose behavior is, however, basically different at cooling. In one type of crystals there is observed evident macroscopic foliation which demonstrates itself as weak but clearly seen with HRFD splitting of the diffraction peaks. Crystals of the other type also experience phase foliation under cooling, though it occurs on the microscopic level (<100 nm) and at much lower temperatures.

What is no less important about the creation of HRFD at IBR-2 is that it is a new instrument for pulsed neutron sources. It has opened quite new possibilities for IBR-2 and has actually placed the reactor in the rank of the best neutron sources in the world. The construction of HRFD has influenced the development of neutron investigations in the world. In a number of neutron centers projects to build diffractometers of the type opened. An additional argument for neutron sources with a long pulse, such as IBR-2, has appeared. This direction is intensely developing nowadays.

In parallel with diffraction, time-of-flight diffractometers make it possible to obtain information about the scattering of neutrons at small angles. This unique advantage, that was also first understood and realized in Dubna [16], permits real time observation of the evolution of large inhomogeneities (tens or hundreds angstroms), including the nucleation of new phases arising in the phase transition or solid phase synthesis. Small-angle neutron scattering is being wider and wider used in studies of molecular structures in biology, physics of liquid crystals, chemistry of micellar solutions, surface-active substances, and polymers.

The most developing field of neutron application is the investigation of polymers. Figure 4 shows a fragment of the structure of one of the new polymers, polyallylcarbosilane dendrimers, synthesized in the Institute of Synthetic Polymer Materials RAS [17]. A dendrimer of this type consists of 384 silicon and 382 allyl groups $CH{=}CHCH_2$–, and it is monodispersive. Using small-angle neutron scattering the parameters of the dendrimer in Fig. 4, including the sphericity, radius of sphere, density, and the monodispercity, are conducted at the YUMO facility, called after Yu.M.Ostanevich who created it. The application of the isotopic contrast of solvents, which are the benzenes C_6H_6 and C_6D_6, in the discussed case, turns small-angle neutron scattering into a practically single method that permits measuring of the parameters of polymers and enables the correction of their manufacturing technologies.

Decreasing the neutron incidence angle on the sample one may reach a certain critical value of the angle at which total (specular) reflection is observable. Measuring the wavelength dependence of the reflection coefficient we obtain information about the crystalline and magnetic structure of surfaces and multilayer structures. This is the essence of neutron reflectometry. Dubna is the only place in our country where neutron reflectometry has developed for over 10 years and which has three reflectometers, two of which being polarized neutron instruments.

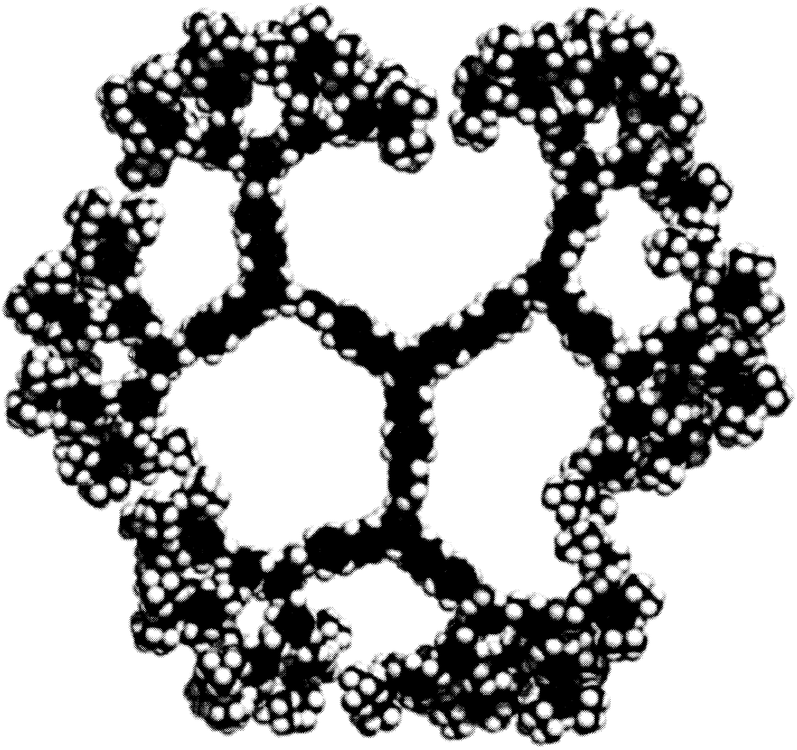

Fig. 4. The fragment of the polymer structure – polyallylcarbosilane dendrimer – studied by small-angle neutron scattering. Dark circles – silicon atoms, light circles – allyl groups

Neutron reflectometry is a young science. It has been used as a measuring method since the beginning of the 1980's. Recently, JINR physicists together with colleagues from PNPI RAS, Instutute Metal Physics of the Ural Branch RAS, and ILL managed to account for off-specular effects in the experiment, which provides additional information about the structure. Figure 5 illustrates the results of the investigation of the magnetic structure of a multilayer system consisting of thin iron and chromium layers. Such systems have a so-called giant magnetic resistance (GMR) and their application relates to the development of computational technologies, namely, the increasing of the memory volume of hard disks. To use these systems in practice, it is necessary to know the mechanism of GMR, however. Till recently this mechanism has been associated with the idea of a file of homogeneously ordered antiferromagnetic iron layers, which followed from the data on the specular reflection of polarized neutrons. According to recent experiments taking into account the effects of off-specular reflection each iron layer contains domains 200-300 nm in diameter [18]. These domains seem to play the main role in the processes leading to GMR.

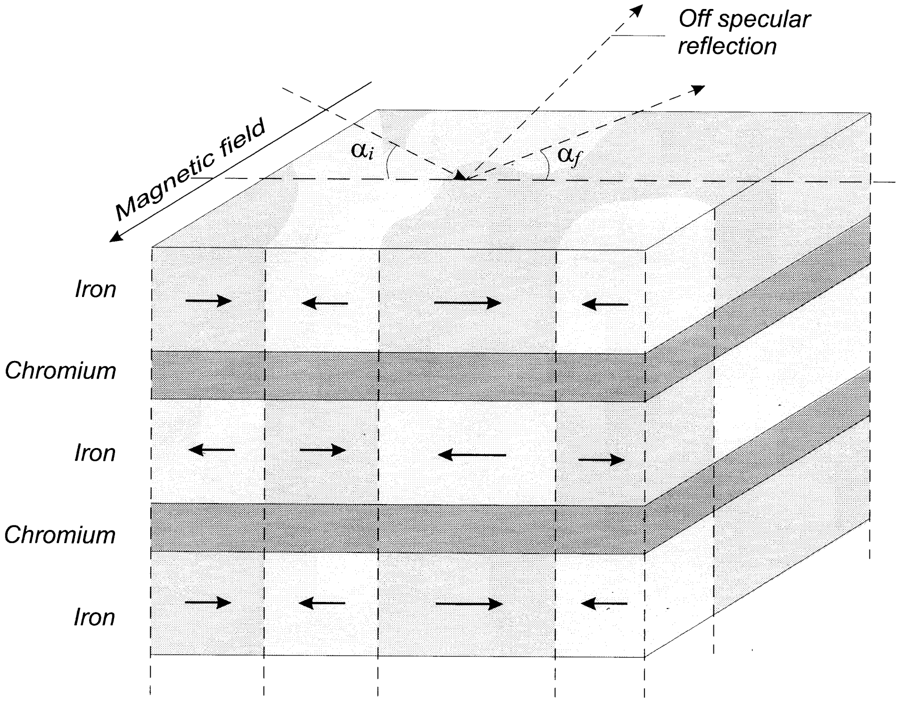

Fig. 5. The magnetic domain structure of the multilayer system iron-chromium obtained by measuring the off-specular reflection of polarized neutrons.

CONCLUSION

Forty years of operation of pulsed reactors in JINR have eventually resulted in the formation of a scientific school in neutron physics that determines many directions in the development of the science in the world. The JINR neutron sources are open to all scientists and are attracting a growing number of users from not only physical centers but also from centers of biology, chemistry, materials science, and other "nonphysical" fields, whose portion is increasing. What we call the user policy plays an important role in involving scientific centers into neutron investigations.

The policy consists of providing best possibilities of access to experimental facilities for non-JINR specialists. Scientific committees for particular research directions select proposals for experiments. For example, experimentalists from over 30 countries do about 200 experiments at IBR-2 every year. The portion of FLNP is approximately 30% of the beam time. Around 35% of the beam time are allocated to scientists from over 20 research institutions in Russia.

This organization of work attracts young scientists. JINR collaborates actively with leading establishments of higher education in the country. Since 1961, the Branch of the Physical Faculty of

Lomonosov Moscow State University (MSU) has worked in Dubna. Nowadays, the integration with the higher school carries on through the MSU Interfaculty Center «Structure of Matter and New Materials» and the JINR Educational Research Center. Every year tens of students take training courses in JINR. Scientific schools and conferences are organized on a regular basis.

This has served a full-value realization of creative cooperation between leading scientists in our country aimed at development of new methods in neutron physics which have promoted Russia to the front line of neutron investigations of matter in the world.

The author thanks Academicians Yu. M.Kagan and A.Yu. Rumiantsev for stimulating discussions of the material lying in the basis of this article.

REFERENCES

1. *Frank I.M.* Development and application for scientific research of the IBR pulsed reactor // Particles and Nucleus.1972. V. 2. P. 807-860 (in Russian).
2. *Aksenov V.L.* Pulsed reactors for neutron research // Particles and Nucleus.1995. V. 26. No. 6. P. 1449-1474 (in Russian).
3. *Aksenov V.L.* Nuclear pulsing reactor // Priroda. 1996. No. 2. P. 3-17 (in Russian).
4. *Alfimenkov V.P., Pikelner L.B.* Experiments with polarized neutrons and nuclei // Particles and Nucleu. 1995. V. 26. No. 6. P. 1524-1538 (in Russian).
5. *Abov Yu.G.* Coherent processes in n uclei and crystals // Uspekhi Fiz. Nauk. 1996. V. 166. No. 9. P. 949-954 (in Russian).
6. *Shapiro F.L.* Electric dipole moments of elementary particles // Uspekhi Fiz. Nauk. 1968. V. 95. No. 1. P. 145-158 (in Russian).
7. *Mostovoi Yu.A., Mukhin K.N., Patarakin O.O.* The neutron of yesterday, today, tomorrow // Uspekhi Fiz. Nauk. 1996. V. 166. No 9. P. 987-1022 (in Russian).
8. *Bagrianov B.V., Kartashov D.G., Kuvshinov M.I., et al.* Dynamic converter of ultracold neutrons at pulsed reactor // Yad. Fiz. 1996. V. 59. P. 1938-1988 (in Russian).
9. *Natkaniec I., Janik J.A., Mayer J. et al.* Inverted geometry multipurpose spectrometer for pulsed neutron sources // Neutron Scattering in Nineties. Vienna. IAEA. 1985. P. 411-412.
10. *Blagoveshenskii N.B., Bogoyavlenskii I.V., Karnatsevich L.V. et al.* Structure of the excitation spectrum of liquid ^{4}He // Phys. Rev. B. 1994. V.50. No. 22. P. 16550-16565.
11. *Dubrovskii L.B., Rumiantsev A.Yu.* Restoration of the Fermi surface in metals and alloys // Priroda. 1997. No. 1. P. 13-25 (in Russian).
12. *Aksenov V.L., Balagurov A.M.* Time-of-flight neutron diffractometry // Uspekhi Fiz. Nauk. 1996. V. 166. No. 9. P. 955-986 (in Russian).
13. *Gordelii V.I., Islamov A.Kh., Syrykh A.G.* Determination of fluctuations of the repetition period in lipid and biological membranes by the method of time-of-flight neutron diffraction // Biologicheskie membrany (Biological membranes). 1992. V. 9. P. 193-200 (in Russian).
14. *Ivankina T.I., Klima K., Lokaichek T., et al.* Investigation of the anisotropy of olivine xenolyte using acoustic waves or neutron diffraction // Fizika Zemli (Physics of earth). 1999. V. 5. P. 29-39 (in Russian).
15. *Pomjakushin V.Yu., Amato A., Balagurov A.M. et al.* Phase separation in La_2CuO_{4+y} single crystal studies by μSR and neutron diffraction // Physica C. 1997. V. 282-287. P. 1353-1354.
16. *Gladkikh I., Kozlov Zh.A., Ostanevich Yu.M., Czer L.* Time-of-flight small-angle neutron scattering // JINR Communications.No. 3-7655. Dubna: JINR. 1974 (in Russian).
17. *Gordely V.I., Mukhametzianov R.I., Kuklin A.I. et al.* Investigation of 7 generation dendrimers. // FLNP Annual Report 2000, Dubna: JINR. 2000.
18. *Lauter-Pasyuk V., Lauter H.J., Toperverg B. et al.* Magnetic off-specular neutron scattering from Fe/Cr multilayers. // Physica B. 2000. V.283. P.194-198.

Received by Publishing Department
on December 18, 2000.

Аксенов В.Л. Д3-2000-300
40 лет нейтронным исследованиям в Дубне

Публикуемая статья написана на основе доклада, сделанного автором на юбилейном заседании 88-й сессии Ученого совета Объединенного института ядерных исследований 8 июня 2000 г., посвященной 40-летию нейтронных исследований в Дубне. ОИЯИ является одним из ведущих научных центров в мире по использованию нейтронов для исследований фундаментальных взаимодействий и симметрий, структуры атомного ядра и конденсированного состояния вещества. Ученые из 30 стран проводят эксперименты на источниках нейтронов ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 2000

Перевод Т.Ф.Дроздовой

Aksenov V.L. D3-2000-300
40 Years of Neutron Physics in Dubna

This publication is based on the report presented by the author at the jubilee meeting of the 88th session of the Scientific Counsil of the Joint Institute for Nuclear Research (JINR) on June 8, 2000 devoted to the 40th anniversary of neutron investigations in Dubna. JINR is one of the world leading scientific centers in the use of neutrons for the investigation of fundamental interactions and symmetries, the structure of atomic nuclei, and the condensed state of matter. Scientists from 30 countries conduct experiments at the JINR neutron sources.

Preprint of the Joint Institute for Nuclear Research. Dubna, 2000

Макет Т.Е.Попеко

Подписано в печать 21.12.2000
Формат 60 × 90/16. Офсетная печать. Уч.-изд. листов 1,8
Тираж 270. Заказ 52417. Цена 1 р. 30 к.

Издательский отдел Объединенного института ядерных исследований
Дубна Московской области