vacuum value is a result of the interference of a wave incident on the medium and the waves scattered by all the elementary scatterers. In the case of neutron waves, such scatterers are atomic nuclei. In a noninertial frame of reference related to the medium undergoing acceleration or in the equivalent case of a force acting on a particle, all the waves in the medium stop being spherical, and the conditions for interference should change. The significance of this circumstance has not yet been studied, and the appearance of new experimental data may shed light on this problem.

In this talk I wanted to show that many of the ideas advanced by Il'ya Mikhailovich Frank nearly forty years ago still retain their importance, while many of them have undergone essential and sometimes unexpected development. Concerning the author's own results dealt with above and in quoted works, most of them were obtained in collaboration with numerous colleagues. The author expresses his sincere gratitude to all of them.

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Pulsed nuclear reactors in neutron physics

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1. Introduction

The first pulsed nuclear reactor IBR was put into operation at the Joint Institute for Nuclear Research (JINR) in Dubna in 1960. By the end of the 1960s, outstanding scientific results had already been obtained, and the advantages of this type of neutron source, as well as ways of further developing, had also been understood. In 1971, a group of authors, which included I M Frank, was awarded a State Prize for work on the creation of a fast pulsed reactor (IBR in *Russ. abbr.*) for research and an IBR with an injector. At the same time, construction of the new pulsed reactor IBR-2 had already started.

In 1971, an article by I M Frank, "Issues of the development of neutron optics" [1], was published in the journal *Dokl. Akad. Nauk SSSR* (*Sov. Phys. Dokl.*), in which a comprehensive formulation is given of the fundamentals of pulsed reactors, of experimental methods, and of lines of research. I M Frank stressed that the utilization of neutrons in scattering experiments is governed by the laws of optics and that the optics of thermal and cold neutrons in many aspects resembles the optics of electromagnetic radiation (light), especially in the X-ray range. There exist, however, differences, related, first, to the difference in their interaction with matter and, second, to the neutron having a finite mass. The latter circumstance provides for the possibility of developing the time-of-flight method in neutron optics, and this method is most effectively applied to pulsed neutron sources. In this talk we shall consider development of the time-of-flight method and the role which pulsed reactors have played in neutron physics.

2. The time-of-flight method

The time-of-flight method in neutron physics consists in neutrons being registered at a given distance L from the

source and their time of flight t measured for this distance. Knowledge of L and t permits determining the neutron velocity v and, consequently, its energy. To realize the method, a blinking source is required in order to fix the instant of time when the neutron escapes. This method was first realized by L W Alvarez in 1938 with the aid of a blinking cyclotron. In 1947, E Fermi at a stationary reactor (continuous flow nuclear reactor) made use of a mechanical chopper of the neutron flux, which represented a rotating disk with a slit transparent to neutrons. Such a chopper — a Fermi chopper — transmits neutrons periodically during a short time interval Δt. The period of pulse repetition must be significantly longer than the measured time of flight t. The intensity of a beam of slow neutrons of energies E_n below 10 MeV, mostly used in neutron physics, was significantly higher than in accelerators. Therefore, for a long time reactors with Fermi choppers were used for realizing the time-of-flight method, and the results obtained were very important for the development of nuclear power engineering. However, as the accelerator machinery underwent development, the roles were separated. In research with thermal neutrons (10^{-3} eV $< E_n < 10^{-1}$ eV) reactors still prevailed, while in research with resonance neutrons (1 eV $< E_n < 10^4$ eV) accelerators were preferred.

The reasons for this are the following [1]. The resolution of a spectrometer making use of the time-of-flight method is $R = \Delta t/L$, where Δt is the error in time measurement. For $R = \Delta t/L$ [μs m^{-1}], the error in measuring the energy is given by $\Delta E = 0.028\, E^{3/2} R$ [eV]. Then, for resonance neutrons, for example, when $L = 10^3$ m and $\Delta t = 1$ μs, the resolution $R = 10^{-3}$ μs m^{-1}, while for $E_n = 10^4$ eV the error amounts to $\Delta E = 28$ eV, and for $E_n = 1$ eV it is $\Delta E = 2.8 \times 10^{-5}$ eV. In the case of thermal neutrons, for example, when $L = 20$ m, and $\Delta t = 100$ μs, the resolution $R = 5$ μs m^{-1}, and for $E_n = 2.5 \times 10^{-2}$ eV the error $\Delta E = 1.1 \times 10^{-4}$ eV. Another parameter that is important for neutron spectroscopy is luminosity. Given equal conditions and a fixed resolution, the smaller Δt, the greater the luminosity. The luminosity of a reactor with a chopper is proportional to $\Delta t/\tau L^2$. Therefore, if Δt and L are decreased by a given factor, the resolution R will remain the same, while the luminosity will increase by a factor of $1/L$. However, in the case of a stationary reactor, enhancement of its luminosity is limited owing to, first, the technical difficulties in reducing Δt mechanically and, second, the fact that a decrease in Δt means utilization of a fraction of the reactor's radiation, which will be the smaller the smaller $\Delta t/\tau$, where τ is the time between the instants of time when the beam is transmitted. Moreover, during those time intervals that the chopper does not let the beam pass, the reactor's radiation not only is not utilized, but creates a parasitic background. Therefore, for neutron spectroscopy it is more advantageous to have pulsed neutron sources in which Δt can be small and all the radiation is concentrated in the pulse. Such neutron sources are created on the base of electron or proton accelerators. In the middle of the 1980s, powerful pulsed neutron sources were created on the base of proton accelerators with proton energies of about 1 GeV, which satisfied all the conditions for realization of the time-of-flight method within the whole energy interval of slow neutrons [2].

3. From the pulsed reactor to the superbooster

A separate chapter in the development of the time-of-flight method was opened by the appearance of periodic pulsed reactors (pulsating reactors) and their combination with blinking accelerators-injectors. The idea of a pulsating reactor was proposed by D I Blokhintsev [3] in 1955, and the theory of this reactor was developed by I I Bondarenko and Yu Ya Stavissky in 1956. The action of the reactor is based on mechanical modulation of its reactivity: the active core is in a subcritical state, and a piece of uranium on a rotating disk transfers the system for a short time into an above-critical state for prompt neutrons. As a result, a power impulse and pulsed neutron flux arise.

The average power of the first IBR reactor was initially low: 1 kW, later 6 kW. However, the pulse power with a repetition rate of 8 pulses per second amounted to 3 and 18 MW, respectively, while in the mode of rare pulses (once every 5 s) it was 1000 MW. In 1968, IBR was shut down, and a new reactor of the same type (IBR-30) with an average power of 25 kW took its place in 1969. The flux of thermal neutrons in the pulse amounted to 10^{15} neutrons per cm^2 per s. However, the relatively long pulse — 60 μs — provided a resolution 60 times lower than the aforementioned estimates. Therefore, research with resonance neutrons, for which the IBR reactor was made, was limited to a range of problems requiring high luminosity but quite moderate resolution.

At the same time, the IBR and IBR-30 reactors turned out to be quite efficient for studies of condensed matter. The investigation of such matter makes use of thermal and cold ($E_n < 10^{-2}$ eV) neutrons. The time during which such neutrons are emitted by the moderator is determined by neutron diffusion and reaches approximately 100 – 200 μs. Therefore, the length of the pulse from the IBR reactor turned out to be totally satisfactory for the needs of neutronography. A brief review of the main results was given in Refs [4, 5].

The main result of application of the IBR and IBR-30 reactors in neutronography consisted in utilization of the time-of-flight method in neutron diffraction. The geometrical optics of neutrons coincide with the geometrical optics of X-rays for both diffraction and a grazing angle of incidence. Therefore, neutronographic experiments were arranged in accordance with the scheme of X-ray diffraction experiments. Thus, starting from the first experiments in 1936 neutron diffraction was performed as follows. A certain wavelength λ is singled out in the radiation spectrum, and the angle is empirically sought at which the Bragg–Wulf condition is satisfied: $2d \sin\theta = n\lambda$, where d is the distance between the reflecting planes in the crystal, θ is the angle between the direction of the radiation and the surface of these planes, and n is an integer; the incidence angle is equal to the angle of reflection. However, one may proceed in a different way, namely, to apply the time-of-flight method making use in the Bragg–Wulf condition of the fact that the neutron wavelength is inversely proportional to the neutron velocity [6].

The possibility of applying the time-of-flight method in neutron diffraction was first discussed by P Egelstaff in 1954. In 1961, B Buras attempted to apply this method at a stationary reactor with a Fermi chopper in Swierk (Warsaw). However, the intensity of this source happened to be insufficient. In 1962, B Buras initiated the arrangement of such an experiment at the IBR reactor. The experiments were successful, so the time-of-flight method in neutron diffraction was realized. In this field of research practically all further techniques for the IBR-30 reactor were proposed by researchers at the laboratory of neutron physics and subsequently applied in other neutron centers at pulsed sources. When high-flux pulsed neutron sources appeared in the middle of

the 1980s, the time-of-flight method in neutron diffraction became widespread as a powerful method for structural studies [2].

Let us now return to the spectroscopy of resonance neutrons, for which, as was already mentioned, it is desirable to have a short neutron pulse. In principle, the solution to this problem was known. In 1958, a booster-multiplier was created at the British nuclear center at Harwell that consisted of a target for photonuclear reactions placed in a subcritical assemblage and an electron accelerator-injector. In the case of the IBR reactor, a new possibility opened up — the creation of a booster with a pulsed target, or a superbooster [1, 7]. In this case, when the neutrons are injected by a pulsed electron accelerator, with the aid of a reactivity moderator the reactor receives maximum reactivity which then rapidly falls. The process of neutron multiplication is only due to prompt neutrons, while retarded neutrons that prolong the chain reaction do not have time to contribute. Since the duration of a single link of the multiplication chain in the IBR amounts to 10^{-8} s, multiplication stops in 2 μs for a multiplication coefficient equal to 200. Thus, it is possible to amplify the pulse by a factor of several hundred with its length increasing up to 3 or 4 μs. In a stationary booster with such a multiplication the pulse will become nearly critical for the retarded neutrons, and the system will cease being pulsed.

In 1965, a microtron was installed as the injector for the IBR reactor; it was constructed at the Institute for Physical Problems (IPP) of the USSR AS. In 1969, a linear electron accelerator with a pulse current of 200 mA and pulse duration of about 1 μs was established at the IBR-30 reactor. A plutonium target was initially used, and then subsequently replaced by tungsten. In 1971, D I Blokhintsev and I M Frank, together with a group of authors, were awarded the State Prize of the USSR for the "IBR research reactor and the IBR reactor with an injector". The IBR-30 reactor operated in two modes up to 1996: as a pulsating reactor, and as a pulsed superbooster. Since 1996 the reactor mode has not been used, and until 2001 IBR-30 operated as a booster-multiplier with a pulse frequency of 100 pulses per second, an average power of the multiplier-target of 12 kW, and a pulse half-width equal to 4 μs. Since 1994 JINR has been developing a project for a new pulsed neutron source IREN (the *Russ. abbr.* for the source of resonance neutrons) [8] making use of an electron linear accelerator and a multiplier-target. At the end of 2008 the first stage should be completed — without the multiplier-target.

Creation of the pulsed booster-multiplier IBR-30 became the basis for an essential development of neutron nuclear spectroscopy, which at all stages of advancement of neutron physics served as the principal supplier of experimental data [9]. Luminous neutron nuclear spectroscopy opened the way for studying highly excited nuclear states in the interval of energies from 6 MeV up to 10 MeV with an accuracy unachievable by other methods. Besides work on neutron nuclear spectroscopy, at the IBR-30 original studies were also initiated and developed in the physics of the atomic nucleus and of fundamental interactions (see, for example, Refs [4, 5]).

4. The fast pulsed reactor IBR-2

The successful operation of the IBR reactor and of its modifications stimulated further development in this area. In the middle of the 1960s several projects were started. The first announcement concerned the pulsed reactor Sora with a moving reflector and average power equal to 1 MW. The reactor was to be built at the research center of Euroatom in Ispra (Italy). A powerful periodic pulse reactor with an average power of up to 30 MW was proposed to be constructed at the Brookhaven National Laboratory (USA). In 1964, work started in Dubna on a project for a new reactor, the IBR-2. Its essential differences from the IBR reactors consisted in modulation of the reactivity with the aid of a movable reflector and in cooling the active core by liquid sodium. Of all the proposed projects of high-flux pulsating reactors, only the IBR-2 project was implemented, which became possible owing to the experience in operating such systems in Dubna and Obninsk and to the active participation of the USSR Ministry of Medium Machine Building. [1]

I M Frank at the control panel of the IBR-2 reactor (1976).

Officially, work on the IBR-2 project started in 1966, and actual construction in 1969. The first critical assemblage was

[1] Besides JINR and the Institute for Physics and Power Engineering (IPPE) (city of Obninsk, Kaluga region) a whole number of institutions of the USSR Ministry of Medium Machine Building took part in the construction of the IBR-2 reactor. The main designing institution was the Research and Development Institute of Power Engineering, development work was carried out by the State Specialized Design Institute, fuel elements were prepared by the All-Union (at present, All-Russian) Research Institute of Inorganic Materials and the Mayak industrial complex. For resolving other individual problems, other specialized institutions and design offices of the powerful industry pertaining to the Ministry of Medium Machine Building were recruited. It can be asserted that the creation of pulsating reactors represents one of the striking manifestations of the highest potential of nuclear and technical sciences in our country.

The hot core of IBR-2, which represents a tank with a volume of 22 l, which is filled with the fuel, 92 kg of plutonium dioxide. The tank is charged into the body of the reactor.

prepared at IPPE in 1968, and between 1970 and 1975 the model of the movable reflector was investigated at a test bench in Dubna. Physically, the reactor was put into operation (without the heat carrier) 8 years after the beginning of the construction: at the end of 1977 and the beginning of 1978. Then came preparation and launching of the power operation (with sodium), which was actually completed on April 9, 1982, when the average power attained was 2 MW for a pulse repetition rate of 25 Hz, and the first physical experiments were performed with extracted beams. After the death of D I Blokhintsev in January 1979, I M Frank became the scientific leader of IBR-2. Officially, the reactor was commissioned on February 10, 1984, with implementation of the program of physical experiments starting on April 9, 1984 after the power reached 2 MW for a pulse frequency of 5 Hz.

Reactor hall of IBR-2.

Experimental hall of IBR-2.

The hot zone of the reactor, 22 l in volume, contained 92 kg of plutonium dioxide. Modulation of the reactivity was realized by a steel movable reflector consisting of two parts rotating with different velocities (1500 and 300 revolutions per minute). When both parts of the reflector traversed the zone, a power impulse was generated (1500 MW). During the regular operation mode of the reactor — 2500 hours per year for experiments — the hot zone was in operation for not less than 20 years without any change of fuel, while the moving reflector could be in operation for 5–7 years. In 1995, IBR-2 started operating with a new movable reflector (the third consecutive one). In 2002, the plans were to replace the active core together with the movable reflector. However, the financial situation in the 1990s did not permit starting modernization of the reactor in time. Modernization of the IBR-2 reactor is a long-term program of scientific and technical tasks, actually representing the creation of a new reactor, only without having to construct a new building, which would take 10 years. This program was initiated in 2000 with the financial support of the RF Ministry of Atomic Energy (successor to the USSR Ministry of Medium Machine Building) and personally of the minister E O Adamov. To prolong the time of operation of the IBR-2 reactor, the average power was lowered to 1.5 MW and the operation time with power was reduced to 2000 hours per year. In December 2006, the reactor was stopped in order to replace all technological systems. In 2010, a new IBR-2M reactor is planned to be put into operation with improved parameters and modern systems for safety control.

Thus, the pulsating IBR-2 reactor is an economical, relatively cheap and, as revealed by the experience accumulated in working with it, a simple and safe device to operate. Creation of IBR-2 cost about 20 million rubles (cost in 1984). Today operation, further development, and improvement of the reactor will cost less than 1 million dollars US per year. This is 10–50 times less than for other modern neutron sources in the world. At the same time, the reactor provides a pulsed neutron flux that is a record for research neutron sources and is equal to 10^{16} neutrons per cm^2 per s.

In 1996, D I Blokhintsev and I M Frank were awarded (both posthumously) together with a group of coauthors a Prize of the Russian Government for the creation of the research high-flux pulsed reactor IBR-2.

5. The inverse time-of-flight method

The IBR-2 reactor, possessing a record high pulsed flux of thermal neutrons, had a great advantage from the standpoint of the usual formulation of a diffraction experiment for studies not requiring high resolution. However, an accuracy at the level of 1% was not sufficient for precision measurements.

The resolution of a time-of-flight powder diffractometer is described by the following expression

$$R = \frac{\Delta d}{d} = \left[\left(\frac{\Delta t_0}{t}\right)^2 + (\gamma \cot\theta)^2\right]^{1/2},$$

where Δt_0 is the width of the neutron pulse, γ describes the geometric uncertainties, $t = 252.778\, L\lambda$ is the neutron time of flight from the source to the detector, λ is the neutron wavelength, and θ is the Bragg angle. Clearly, the time contribution can be reduced by either reducing Δt_0 or by increasing the path of the neutron flight, i.e., by moving the sample away from the neutron source.

For example, at one of the best powder diffractometers in the world (HRPD, or High-Resolution Powder Diffractometer) at the pulsed neutron source ISIS (In situ Storage Image Sensor) at the Rutherford–Appleton Laboratory (RAL, Great Britain), the resolution amounts to $\Delta d/d \approx 6 \times 10^{-4}$ within quite a broad interval of wavelengths. This resolution is practically the limit of the achievable value for structural studies with either neutrons or X-rays. However, with the width of the neutron pulse amounting to $\Delta t_0 \approx 15$ μs Å^{-1}, the time-of-flight base at HRPD reaches $L = 100$ m. As a result, the neutron flux hitting the sample exhibits the quite moderate value of $\Phi_0 \approx 10^6\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.

In the case of the IBR-2 reactor, such a usual method for enhancing the resolution by increasing the flight base is of no use because $\Delta t_0 = 320$ μs. Therefore, the inverse time-of-flight method making use of a Fourier chopper was proposed and adapted for use at the IBR-2 reactor [2]. The key element of the scheme proposed was a Fourier chopper which, unlike the ordinary Fermi chopper, has many slits instead of one. In our case, it is a disk 50 cm in diameter with 1024 slits, the width of which (1 mm) equals the distance between them. The disk rotates with a variable velocity of up to 9000 revolutions per minute. At the maximum revolution velocity, the pulse length is reduced to 2 μs. Since there are many slits, the neutron flux decreases insignificantly, but the recycling effect shows itself, resulting in the registered spectra overlapping. The idea of the inverse time-of-flight method that permits deciphering overlapping diffraction spectra consists in the following. Although it is not possible to say precisely which velocity a neutron registered by the detector had, it is possible to indicate which velocities it could have had by controlling the state of the chopper and of the reactor at corresponding preceding instants of time. It turns out that by varying the revolution velocity of the chopper from zero up to a certain maximum velocity and by accumulating a large number of events sorted out in this manner, it is possible to obtain a usual spectrum of elastically scattered neutrons, evolved in time. The possibility of sorting is provided by the formation of fiducial signals coinciding with the instants of time when the reactor and chopper are in an 'open' state and controlling operation of the fast shift register through which the accumulation of detector signals proceeds. The time part of the resolution function assumes the form

$$R(t) \sim \int_0^{\Omega_\mathrm{m}} g(\omega) \cos\omega t \, \mathrm{d}\omega\,,$$

where $g(\omega)$ is the frequency distribution function, and Ω_m is the maximum revolution frequency of the Fourier chopper. In the simplest case, $g(\omega)$ can be approximated by the Blackman function. In this case, the half-width $R(t)$ is equal to Ω_m^{-1} and can be made equal to 7 μs. Then, one has

$$\frac{\Delta t_0}{t} = \frac{\Delta t_0}{253 L\lambda} \approx \frac{10^{-4}}{d}\,.$$

The high-resolution Fourier diffractometer (HRFD) at the IBR-2 reactor has the following parameters: $\Delta d/d \approx 5 \times 10^{-4}$ ($d = 2$ Å), $L = 20$ m, and $\Phi_0 \approx 10^7\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.

Creation of the HRFD at the IBR-2 reactor was of essential importance. First, the possibility arose of performing precise structural studies, which was immediately made use of for studying new materials, such as high-temperature

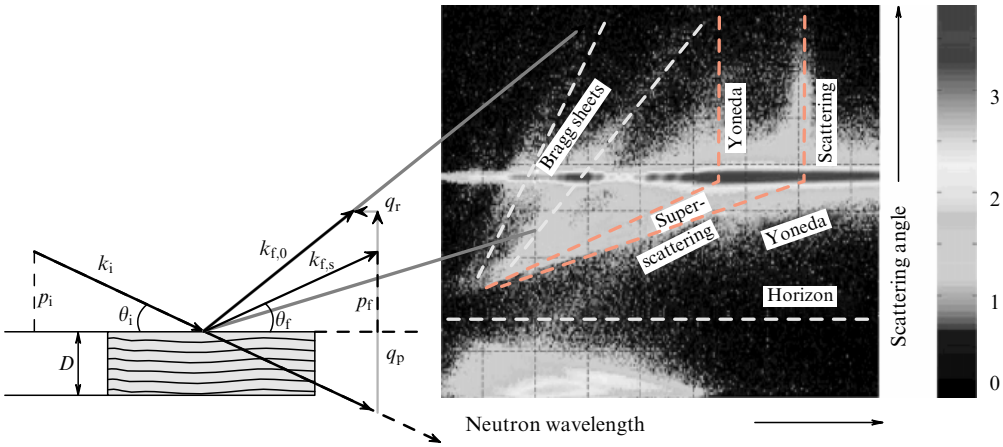

Figure 1. Layout of a reflectometric experiment. The angle $\theta_i \leqslant \theta_c$, where θ_c is the critical angle at which total external reflection occurs. If the angle of the reflected beam $\theta_f = \theta_i$, then the reflection is specular; if $\theta_f > \theta_i$, then off-specular. k_i is the wave vector of the incident neutron, $k_{f,s}$, $k_{f,0}$ are the wave vectors of the neutron in the case of specular and off-specular reflection, respectively; $p_{i,f}$ are the projections of the wave vectors onto the normal to the surface: $p_{i,f} = k_{i,fs} \sin \theta_{i,f}$.

superconductors [11] and manganites with giant magnetoresistance [12]. Second, it was shown that if sources of long-pulse neutrons are handled skillfully, they exhibit practically the same feasibilities as short-pulse sources based on proton accelerators, and the cost of the latter is one or two orders of magnitude higher. This experience is already being applied throughout the world. Thus, the new European neutron supersource (European Spallation Source, ESS) is projected as a source with a long pulse.

With the commissioning of the HRFD, the creation of a broad-profile complex of spectrometers at the IBR-2 was completed. This complex permitted obtaining a number of original results in studies of the structure of materials. For the development and realization of new methods of structural neutronography at pulsed and stationary reactors, a team of authors from JINR, the B P Konstantinov Petersburg Institute of Nuclear Physics of the Russian Academy of Sciences, and the Russian Research Centre 'Kurchatov Institute' was awarded the RF State Prize in science and technology in 2000.

6. IBR-2 in studies of nanomaterials

The parameters of the IBR-2 reactor — the record high thermal neutron flux in the pulse, and a high fraction of cold neutrons in the spectrum — are ideal for carrying out research into the condensed state of matter. Today, the IBR is applied effectively in studies of problems of the physics of condensed media, chemistry, the materials science, molecular biology, the synthesis of composites for pharmacology and creating materials for medicine, as well as in the engineering sciences and geophysics [5]. Among the objects of research there are also materials that have recently been considered a separate class of nanomaterials. The IBR-2 reactor is also efficient as a physical device for interdisciplinary studies, exhibiting radiation parameters in the nanorange, as well as for nanodiagnostics and investigations of nanomaterials (see, for example, Ref. [13]).

I M Frank supported studies of condensed media, being particularly interested in the problems of biology and biophysics and in the development of methods for neutron optics. Thus, for example, he was attracted by the problem of describing optically the behavior of neutrons in the case of their grazing incidence on the surfaces of dense materials. This branch of neutron optics started developing rapidly in the middle of the 1980s after the appearance of high-flux pulsed neutron sources, such as IBR-2. It turned out to be that reflectometry (this is the term used for methods of studying surfaces, thin films, and interfaces in layered structures based on neutron optics in the case of grazing incidence angles), like diffraction, has its advantages for time-of-flight experiments. The utilization of polarized neutrons is of particular interest for neutron reflectometry [14].

The JINR's Laboratory of Neutron Physics was among the pioneers in creating a new scientific line of research — the optics of polarized neutrons for grazing incidence angles (reflectometry of polarized neutrons), and all the issues related to establishment of this line of research were discussed with I M Frank. At present, the reflectometry of polarized neutrons has been established as one of the powerful currently available methods for diagnostics and investigation of nanostructured materials. Neutron reflectometry constitutes an ideal method for studying and diagnosing nanostructured materials, for example, layered systems and systems with structured surfaces. The weak interaction of neutrons with matter makes this method nondestructive when the radiation penetrates deep into the sample. In the case of objects containing hydrogen there exists an excellent contrasting method with the aid of deuterium exchange. Finally, new research methods taking advantage of the magnetic moment of the neutron open up new possibilities for studying magnetic and nonmagnetic nanosystems.

During the last decade, on a level with advancing the technique of specular reflection, which provides information on the in-depth structure of a sample (say, along the z-axis), successful development is also proceeding on the technique of nonspecular (diffuse) scattering, which permits obtaining information about the structure variations in the plane of the sample along one of the coordinates (say, along the x-axis). Finally, in recent years the technique of small-angle scattering close to the grazing angle (Grazing Incidence Small-Angle Neutron Scattering, GISANS) has started to develop, and it yields information on structural changes in the plane of the sample along another coordinate (coordinate y). Thus, the possibility arises of the complete investigation of the structure of low-dimensional systems at the nanolevel. Typical examples of nanosystems investi-

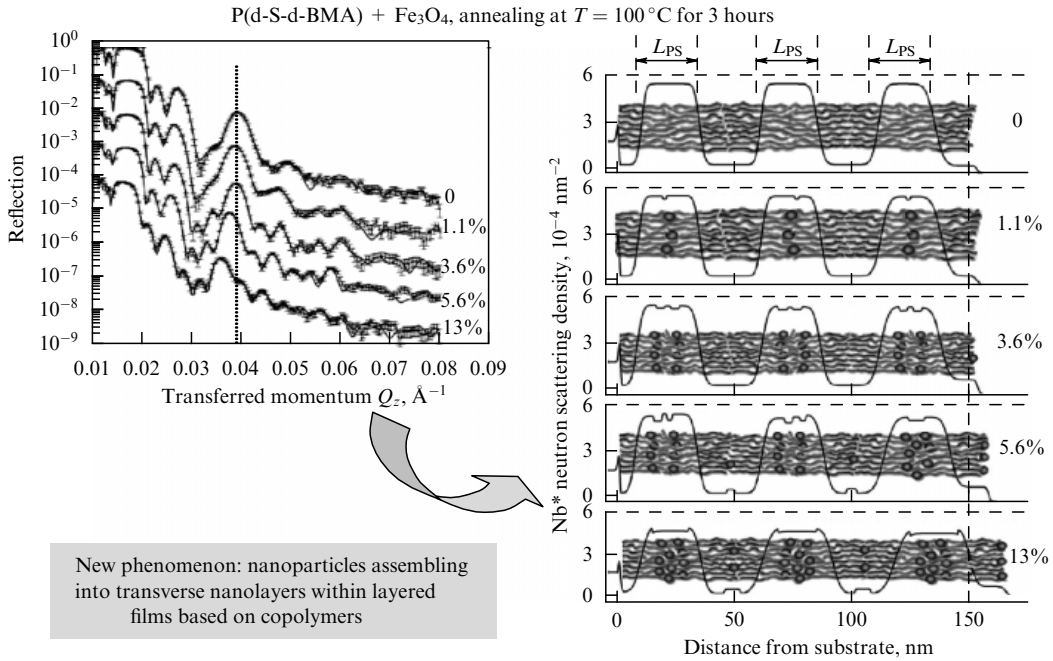

Figure 2. Distribution of magnetite nanoparticles (points) in P(d-S-d-BMA) depending on their concentration and obtained from experimental data on specular and off-specular neutron scattering [15]. The respective percentages of nanoparticles in the samples are indicated to the right of the curves.

gated with the aid of neutron reflectometry include magnetic multilayer films, stripe structures, quantum dots, nanowires in porous silicon, polymers with the inclusion of magnetic nanoparticles, multilamellar vesicular bodies, and magnetic liquids.

The layout of a reflectometric experiment is essentially simple (Fig. 1). A neutron beam with a wave vector k_i is incident on the surface of the sample at a small grazing angle θ_i. In the case of specular reflection, when the angle of the reflected beam $\theta_f = \theta_i$, the transferred momentum $q = k_f - k_i$ (where k_f is the wave vector of the reflected beam) is perpendicular to the substrate. In the case of nonspecular reflection ($\theta_f > \theta_i$) there appears a component, parallel to the surface of the substrate, of the transferred momentum, q_x, that carries information on distortions of the surface in this direction, for example, of roughnesses or of nanoparticles introduced into the medium. In the case of a time-of-flight experiment, the intensity of the specular reflection on the detector, which depends on the neutron wavelength, is registered at a fixed point (at the angle of reflection). The intensity of the nonspecular scattering is 'seen' at points above and below the line of specular reflection in the form of wings of the Bragg scattering, responsible for the condition $q_0 = p_i + p_f = \text{const}$, or Yoneda scattering, for which $k_i = k_c$ or $k_f = k_c$, where k_c is the critical value of the wave vector, for which the condition of total external reflection of the neutrons is satisfied.

The advantage of a time-of-flight experimental technique consists in the fact that the direct beam does not come close to the line of intensity of the specular reflection as it does in the case of constant-wavelength reflectometers, where it is necessary to rotate the sample. As a result, when the time-of-flight technique is applied, the intensity of the background for the critical angle and large wavelengths in the region of Yoneda scattering turns out to be very low compared to the background intensity in the method where the angle θ_i is variable and the wavelength is constant.

In a reflectometric experiment, specular reflection from an ideal flat multilayer structure, i.e., without any roughnesses on the surface or at the interlayer boundaries, gives the value of the film's thickness D, which is determined by the position of oscillations of the reflection coefficient R at points of the inverse space, $q = 2\pi n/D$. In the case of a multilayer system, the positions of the Bragg peaks $q = 2\pi n/d$ yield the values of the layer thicknesses d. The intensity of the Bragg peaks grows with increasing the contrast of neutron scattering between the layers. Nonspecular scattering arises when there are roughnesses at the boundaries between the layers and on the surface. Magnetic inhomogeneities may also be sources of nonspecular scattering.

The intensity of nonspecular scattering depends not only on the intensity of scattering from the roughnesses in the layers, but also on the change in amplitude of the neutron wave field inside the multilayer system, caused by multiple reflections and passages of neutrons through the interlayer boundaries. These processes of resonance amplification are taken into account by the Born approximation of distorted waves. In single-layer thin films, for example, in liquid films, these effects are absent and, subsequently, no high-intensity Bragg wings arise.

As an example of neutron nanodiagnostics, we shall consider investigation of a magnetic polymer layered structure, representing a thin film of a symmetric diblock-polymer made of deuterized polystyrene (d-PS) and polybuthylmethacrylate (PBMA). Such a system, P(d-S-d-BMA), constitutes a self-assembled matrix for lamellar arrangement of nanoparticles in the magnetite Fe_3O_4 [15]. Self-organizing polymer films are quite promising artificially created functional materials in which the polymer matrix serves as a medium for nanoparticles of various properties. As a result, a new functional material is obtained with properties formed on a nanoscale.

In the example considered, the material is created by mixing the components layer-by-layer by rotation (spin-

Table 1. Parameters of the nanocomposite P(d-S-d-BMA) $+Fe_3O_4$.

Parameter	$x = 0$	$x = 13\,\%$
D, nm	153.3 ± 1.0	170.5 ± 1.0
L, nm	50.2 ± 0.5	55.3 ± 1.0
L_{PS}, nm	24.4 ± 0.5	29.0 ± 1.0
ξ, nm	600.0 ± 5.0	400.0 ± 5.0
σ, nm	3.5 ± 0.5	5.8 ± 0.5
ζ	6	4

coating). The base matrix in the form of a lamellar structure results from annealing. The magnetic nanoparticles introduced into one of the diblock-copolymers form nanosheets of dimensions depending on the concentration of nanoparticles. One problem consists in investigating the stability of the structure of such a composite polymer film. The stability problem of structures obtained by self-assemblage is common for nanotechnologies. When the conditions for the stability of a new material are found, its physical properties (in our case, magnetic) can start to be studied.

As seen from Fig. 2, the nanoparticles of magnetite assemble into PS-layers and thus avoid interaction with PBMA. This represents a new phenomenon. Already in 1907 S U Pickering found that mixtures are stabilized by nanoparticles that are resided at the interfaces between the components. But here, nanoparticles assemble into nanosheets within the layers of the copolymer multilayer film.

The parameters of the composite determined from the neutron experiment are given in Table 1 for a pure system (the admixture concentration $x = 0$) and for a system with the admixture concentration $x = 13\%$.

From a structural point of view, the introduction of admixtures results in the following changes. The total thickness D of the composite film increases. This increase is due to the thickness L of each bi-layer increasing, which, in turn, is caused by enhancement of the thickness L_{PS} of the PS layer.

A noticeable enhancement of the roughness parameter σ is observed, which signifies weakening of the composite's stability. This is also testified to by the behavior of the correlation length ξ in the layer (the size in the domain plane). A decrease in ξ signifies a change in the parameters of the boundaries between the layers and a decrease in the elasticity γ between the two polymers. This serves as one more indication that the composite's stability is reduced.

The decrease in the conformity parameter ζ signifies an enhancement of the noncoincidence between the interlayer roughness boundaries and the boundaries of the domains.

The structural data presented on the arrangement of nanoparticles and on their influence on thicknesses and other parameters of the layers represent important information for technologists.

7. Conclusion

Thus, the pulsed nuclear reactors created at the Joint Institute for Nuclear Research with the active participation of I M Frank have during the nearly 50 years of their operation permitted forming a whole series of scientific lines of research in neutron physics that have become determinant throughout the world. The scientific school in neutron optics that arose under the leadership of I M Frank is still being developed by several generations.

While appreciating the enormous contribution by I M Frank to the development of world and domestic science and to the defensive capability of our country, I believe that at the same time one may conclude that his legacy includes the no less important influence he exerted on the people surrounding him, which still continues to be felt. No one can better express this influence than he himself. In his memoirs about his teacher, I M Frank wrote [16]: "...the creative legacy of such physicists, like S I Vavilov, does not only include works signed by him, or works done by his collaborators and pupils, who continue to work on the same problems. There exists something no less important, which, however, cannot be quoted in published works. This is the ideological influence, direct or indirect, exerted by a scientist... . Precisely this represents the influence that must be considered the scientific school of the scientist, which cannot be simply identified with all those who worked or work under his direct leadership. Here, I also mean something more significant than help in organizing the work, although, in the conditions of modern science, it does play a most important role. Also essential is another thing — the individual influence of the scientist which in many respects cannot be separated from his human characteristics."

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