must be wrong in my recalcitrance. And I signed the letter, but now I cannot forgive myself.''

On January 3, 1990, a Dubna newspaper published I M Frank's article entitled ''The truth invariably gains the upper hand''. It contained the following words:

''Recently we experienced a severe shock. The great fighter for justice A D Sakharov passed away, and the mental anguish has not yet subsided. Of course, no one forgets about the persecutions which he recently endured. The blame is to be ascribed also to the USSR Academy of Sciences. I was not among those who condemned the awarding of the Nobel Peace Prize to him, and I believe this award to be well-deserved. However, a part of the blame for what the Academy of Sciences published against Sakharov should be ascribed to me. I realized it many years ago and never forget about it. Like D S Likhachev I say not only 'Farewell to you', but also 'Forgive me'.''

The title of the newspaper article — ''The truth invariably gains the upper hand'' — is a part of a phrase which I M Frank heard from S I Vavilov: ''The truth invariably gains the upper hand, but human life may turn out to be not long enough for that.''

Of the forty academicians who signed the letter against Sakharov, I know of only two of them who expressed their apologies to him. They are Il'ya Mikhailovich Frank (his words are given above) and Sergei Vasil'evich Vonsovskii. Vonsovskii confessed at a general meeting of the Academy of Sciences in Sakharov's presence. And my respect for these two physicists — Vonsovskii and Frank — became even more profound after that.

* * *

The times in which Il'ya Mikhailovich Frank lived and worked were ones of rapid progress in physics in our country. This time has been superseded by a period of disorder and stagnation. It is necessary to restore much of what was lost during the last decades. To restore and go further. And the memories of those who earlier paved the way to knowledge, the comprehension of their experience, achievements and, last but not least, standards of morality will contribute to faster advancement.

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I M Frank and the development of the Joint Institute for Nuclear Research

A N Sissakian, M G Itkis

Il'ya Mikhailovich Frank belongs to the brilliant constellation of physicists in our country over the past century. He was born on October 23 (October 10 according to the Old Style), 1908 in Saint Petersburg into a family that gave Russian culture several outstanding public figures (his father, Mikhail Ludvigovich Frank, a mathematician and professor at the Crimea (Tavrichesky) University; his brother, Gleb Mikhailovich Frank, a well-known biophysicist and Full Member of the USSR Academy of Sciences; his uncle, Semyon Ludvigovich Frank, an outstanding Russian philosopher and psychologist). In 1926, Il'ya Mikhailovich entered Moscow State University. After graduating from there in 1930 he worked for several years at the State Optical Institute (SOI) in Leningrad, where he studied photochemical reactions by optical methods. His original work in this field served as the basis for conferring a doctorate on twenty-six-year-old I M Frank.

In 1934, Il'ya Mikhailovich started working at the P N Lebedev Physical Institute (LPI, RAS), which at the time was headed by S I Vavilov. Here, in 1937, in a work that became a classic, I E Tamm and I M Frank gave a comprehensive explanation of the 'mysterious Vavilov–Cherenkov glow', for which in 1958 Cherenkov, Frank, and Tamm received the Nobel Prize in Physics.

In the following years, Il'ya Mikhailovich concentrated more and more on research in the field of nuclear physics. In 1946, he became head of the Laboratory of Atomic Nucleus, newly established at LPI, RAS. One of the important problems in this field, which Il'ya Mikhailovich and his collaborators started to resolve, consisted in precise determination of the parameters of uranium–graphite lattices and in elucidating the physical regularities of neutron transport in them. The proposal put forward by Il'ya Mikhailovich to make use of a pulsed neutron source in these studies was a new idea. In 1956, I M Frank started working in Dubna, at the Joint Institute for Nuclear Research (JINR).

As is known, on March 26, 1956, in the conference hall of the RAS Presidium in Moscow an agreement was signed that established an international research organization called the Joint Institute for Nuclear Research. The institute comprised two already active laboratories: a laboratory of the Institute of Nuclear Problems of the USSR Academy of Sciences and the Electro-physical Laboratory of the USSR Academy of Sciences, which were further called the Laboratory of Nuclear Problems and the Laboratory of High Energies within the structure of the new institute. However, during the discussion of its structure at the Academy of Sciences, D I Blokhintsev, the first JINR director, proposed creating and including in the JINR structure, in addition to the two laboratories, a Laboratory of Theoretical Physics (LTP) and a Laboratory of Neutron Physics (LNP) based on a reactor with a high-density neutron flux. D I Blokhintsev's proposals were approved and reflected in the concluding announcement about the organization of JINR. He also asked I M Frank to work at JINR. Thus, in 1956 the Laboratory of Neutron Physics was organized, and it was subsequently named after its founder and first elected director, I M Frank, who occupied this position for over 30 years, and the last two years of his life he was the LNP honorary director (the person asked to be the first LTP director was the remarkable scientist N N Bogoliubov, mathematician, mechanic, theoretical physicist). Blokhintsev himself transferred to JINR from the Institute for Physics and Power Engineering in Obninsk, where in 1955 he proposed the idea of an original pulsed fast-neutron reactor of periodic action. The theory of such a reactor was fully developed in 1956, although its publication in the open press took place only in 1959 [1].

The decision was taken to create such a reactor in Dubna, and I M Frank was asked to direct the work. The choice was naturally not arbitrary. For many years Il'ya Mikhailovich had been in charge of the laboratory at LPI, RAS, the main task of which was the development of issues relevant to the creation of nuclear reactors in the Soviet Union.

Frank himself recalled: ''I was instructed by Igor' Vasil'evich Kurchatov to work at and even to control operation of the first Soviet reactor nearly immediately after it was commissioned — that is, at the end of 1946, the beginning of 1947'' [2].

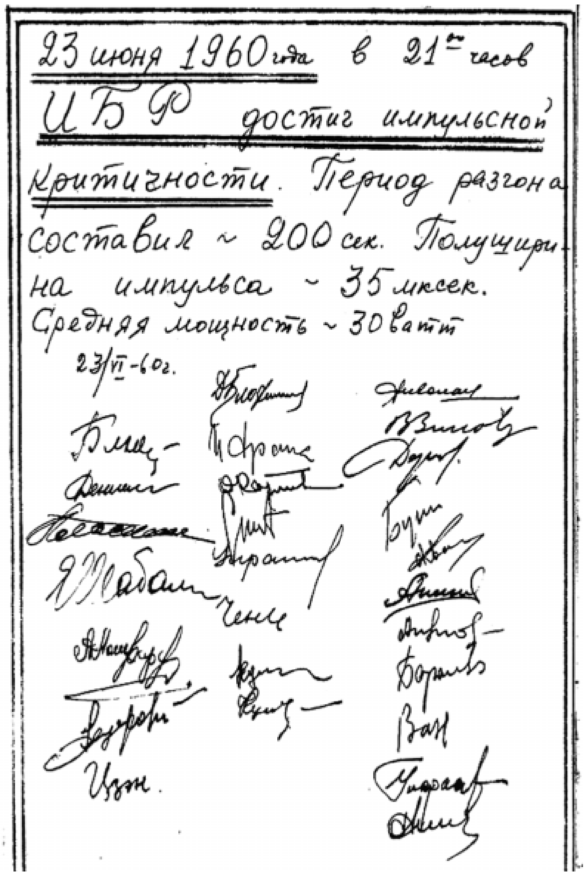
23 июня 1960 года в 21 часов
ИБР достиг импульсной
критичности. Период разгона
составил ~ 200 сек. Полуширина
импульса ~ 35 мксек.
Средняя мощность ~ 30 ватт
23/VI-60г.

Figure 1. Extract from the operative journal of the IBR-1 reactor, stating the achievement of pulsed criticality.

In parallel, the laboratory also dealt with other issues of nuclear physics, including the interaction of fast and slow neutrons with nuclei, nuclear fission, and the investigation of neutron reactions with light nuclei, of neutron diffusion in various media, etc.

In May, 1957 at the session of the JINR Scientific Council, Il'ya Mikhailovich presented a talk on the project of a reactor and on the potential of its application in scientific research. Immediately after approval of the project by the Scientific Council, its realization was initiated. The pulsed character of the operation of the new neutron source required development of original equipment for the control and safety systems, and for dosimetric control. For the first time in the USSR, a multichannel time analyzer was developed for time-of-flight experiments. A significant part in the implementation of this unique project was also played by staff members of the Research and Development Institute of Power Engineering (RDIPE) under the leadership of N A Dollezhal.

In 1959, the main construction work and work on creation of the equipment for the reactor called IBR (the Russian abbreviation of pulsed fast reactor) were completed, and assembly work started. On June 23, 1960 the reactor was put into operation in the mode of pulsed criticality, and its main parameters were measured and fully complied with the predictions of calculations. Figure 1 shows a photograph of an extract from the operative journal of the experimental installation, in which the signatures of all the participants, including I M Frank and D I Blokhintsev, can be seen.

At the ninth session of the JINR Scientific Council a report was presented under the title "The pulsed reactor of the

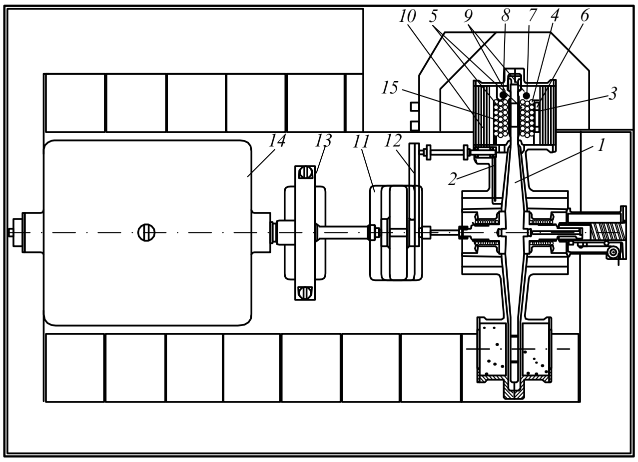

Figure 2. Layout of the reactor: *1*, main rotating disk; *2*, auxiliary rotating disk; *3*, main movable core (MMC); *4*, fixed active core; *5*, emergency rods (ERs); *6*, plate of rough regulator (RR); *7* and *8*, regulating rods; *9* and *10*, neutron reflector; *11*, gearing for enhancing the number of revolutions; *12*, driving gear for shaft of auxiliary disk; *13*, decelerating device for rapid stopping of rotation; *14*, electric motor for rotating disk, and *15*, auxiliary movable core (AMC).

Laboratory of Neutron Physics at the Joint Institute for Nuclear Research". This report described the principle of operation of this unique installation, which has no analogs in the world. The fundamental layout of IBR is depicted in Fig. 2 [3]. The pulsed character of the reactor operation was provided for by the active core *4*, which consisted of metallic plutonium, divided into two parts, in between which there was a rotating steel disk *1*, into which inserts of enriched uranium were pressed. When the uranium insert coincided with the fixed active core, the reactor for a short time underwent transition to the above-critical state and the generation of a powerful neutron pulse occurred. The average power of IBR-1 amounted to 1 kW, the length of the neutron pulse was 40 μs for a pulse repetition rate equal to 8.3 s^{-1}. The peak (pulse) power amounted to 3 MW.

Even these parameters permitted IBR to become the world's best installation for investigation of low-energy nuclear resonances and reactions exhibiting small cross sections. In Ref. [4], the parameters of the Dubna reactor are compared to the parameters of neutron sources of that period based on accelerators and stationary neutron sources.

The power of the reactor was subsequently increased to 6 kW. In 1965, for reducing the length of the neutron pulse, application of a microtron developed under the leadership of S P Kapitsa was proposed. Electrons accelerated up to an energy of 30 MeV irradiated a tungsten target and, thus, generated primary neutrons owing to photonuclear reactions. These neutrons then multiplied within the active core of the reactor. As a result, it turned out to be possible to reduce the neutron pulse length to 3 μs. In this configuration, the installation operated until 1968.

On June 10, 1969 the new reactor IBR-30 was commissioned under the guidance of I M Frank, its average power amounting to 25 kW (the pulse power of the reactor was 100 MW) for a neutron pulse length of about 60 μs and pulse repetition rate of 5 Hz. These parameters were achieved owing to the new construction of fuel elements of the active core of the reactor and to the use of two uranium inserts in the rotating steel disk, instead of one, as in IBR-1. The resulting

Table 1. IBR-30 parameters.

Date of physical commissioning Beginning of operation of electron injector	June 10, 1969 March 24, 1970
Average thermal power*	25 kW
Total neutron flux	1.3×10^{15} n s^{-1}
Average flux density of thermal neutrons on the surface of the moderator	5×10^{10} n cm^{-2} s^{-1}
Pulsed flux density of thermal neutrons on the surface of the moderator	10^{14} n cm^{-2} s^{-1}
Flux of resonance neutrons at a distance of 100 m, reduced to a power of 1 kW, in the 1 eV – 10 keV range	$F(E) = \dfrac{2.7 \times 10^6}{E^{0.9} L^2} W$ [n cm^{-2} s^{-1} eV^{-1}], where E is the neutron energy in [eV], L is the time-of-flight base in [m], W is the power in [kW]
Neutron pulse length	4 μs
Repetition rate	100 Hz
* After the Chernobyl accident (1986) work was carried out only in the booster mode at a power of not more than 10 kW.	

neutron flux from the new installation was nearly 100 times larger than the maximally attainable fluxes at neutron sources based on electron accelerators existing at the time.

On March 24, 1970 a new injector, based on the linear electron accelerator LEA-40, was commissioned. As a result, it became possible to operate the installation not only as a pulsed reactor, but also in the electron booster mode (IBR-30+LEA-40). This permitted implementing a whole series of original scientific experiments, both in the field of nuclear physics and in the field of neutron studies of condensed media, which will be briefly dealt with below. The neutron source in the IBR-30+LEA-40 configuration operated for physical experiments for nearly 80 thousand hours until June 2001. The main parameters of IBR-30 are presented in Table 1.

For the development and creation of pulsed research reactors and pulsed boosters, I M Frank, together with a group of authors, was awarded the USSR State Prize in 1971.

As mentioned above, the reactor was created for research in the field of nuclear physics. In a series of research lines pioneering results were obtained, many of which are still being actively developed at world research centers. I M Frank worked out the scientific program of research in the Laboratory of Neutron Physics in close collaboration with his deputy, friend, and closest colleague F L Shapiro. Part of the scientific program developed and realized at the LNP is briefly described below.

High-luminosity spectroscopy of neutron resonances. Having no electric charge and, consequently, no Coulomb barrier preventing a neutron from penetrating into a nucleus, neutrons can be used for obtaining excited nuclei lying in the region of beta-stable isotopes. The capture of a neutron by a nucleus results in an excited state of a compound nucleus with an energy close to the neutron binding energy with a lifetime of the order of 10^{-15} s and an energy width of about 0.66 eV. Considering the nuclear reaction to be a process proceeding via two independent stages, the reaction cross section may be represented as [5]

$$\sigma_x = \sigma_c w(x) , \tag{1}$$

where σ_c is the production cross section of the compound nucleus, and $w(x) = \Gamma_x/\Gamma$ is the branching ratio of its decay via the channel involving the production of particle x. The energies and widths of the nuclear levels of the compound nucleus can be determined by studying resonance behavior in the energy dependences of the cross sections. Registering of various decay channels of compound states permits determining the partial decay probabilities of the compound states.

Effects of hyperfine interaction in neutron resonances. One of the most striking examples demonstrating the potential of the technique of neutron spectroscopy at the IBR-30 reactor is presented by experiments making use of hyperfine interaction effects in neutron resonances for investigation of the properties of compound states, namely, of magnetic moments and of the root-mean-square radii of nuclei. Series of such studies were carried out at the LNP in the years 1973–1976 [6, 7] and in 1981 [8].

Conventional methods for measuring the magnetic moments of nuclei (based on the Mössbauer effect and on the perturbation of angular correlations) could not be applied in the case of compound states. F L Shapiro [9] was the first to point to the possibility of measuring magnetic moments of neutron resonances taking advantage of the energy shift in neutron resonances due to hyperfine interaction of the magnetic moment of a nucleus with the interatomic magnetic field in experiments with polarized neutrons or nuclei. The mechanism by which an energy shift in the position of a neutron resonance appears is explained by the existence of an interatomic magnetic field H, the interaction of which with the nucleus exhibiting spin I, spin projection m, and magnetic moment μ_0 results in an energy shift $\mu_0 Hm/I$, a similar shift being experienced, also, by the compound nucleus; thus, the resulting shift is expressed in the form

$$\Delta E_{mm'} = H\left(\frac{\mu_b m'}{J} - \frac{\mu_0 m}{I}\right). \tag{2}$$

To obtain the final expression describing the shift of a neutron resonance, ΔE_0, one must take the sum of $\Delta E_{mm'}$ over all possible states, taking into account the statistical weights and populations of the sublevels. Thus, in the case of zero polarization $f_n = 0$ of the neutron beam, we arrive at

$$\Delta E_0 = -f_N H\left\{\left[1 - \frac{1}{(2I+1)(I+1)}\right]\mu_b - \mu_0\right\}, \quad J = I + \frac{1}{2},$$

$$\Delta E_0 = -f_N H(\mu_b - \mu_0), \quad J = I - \frac{1}{2}. \tag{3}$$

The quantity ΔE_0 turns out to be quite small: assuming μ_b and μ_0 to differ from each other by one nuclear magneton, and the field on the nucleus to amount to 10^6 Oe, the shift turns out to be equal to $\Delta E_0 \approx 3 \times 10^{-6}$ eV, which is 4–5 orders of magnitude less than the proper width of the neutron resonance.

At the IBR-30 reactor, the transmission of neutrons through metallic foils of the rare-earth elements Tb, Dy, Ho, and Er was observed by the time-of-flight method. The nuclei of these elements were polarized by deep cooling (≈ 30 mK) in a cryostat with dilute solutions of ^{3}He in ^{4}He. The internal magnetic fields on the nuclei of these elements were of the order of $(3-7) \times 10^6$ Oe, and polarization of the nuclei inside the domains was between 0.84 and 0.99. For destruction of the polarization, the temperature on the target was increased to 0.5–1.5 K. Alternating measurements with polarized and nonpolarized nuclei made it possible to take time-of-flight spectra in which the relative shift of resonances was described by expression (3). To derive the value of the shift, the spectra were fitted by the method of least squares. Prolonged measurements (for about 300 h for each element) permitted deriving the values of magnetic moments of the nuclear compound states. Analysis of the data on magnetic moments of rare-earth nuclei, in spite of its relatively low precision (here one must acknowledge the skill manifested by the experimenters and the stability of the neutron source: the shifts in the resonances measured were of the order of 10^{-4} of their proper width), permits, nevertheless, providing a general description of the magnetic moments of compound states of rare-earth nuclei and comparing them with the theoretical estimates of these values. Theoretical analysis has permitted making the conclusion that the description of magnetic moments of the compound states of nuclei within the framework of the statistical model is rightful and, thus, the model receives confirmation in one more field.

Violation of space* (P) *and time* (T) *parity in compound nuclei. In accordance with the model of universal electroweak interaction, the Hamiltonian describing the interaction of nucleons in a nucleus can be represented in the form $H = H_0 + W$, where W is a small addition, due to the weak interaction, that violates P-parity. The existence of such a term in the Hamiltonian can result in the appearance of P-odd additions in the experimentally examined quantities. Estimations made for simplest one-particle nuclear processes have shown that the magnitudes of such effects should amount to $10^{-6} - 10^{-7}$; however, there have also been approaches within which it was shown that in complex nuclei the mixing of excited states of different parities and of the same spin (s- and p-resonances of the same spin in the case of excited states produced by neutron capture), resulting in P-odd effects, may be significantly heightened when they are close to each other in energy. Such heightened effects were observed in experiments starting from 1964 [10]. In the middle of 1981, publication started of experimental works carried out in the LNP of JINR at IBR-30 [11–14], in which for a number of nuclei the dependence of the total neutron cross sections on the neutron helicity was studied. Experimentally, measurement was performed of the transmission effect:

$$\varepsilon = \frac{T_+ - T_-}{T_+ + T_-}\,, \tag{4}$$

where $T_\pm = \exp(-n\sigma_\pm)$ represents the transparencies of the target for neutrons with positive and with negative helicities, and n is the target thickness expressed by the number of nuclei per square centimeter, from which the magnitude of the P-odd effect and, if the spins of the mixing resonances are known, the weak matrix element are derived. The area of the target amounted to 30 cm^2, the neutron beam polarization was at a level of 60%, which was provided for by a polarized proton target designed and made in the LNP on the base of lanthanum–magnesium nitrate $[(La_2Mg_3(NO_3)_{12} \times 24H_2O$ with a paramagnetic admixture of ^{142}Nd substituting for La in the extent of 0.4%.

The dependences of the total cross sections on the neutron helicity were measured for 14 resonances of the nuclei ^{81}Br, ^{93}Nb, ^{111}Cd, ^{117}Sn, ^{127}I, ^{139}La, ^{145}Nd, and ^{238}U. In the case of four resonances, a statistically significant effect due to the violation of spatial parity was found for the first time. Further development of these studies led to a broad international collaboration involving participants from JINR, the USA, Holland, Japan, and Canada (the Triple Collaboration). This collaboration resulted in several dozen p-wave resonances in different nuclei studied and their spins being determined, which made it possible to derive the weak matrix element from experimentally observed effects and to obtain values of root-mean-square weak interaction matrix elements that are in agreement with theoretical predictions.

The alpha decay of compound nuclei. In accordance with the notion of a nuclear reaction resulting in the production of a compound nucleus via a two-stage process, investigation of the (n, α)-reaction with resonance neutrons is interesting from two standpoints. On the one hand, it represents a line of research in neutron spectroscopy that permits studying total and partial alpha widths — a set of characteristics of neutron resonances complementary to the known neutron and radiative widths. On the other hand, it involves the alpha decay of complex highly excited compound states. Since the lifetimes of compound states are much longer than nuclear times, a compound state can be considered quasistable, and its alpha decay can be dealt with by analogy with the alpha decays of the ground states of nuclei.

In a number of cases the investigation of alpha decays of compound states permits putting aside the individual structural peculiarities of the decaying state and essentially broadening the range of energies and half-life periods studied. Thus, the alpha decay energy of the ground state of the ^{144}Nd nucleus is $E_\alpha^0 = 1.83$ MeV, while for the compound states it is $E_\alpha^c = 9.4$ MeV. This leads to a difference of 33 orders of magnitude between the half-life periods of the ground and excited states of the ^{144}Nd nucleus.

One of the possible decay paths of the excited state of a nucleus consists in the emission of a gamma quantum and the subsequent alpha decay of the produced intermediate state. Here, the energy spectrum of alpha particles will exhibit, together with narrow peaks corresponding to direct alpha transitions to the ground and excited states, a broad maximum due to the gamma–alpha process. Since a large number of intermediate states take part in a two-stage process, this will result in a good averaging of its probability and permit making quite general conclusions regarding the properties of intermediate states and the peculiarities of gamma transitions with energies $\leqslant 1$ MeV between the highly excited states (C$-$C transitions).

The calculated energy dependence of the alpha width averaged over the alpha spectrum was used for restoring the relative energy dependence of the radiation force function of the primary gamma quanta. At the same time, the precision in the absolute determination of the force function turned out to be low owing to the limited calculation accuracy of the barrier penetrability for the alpha particle. Studies of the (n, α)-reaction cross sections [15–17] averaged over the resonances permitted essentially enhancing the effective number of resonances and reducing the normalization uncertainty in calculating the barrier penetrability. All the above permitted performing straightforward restoration of the absolute value of the radiation force function of the primary soft gamma transitions from the experimental spectrum of secondary alpha particles in the $(n, \gamma\alpha)$ reaction [18] and performing for the first time comparison of experimental data on the radiation force function for gamma transitions of multiplicity E1 over the entire range of energies studied: from 0.2 up to 20 MeV.

The discovery of ultracold neutrons. In spite of the fact that many specialists working in neutron physics attribute the idea of neutron storage to E Fermi, the first work [19] in which the possibility of storage is indicated and the first estimates are given for the density of ultracold neutrons (UCNs) attainable in an installation with a liquid-helium converter was published in 1959.

UCNs are neutrons of extremely low kinetic energy: $\sim 10^{-7}$ eV. The main property distinguishing UCNs lies in the fact that they can be reflected from vacuum–medium interfaces at any angles of incidence. This is true if the neutron energy is smaller than the so-called Fermi potential

$$U = \frac{\hbar^2}{2m_{\rm n}} 4\pi N_0 b \,, \tag{5}$$

where $m_{\rm n}$ is the neutron mass, N_0 is the density of the nuclei, and b is the coherent neutron scattering amplitude. This property of UCNs underlies their attractiveness as objects for studying the properties of the neutron itself and the interaction processes of neutrons with surfaces.

In 1968, F L Shapiro once again drew attention to UCNs. While analyzing the possibility of experimental determination of the electric dipole moment (EDM) of the neutron, Shapiro proposed making use of UCNs to search for the neutron EDM [20]. This stimulated experimental work for obtaining and storing UCNs. In 1968, UCNs were registered [21] for the first time at the pulsed reactor IBR-1. Thus, it was shown that the apparently unresolvable problem of distinguishing UCNs against a background of thermal neutrons could be effectively resolved by extracting UCNs from the active core of a reactor along a bent specular neutron guide.

The improvement of UCN sources still continues. The number densities achieved are on the order of 50 n cm^{-3}, which is four orders of magnitude more than in the first experiments. There are projects in which it is planned to increase the number density up to 10^3 or 10^4 n cm^{-3}. The most accurate values of the neutron lifetime, the limits for the neutron charge ($\leqslant 10^{-25}e$), and EDM ($\leqslant 10^{-26}e$ cm) have been obtained with the aid of UCNs.

Further development of UCN sources will, doubtless, lead to an improvement in the experimental accuracy and, consequently, to new confirmations (or corrections) of modern electroweak interaction models, of the fundamental properties of the neutron, and of the astrophysical processes involving neutrons.

At the same time, the Polish physicists B Buras and E Janik have proposed experiments which have been started on neutron sources at the LNP for studying the structure and dynamics of condensed media. Diffractometers and spectrometers of inelastic scattering have been created, with which investigations have started of the structure of crystals, atomic and molecular dynamics, the structure and dynamics of liquids, the level spectroscopy of the crystalline electric field in rare-earth chemical compounds, etc. At the beginning of the 1970s, I M Frank initiated studies of the properties of biological objects making use of neutrons. Owing to this fact, an installation for small-angle neutron scattering was created at IBR-30 under the leadership of Yu M Ostanevich, which turned out to be exceptionally efficient in resolving a whole series of problems related to biology. But the most rapid advancement of studies into condensed media has taken place at the newer IBR-2 reactor.

I M Frank (to the right) and N A Dollezhal.

The IBR-2 reactor. From 1966, I M Frank and D I Blokhintsev were engrossed in the idea of creating the powerful pulsed reactor IBR-2. The prerequisites for this were the enhanced interest of the world scientific community in neutron sources, both stationary and pulsed, the successful experience of the IBR operation, and the necessity of increasing the neutron flux density in extracted beams. The idea was supported at JINR and by the USSR Government. With the active participation of I M Frank, research and design work started for creating IBR-2. The chief designer was N A Dollezhal (RDIPE) and the scientific project leader was D I Blokhintsev (1967 – 1979) and, after 1979, I M Frank. On the initiative of I M Frank a department was created at the LNP, the scope of which included scientific guidance and supervision of work for IBR-2.

In 1969, construction of this very complex, unique facility started. The construction of IBR-2 proceeded with the determined support of the Ministry of Medium Machine Building: this included financial resources, new technologies, and engineering and intellectual support by its specialized institutions. The role of I M Frank in coordinating all these efforts was great.

In 1977, successful physical commissioning of IBR-2 took place without the heat carrier (sodium) [22]; physical

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

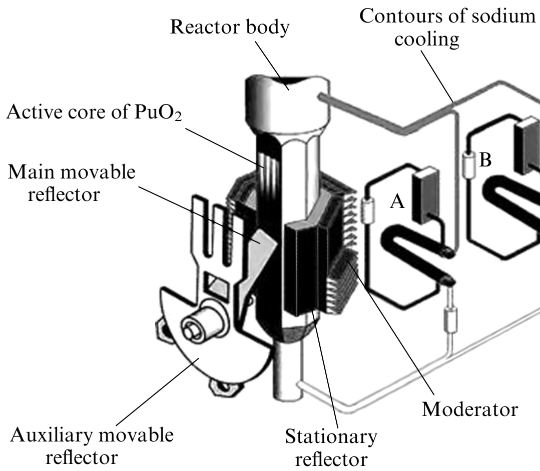

Figure 3. Schematic layout of the IBR-2 reactor.

Table 2. Main parameters of the IBR-2 reactor.

IBR-2 parameter	Value
Average power, MW	2
Kind of fuel	PuO_2
Number of RFAs	78
Maximum burnout, %	6.5
Pulse frequency, Hz	5; 25
Pulse half-width, μs	215
Average thermal neutron flux, $cm^{-2}\ s^{-1}$	5×10^{12}
Peak flux of thermal neutrons, $cm^{-2}\ s^{-1}$	10^{16}

commissioning with the heat carrier and then the power commissioning was in 1980–1984 [23]. As scientific leader, I M Frank took immediate part in all commissioning work. Figure 3 shows the schematic layout of the IBR-2 reactor.

In this reactor, the horizontal cross section of the active core made of plutonium dioxide has the shape of an irregular hexagon. Near one of the active core's sides there is a reactivity modulator which consists of the main and auxiliary movable reflectors. The blades of these reflectors rotate with different velocities, and when they cross the middle of the active core simultaneously, the reactor undergoes a transition to the above-critical state. Cooling of the active core is realized with the aid of liquid sodium. Such a scheme has permitted obtaining parameters that are truly unique from the point of view of the pulsed yield of neutrons from the reactor. IBR-2 is still the most high-flux research pulsed neutron source in the world. The main parameters of the reactor are presented in Table 2.

IBR-2 in Dubna is distinguished among other pulsed neutron sources in the world by its record high average power (2 MW) and its peak neutron flux value ($10^{16}\ cm^{-2}\ s^{-1}$), as well as its small pulse repetition frequency (5 Hz instead of the standard 30 – 50 Hz). A unique experimental base has been created at the reactor. The creation of most of the installations was based on international cooperation; for example, the small-angle experimental setup was prepared in collaboration with Hungary, the inelastic scattering spectrometer in collaboration with Poland, the complex of diffractometers for geological studies in collaboration with Germany, and the Fourier diffractometer in collaboration with Finland, and so forth. A distinguishing and unique feature of IBR-2 consists in the existence of a channel for irradiation over a large area — 20×40 cm in diameter — with an easy accessibility for the delivery of samples. The flux of fast neutrons in the channel is $3 \times 10^{12}\ cm^{-2}\ s^{-1}$. Moreover, the channel is equipped with a setup for irradiating small samples at low temperatures (down to 10 K); no other cryogenic setup for irradiation in a high neutron flux exists in Russia.

The presence in the neutron spectrum of the fast pulsed IBR-2 reactor of a significant fraction of epithermal and resonance neutrons provides a unique possibility for performing neutron activation analysis (NAA) with epithermal neutrons, and it thus permits enhancing the sensitivity of the method to elements with large cross sections in the epithermal energy range, primarily to rare-earth elements. Thus, the sensitivity of the pneumo transportation unit (PTU) Regata to rare-earth elements amounts to a value of the order of 10^{-5} ppm, which is two–three orders of magnitude higher than the sensitivity of NAA systems making use of thermal neutrons. Work is carried on in collaboration with Russian and foreign scientific centers with financial support via grants from JINR member states, the European Union, NATO, and others.

Thus, to conclude it can be noted that under the guidance of I M Frank from 1957 until 1989 the Laboratory of Neutron Physics at the Joint Institute for Nuclear Research achieved outstanding results in the creation and operation of periodic-action pulsed reactors utilizing fast neutrons. A scientific and technological school in pulsed neutron sources was founded, gaining recognition from the scientific community.

Many scientific lines of research, work along which started under the leadership of I M Frank, have reached a qualitatively new level and are realized today on the basis of wide international cooperation with JINR member states and numerous partners both in Russia and abroad.

Successful work at JINR on the modernization of IBR-2 and on the creation of the IREN facility (source of resonance neutrons), the commissioning of which took place in December 2008, and a large series of scientific experiments carried out at collaborating scientific centers after the death of Il'ya Mikhailovich, all serve as the best possible memorial to a remarkable scientist.

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I M Frank: founder and leader of FIAN's Laboratory of Atomic Nucleus

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This talk is dedicated to the foundation and development of the I M Frank laboratory, to neutron and nuclear experiments, and to attacking the so-called nuclear problem.

In 1934, when I M Frank accepted S I Vavilov's offer to transfer from the State Optical Institute (SOI) to the Physical Institute of the USSR Academy of Sciences (FIAN *in Russ. abbr.*), the former was a young man, but, nevertheless, a fully formed researcher with about ten years of experience as a scientific worker. I M Frank performed his first work of original scholarship at the Mathematical Society of Tavrichesky University, which had been temporarily transformed into a pedagogical institute, where, although he was not a student of that institute, he attended lectures during the academic year of 1925–1926 and worked in the physical laboratory of the institution. This first work in geometry, which was most likely done under the influence of his father, Mikhail Ludvigovich Frank, a talented mathematician, was published in 1928. At the time I M Frank was a student of the Physics and Mathematics Department at Moscow State University (1926–1930), where he combined educational studies in physics (at the chair headed by L I Mandel'shtam) and mathematics, which involved formulating new problems for special training in physics. Also at that time, I M Frank, under the supervision of S I Vavilov, completed an investigation on the quenching of luminescence, which they published in 1931.

Il'ya Mikhailovich felt a profound respect and warmth for Sergei Ivanovich Vavilov, and called him Teacher, and even when he pronounced this word, it was always and truly with a capital letter. How Sergei Ivanovich estimated his pupil can be seen from his judgment of I M Frank's scientific work [1], expressed in 1938 in his recommendation for I M Frank to be elected Corresponding Member of the USSR Academy of Sciences. "Il'ya Mikhailovich Frank ... has proved to be an excellent, extremely versatile experimental physicist of outstanding theoretical erudition. In one of his first works [devoted to quenching processes in fluorescent liquids — *B.A.B.*] ... he showed good experimental skills and exceptional physical intuition... . These works [studies of photochemical reactions — *B.A.B.*] revealed initiative and originality of the experimental technique used and of I M Frank's scientific thinking. The works are interesting for the elegance of the method and the comprehensive analysis of the experimental data... . In 1933, I M Frank accepted my proposal to start working in a totally different field — in the physics of the atomic nucleus. It was with surprising speed that he accustomed himself to the technique... became familiar with the world literature and became a leading worker in the young laboratory of atomic nucleus*... I M Frank lively participated in performing and explaining P A Cherenkov's experiments... . Thus, for example, I M Frank made the brilliant guess that we were confronted with a totally new phenomenon peculiar to the propagation of electrons traveling with a velocity exceeding the phase velocity of light in a dense medium. This idea underwent complete and quite rigorous development in the theoretical work by I E Tamm and I M Frank... . I M Frank being exceptionally gifted, his erudition and excellent scientific results were already manifested in the fact that the Presidium of the USSR Academy of Sciences conferred on I M Frank the degree of Doctor of Physicomathematical Sciences in 1934, when he was 26 years old."

The doctorate thesis, which was completed in three years at SOI in the laboratory headed by A N Terenin, was devoted to experimental investigation of photochemical reactions by optical and spectrometric methods.

* The future Department of Nuclear Physics chaired by D V Skobel'tsyn at the FIAN. (*Comment by B.A.B.*)