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

B A Benetskii

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.*)

To understand the scale of Il'ya Milhailovich's breadth of interests and capabilities, one must supplement the aforementioned with the following. In 1934–1935 he carried out an investigation of cosmic rays, applying the Wilson chamber on Elbrus; in 1937–1940, together with L V Groshev, he studied the production of electron–positron pairs by gamma quanta (a study characterized by S I Vavilov as "exceptionally thorough and complete"); in the same years he took part with N A Dobrotin and P A Cherenkov in the work of the Stratosphere Commission of the Academy of Sciences, which led to the discovery of the effect of sharp variation in intensity of the luminosity of the night sky; in 1942, by methods of classical electrodynamics, he carried out a study of the Doppler effect in refractive media, and in 1946, together with V L Ginzburg, he predicted the existence of a new phenomenon, namely, transition radiation emission.

The year 1946 happened to be one of acknowledgment and of new problems. He won the prize that is now known as the State Prize of the First Class for the discovery and explanation of the nature of Vavilov–Cherenkov radiation (he himself used this term for the radiation), was elected Corresponding Member of the USSR Academy of Sciences, and became founder and leader of a laboratory in the Physical Institute of the USSR Academy of Sciences. This laboratory was organized on April 1, 1946, when the Department of Nuclear Physics, led by D V Skobel'tsyn, was divided into three laboratories headed by I M Frank, N A Dobrotin, and V I Veksler. I M Frank's laboratory remained at the FIAN until January 1, 1971, when three FIAN laboratories — of atomic nucleus, of photonuclear reactions, and of neutrinos — were brought together to organize the Institute for Nuclear Research (INR) of the USSR Academy of Sciences (now INR, RAS).

In 1946, the main lines of research of I M Frank's laboratory were determined by the necessity of resolving the 'nuclear problem', namely, of determining the microscopic characteristics of nuclear fission processes and of neutron interactions with nuclei and the macroscopic parameters of nuclear reactors, and of studying reactions with the lightest nuclei (such as the interaction of neutrons with lithium, deuterons with deuterium, and deuterons with tritium).

The newly established laboratory had no experimental means, with the exception of the most powerful radium source in the Soviet Union, which belonged to the FIAN. Besides this, there was actually nothing [2].

When the laboratory was organized, it comprised, including its leader, five researchers, and by the end of the year, fifteen, including a specialist in electronics and three engineers. By the end of 1949 it already had 25 staff members. In these conditions Il'ya Mikhailovich showed himself to be an outstanding organizer and leader of a scientific team: work started immediately.

A witness testifies: "When we arrived in 1946, there was only the central building and nothing else. In the building was Frank's laboratory. On the second floor there were, apparently, three rooms, two of which were adjacent. There was an entrance to the room and two exits to the right and left. There were two other rooms, in which I have never been, because they were secret. As a matter of fact, it was there that work started on neutron multiplication in uranium–graphite systems for reactors. This work was conducted by I M Frank, L V Groshev, L E Lazareva, and later E L Feinberg. What went on there I don't know. There were three rooms — we were in the central one — and they ran back and forth from one room to another. There was no guard, only, so to say, internal discipline" [2].

At the time, the first task was measurement of the deviation from unity of the neutron multiplication coefficient equal to the product of the number ν of secondary neutrons produced in the fission of uranium and the probability φ of their deceleration to thermal energies and the probability of their remaining in the multiplying system, θ:

$$\nu\varphi\theta - 1\,.$$

According to V Weisskopf's pithy remark, the misfortune of humankind was the consequence of God having made this difference, albeit small, positive. If it had turned out to be equal to two-tenths, a reactor with natural uranium would have had to be excessively large. Therefore, it was necessary not only to determine this quantity, but also to try to find ways of increasing it. This was what the people running "back and forth from one room to another" were engaged in.

The rest of the laboratory was only just forming. The laboratory comprised physicists who had come back from the war, i.e., young people without work experience in this field. "We came after a year-long course. Some of us bypassed it... For the rest of the staff tasks pertaining to general nuclear physics were formulated, and the means were very limited" [2]. And further: "Il'ya Mikhailovich apparently understood the necessity of certain technical means for work in nuclear physics, and in the room on the ground floor of the main building we started to assemble an accelerating tube: the Cockroft–Walton cascading voltage multiplier. E M Balabanov (who was a specialist in electrical phenomena in gases and dealt with corona discharges) and L N Katsaurov constructed this tube. Here, E M Balabanov used his connections to procure capacitors, and a certain porcelain intended for other purposes. Anyhow, with makeshift materials they assembled an accelerating tube." At least three such accelerators were assembled, and their energy turned out to be sufficient for creating sources of fast neutrons and for studying their reactions with the lightest nuclei.

On the whole, during the period up to 1952 a new scientific team, as well as the experimental and measuring bases, were created, and theoretical foundations and measurement methods were developed. Studies were carried out in the physics of neutron interactions with matter and in the physics of interactions of fast neutrons with nuclei (including uranium for resolving the blanket problem — of the fissioning casing of a thermonuclear reactor); the cross sections of reactions with the lightest nuclei (nLi, DD, DT) were measured; the practically important characteristics of fission and reactor parameters were determined (including neutron multiplication coefficients, geometrical parameters, probabilities of deceleration to thermal energies). Here, the reactor parameters were determined by the alternative method to the method of assembling critical systems — by the 'prism method'.

At the beginning, the prism theory was developed by I I Gurevich and M Ya Pomeranchuk for a homogeneous system, but it was known *a priori* not to be the optimal version. Il'ya Mikhailovich and his colleagues investigated subcritical uranium–graphite systems in which exponential attenuation of the neutron flux was observed, when a neutron pulse was injected into such a prism (the so-called method of nonstationary diffusion). In 1946–1949, work was carried out for the investigation of equilibrium spectra and the diffusion parameters of neutrons in multiplying and decelerating media. It was revealed that the effective temperature of neutrons flowing out from the moderator can differ from the temperature of the medium. The diffusion cooling effect was discovered — the dependence of the average neutron velocity in the medium and, consequently, of the neutron diffusion coefficient on the dimensions of the moderator.

A logical continuation of this line of research consisted in the development of a method for performing the spectrometry of slow neutrons by their slowing-down time. In the laboratory, within short periods of time the project of an original slowing-down time spectrometer (STS) in lead was designed and constructed on the basis of the Cockroft–Walton generator owing to the efforts of the same group.

Back in 1944 E L Feinberg, while considering the process of neutron moderation in a medium of heavy atoms, exposed an effect that brings to mind the principle of particle autophasing in the case of acceleration. In such a medium, neutrons with higher velocities collide with heavy nuclei more often and are slowed down more effectively, while those with lower velocities are decelerated less effectively. When the deceleration process starts at the same time, a grouping takes place of the spectrum of neutrons being decelerated around the average energy $\bar{E}$. This energy is functionally related to the slowing-down time t, for example, for values of $\bar{E} \gg 1$ eV [3]:

$$\bar{E} = \frac{K}{(t - t_0)^2}\,,$$

where K and t_0 are the parameters depending on the characteristics of the moderator and of the neutron source. Such is the principle of neutron slowing-down time spectrometry. The neutron spectrometer by slowing-down time in lead turned out to be a very efficient means for studies in the field of reactors, including measurement of neutron capture cross sections.

When in 2003 I happened to be collecting material for the 95th anniversary of Il'ya Mikhailovich's birthday, it turned out to be impossible to find any reference to the date when the first STS in the world was put into operation in I M Frank's laboratory. The explanation of such a strange fact happens to be found in the recollections by Evgenii L'vovich Feinberg. It must be noted that I M Frank many times and on different occasions stressed E L Feinberg's contribution to the establishment and development of the laboratory, even introducing a special term: 'associated member of our laboratory'.

In his paper entering the book of memories of F L Shapiro [4], Evgenii L'vovich quite clearly explained what happened: "Those 'who were supposed to keep an eye on us' read my questionnaire very carefully, and in 1950 I was no longer permitted to take part in secret work (apparently, I was admitted at the early stage of development of the Soviet Atomic Project, when there were catastrophically few people...).... But then the 'representative of the Council of Ministers at the FIAN' F P Malyshev, a general from 'security', upon estimating the success offered Fedor L'vovich (Shapiro) and L E Lazareva in registering a patent for this spectrometer and to receive a certificate for the invention. They agreed only under the condition that I was to be one of the authors. The general was opposed, but they refused to give in. So the issue come to naught."

People who worked with Il'ya Mikhailovich know he was an extremely considerate and not too open person, which to some could seem a manifestation of weakness, but actually his principles were unshakeable. Today not everybody can comprehend what courage was required of the staff and the head of the laboratory at the time (about 1948–1949) during the described confrontation.

The invention was registered about four decades later in 1988 on the basis of the results of studies of the stationary and nonstationary diffusion of neutrons. Later on, in our country and in a number of others (the USA, Japan) spectrometers similar to the first STS that was in operation in the Laboratory of Atomic Nucleus until 2005 were constructed on the basis of more powerful neutron sources. And in 2003 the first scientific results were obtained with the 'Great Cube', the new STS in the proton beam of the INR linear accelerator, exceeding in efficiency at the time of commissioning other such spectrometers by at least five orders of magnitude. As Il'ya Mikhailovich used to say, "Neutrons are the specialty of our home."

In 1953, I M Frank and six other staff members of his laboratory were awarded the State Prize 'for work on the physics of reactors and studies of nuclear reactions with the lightest nuclei'. On the whole, for this work 31 people working in the laboratory, i.e., all those who worked in the laboratory from the time it was founded up to 1950 inclusive, had awards conferred on them by the Government. Owing to the restricted time for this talk, I will no longer bring up material from a historical standpoint, and will refer to our publication [5] (see the Supplement, starting from p. 12).

If M Montaigne's assertion that an individual is a style is correct, then it most likely is also valid for a scientific or, generally, a creative community. And Il'ya Mikhailovich, as is known to all who had the luck to communicate with him, as a scientist and scientific leader manifested traits pertaining to the particular style of the 'old' FIAN. What determined this style of scientific activity? I believe it was the following:

— first, aspiration for ultimate clarity and completeness in understanding the essence of the subject studied independently of the assumed value of the result of investigation. Or, which is no less important, a clear definition of the boundaries of such an understanding;

— second, belief in the unity and equality of all the components of what we understand to be expressed by the words 'science' and, in particular, 'physics';

— third, acknowledgment of the priority of experimental methods of investigation in the physical sciences. "Love is good, but a golden bracelet is better." Here, the golden bracelet is meant to be the result of experiment (with the reservation: 'if it is not exaggerated');

— fourth, the aspiration to find the most simple (in the best meaning of this word) way of investigation, in which case the main instrument for studying Nature is the head of the experimenter and the rest is a supplement to it. In this case, his estimates were quite severe: "NN is an instrument person";

— fifth, high criticality in determining the degree of reliability of his own results and conclusions. I well remember an episode where Il'ya Mikhailovich did not 'permit' publishing experimental data obtained in a work with his participation for eight years, until he was not sure of their validity. At the same time, a work was done and the candidate thesis was successfully defended, and its starting point consisted of a check of results obtained earlier. Il'ya Mikhailovich praised the author: "You nicely criticized the Americans";

— sixth, the capability of comprehending the substantiated arguments of a colleague, independently of his/her age and position, as well as respect for the results of work done by colleagues and pupils. "It is better to do one's own work than to criticize the work of others." "Well, how's the work, of which I am not a patriot, going on?" He instilled the first into me when I was a young junior researcher. I heard the second from Il'ya Mikhailovich during our penultimate meeting in a room of the hospital of the Academy of Sciences;

— seventh, strict adherence to ethical principles in all, including business, relationships. As far as I understand, Il'ya Mikhailovich was quite selective in his contacts with the people surrounding him. Being extremely cultured and educated himself, he highly estimated this quality in others. However, while attaching much importance to the rules of 'good behavior', Il'ya Mikhailovich never extended automatically his estimate of the personal qualities of an individual to the results of their work.

Il'ya Mikhailovich wrote the following about his understanding of intelligence [6, p. 85]: "I was born into a cultured family that came from the so-called 'working intelligentsia'. Nearly all my life the word 'intelligentsia' was pronounced depreciatingly with the addition 'rotten' — abusively. My father, of whom I am very proud, and a number of my teachers were significantly more intelligent than I." And further: "I am far from considering all people working in administrative bodies to be bureaucrats. Among them there are many knowledgeable and competent people, but there also exist bureaucrats. And bureaucrats have always been and remain the main malevolent force for the intelligentsia. Scientists-bureaucrats are no less dangerous. A bureaucrat in science is no less dangerous than in management... . And intellectuals and bureaucrats have always been and will always be worst enemies" [6, p. 89].

As a mentor of the young staff, Il'ya Mikhailovich consistently adhered to the principle of 'better later, but better'. "The first to defend themselves are those who very much want to, followed by the most talented, then all the rest." "The exam in the professional subject is necessary (as Sergei Ivanovich Vavilov used to say) in order not to let those pass who shouldn't."

I will permit myself to conclude this article with Il'ya Mikhailovich's reflections about one's soul. I present these lines not from the text of the edited manuscript from the archive [6, p. 85], but the facsimile [6, pp. 170, 171 (photocopy)] in the same edition, since when I read the facsimile text I internally hear the voice of Il'ya Mikhailovich and his manner of speaking.

"People my age must take care of their soul. A human being not only has a soul, but it often hurts. But, nevertheless, and let believers forgive me, I do not believe it to be immortal. But each one of us must remain alone together with his or her conscience, and it will suggest whether to recite our prayers.

No one dies without leaving a trace. Something of us remains to live in those who surrounded us. Inside us something lives that was left by those whom we lost."

I am grateful to everyone who helped me in preparing this talk, in particular to M M Salokhina, researcher at the Laboratory of Atomic Nucleus at INR, RAS.

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I M Frank and the optics of ultracold neutrons

A I Frank

Il'ya Mikhailovich Frank first turned to the problems of neutron optics at the beginning of the 1970s, soon after F L Shapiro and his colleagues discovered ultracold neutrons (UCNs). This, naturally, did not happen by chance. The unusual wave properties of neutrons so vividly manifest themselves in experiments with UCNs that they could not but excite Il'ya Mikhailovich, to whom precisely the wave approach in physics was so close. In neutron optics he most probably recognized a field where his beloved optics and neutron physics, to which he devoted more than a decade, come closely together.

We recall that after the first brilliant studies in which UCNs were observed, there arose a problem that subsequently became more and more apparent. According to expectations, UCNs could indeed be stored in vessels for a long time, but the storage time turned out to be noticeably shorter than the time predicted by theory, which represented the so-called anomaly in UCN storage. This circumstance, doubtless, gave rise to a certain challenge for both experimenters and theorists.

Therefore, it is not surprising that most work on neutron optics [1–7] carried out by Il'ya Mikhailovich belongs to the period immediately following the discovery of UCNs in 1968. Here, I would like to briefly recall some of the results of these studies and to relate the further destiny of the ideas put forward in them.

The results of the first period of research with ultracold neutrons were summarized by F L Shapiro in his talk [8]* presented at a conference in Budapest in summer 1972. I M Frank [3] presented a supplement to this talk at the same conference.

* Since F L Shapiro was ill, this talk was presented by V I Lushchikov.