Neutron physics: A field for the golden ideas of F. L. Shapiro

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In 1995, the scientific community celebrated the 80th anniversary of the birth of Fedor L'vovich Shapiro, the eminent physicist, a doctor of the physical and mathematical sciences, professor, and Corresponding Member of the Academy of Sciences. He began his scientific work in the Nuclear Physics Laboratory of the P. N. Lebedev Physics Institute of the USSR Academy of Sciences in 1945, working in the field of reactor and neutron physics. From then on, his life was mainly associated with neutron physics, in which he made several pioneering investigations: the design of the spectrometer based on measuring the neutron moderation time in lead, the discovery of a new excited level in the ^{4}He nucleus, generalization of the $1/v$ law, the first investigations of p resonances, development of the theory of nonstationary neutron moderation, development of the method of polarizing neutrons by means of a proton filter, investigations with polarized neutrons and nuclei, the discovery of ultracold neutrons, and more. Shapiro was the first who used a variety of methods of neutron physics to make investigations in the physics of condensed media, including the time-of-flight diffraction method and the inverted-geometry method for inelastic scattering. The major part of these investigations was made using the IBR pulsed reactor of the Laboratory of Neutron Physics of the Joint Institute for Nuclear Research, where he was the deputy director of the Laboratory until the end his life. Shapiro made a very great contribution to the development and modernization of the basic facilities of the Laboratory—the pulsed neutron sources. For this work, he was awarded the State Prize. Shapiro died prematurely, in the prime of his creative work. His name is firmly established in the history of physics.

Shapiro's renown as a physicist grew steadily from year to year and continues to grow after his death. — *I. M. Frank*

On April 6, 1995, the well-known physicist Fedor L'vovich Shapiro would have been 80, but he had already left us more that 20 years ago.

Colossal changes have taken place in the world and in our country during these years. Indeed, we live in a different historical epoch. In science it is different. Surveying the scientific legacy of Shapiro, one immediately notes that several scientific directions founded by him are still topical. His natural talents compensated the relative shortness of his scientific career, which he began when he was 30, a rather late age by any criterion. His path to science was not simple.

Having completed his intermediate schooling, Fedor L'vovich was forced to start work because of the difficult material circumstances of his family. Simultaneously, he studied at the Moscow Power Technical School, and a year after he had completed his studies there he joined the Physics Faculty of Moscow University in 1936. He studied and continued to work, initially as a technician and then subsequently as an engineer. He completed his university studies just before the outbreak of the war. He participated in the battle for Moscow as the commander of a reconnaissance company and was awarded the "For Bravery" medal; in December 1941, he was seriously wounded. He then spent many months in hospitals, was demobilized, and worked in an aviation construction bureau.

At last, in February 1945, Fedor L'vovich was taken on as a graduate student of the P. N. Lebedev Physics Institute. His scientific supervisor was Il'ya Mikhaĭlovich Frank, who directed the Nuclear Physics Laboratory of the Institute.

At that time, there was an extensive program in the country for the development of nuclear physics and the creation of an atomic industry, to which the Nuclear Physics Laboratory made an important contribution with its investigations into reactor physics. Besides Frank and Shapiro, L. V. Groshev, L. E. Lazareva, K. D. Tolstov, E. L. Feĭnberg, P. V. Shtranikh, and others participated in this collective work. Of course, it is not possible to separate the work of each of these authors. However, one thing is certain—for Shapiro, this was a good start in neutron physics, in which he was destined to become an eminent specialist. In 1949, he brilliantly defended his candidate's dissertation on the subject "Study of uranium–graphite multiplying systems."

In this paper, I shall omit an account of Shapiro's investigations in the field of reactor physics (although it is difficult to avoid mentioning that Shapiro independently proposed and used the cadmium-ratio method). These studies are fairly fully described in the biographical note in the first volume of his collected works.[1]

What will be discussed in this paper, to the maximum extent that space permits, is Shapiro's work on neutron spectrometry, with which he occupied himself almost to the end of his life.

His early studies on neutron spectrometry were associated with the Nuclear Physics Laboratory of the P. N. Lebedev Physics Institute, where already at the beginning of the forties work had commenced on ion cascade accelerators (of Cockcroft–Walton type) to energies in the range from several hundred kilo-electron-volts to a million electron volts. The beam of deuterium ions obtained in such an accelerator, used to bombard a deuterium target, produced neutrons (so-called *DD* neutrons) with energy of about 2.5 MeV.

There soon became known a further possibility for obtaining, for ions of energy of hundreds of kilo-electron-volts, neutrons with intensity about two orders of magnitude greater than in the case of *DD* neutrons. This possibility was the deuterium–tritium reaction, which has a large effective cross section that reaches at the maximum 5 b (it occurs at an energy of about 100 keV). The first zirconium–tritium targets for accelerators using this reaction (which are now called neutron generators) were developed at the Nuclear Physics Laboratory. Of course, it was not by chance that the investigation of reactions induced in nuclei by *DD* and *DT* neutrons also became the subject of investigations by Shapiro. In particular, in 1953 he made high-precision measurements of the cross section of the (n, α) reaction on ^{6}Li at neutron energy 2.5 MeV (Ref. 2).

It is natural that these studies in neutron physics led to the idea of developing studies on neutron spectroscopy. The neutron generator already gave a fairly high neutron flux ($5\cdot10^8$–10^9 s^{-1}), and therefore the idea arose of converting the facility to a pulsed regime and using it for neutron time-of-flight spectroscopy. This possibility was indeed discussed. However, even if the instantaneous flux in a pulse was appreciably greater than the steady flux (in Shapiro's studies, it was $5\cdot10^{11}$ s^{-1}, i.e., increased in fact by three orders of magnitude), the possibilities of the neutron generator for the spectrometry of slow and resonance neutrons were found to be very limited (it should not be forgotten that at that time the methods of nanosecond electronics did not yet exist).

The talent and scientific foresight of Shapiro were demonstrated by the fact that instead of making the apparently natural attempt to use the time-of-flight method he proposed a new and as yet completely untried path. In 1950, he gave a seminar at the Lebedev Institute on the possibility of neutron spectrometry by means of a method, the idea of which, based on a theoretical result of E. L. Feĭnberg, was developed and extended by Shapiro and L. E. Lazareva (the work of Lazareva, Feĭnberg, and Shapiro was published only in 1955 (Ref. 3) after the method had been implemented).

This method became known as lead-moderation-time spectrometry. The essence of the method is that after a fairly large number of elastic collisions all the neutrons are "monochromaticized"—at each given time, they are grouped in their velocities around a certain mean value, which decreases in inverse proportion to the moderation time. Thus, the relationship between the time and the mean velocity is the same as in the time-of-flight method. For lead, it corresponds to a flight path of about 7 m (the heavier the moderating nucleus, the larger is this quantity). With regard to the spread of the neutron energies around the mean value, below the region of inelastic scattering it depends weakly on the mean energy in a wide range and for lead is about 30%. Thus, although the spectrometer does not possess a high resolution, relatively high neutron energies—tens of kilo-electron-volts—are accessible for it.

The main part of the moderation-time spectrometer is a lead cube of weight more than 100 tons. The target device of the pulsed neutron generator is introduced into a channel in this cube, while investigated materials with detectors connected to a time analyzer are introduced into other channels. Since the neutron moderation takes place within the large lead cube and the flux of neutrons out of it is low, the facility has an exceptionally high luminosity. It was precisely this circumstance that Shapiro noted especially when he proposed the development of this method. Another feature was that the γ background was very low in measurements in lead. The moderation-time spectrometer was therefore very convenient for measurements of the cross sections of radiative capture of neutrons. This was a step forward, since at that time, apart from fission cross sections, neutron spectrometry was mainly concerned with measurement of total neutron cross sections by the transmission method. Finally, the new method permitted measurements to be made in a wide range of energies with normalization of them by the known cross sections in the thermal region.

All these advantages of the spectrometer were actually realized. The creation of the spectrometer and the development of studies using it required great experimental skill. A group of young experimental and theoretical physicists were already occupied with this under the guidance of Shapiro.

The first report on the use of the method of lead-moderation-time spectrometry was made at the International Conference on the Peaceful Uses of Atomic Energy at Geneva in 1955 (Ref. 4). The series of studies made in the first period of investigation was treated in more detail in Shapiro's doctoral dissertation in 1962 and in candidate's dissertations of his students (Yu. P. Popov, A. A. Bergman, and A. I. Isakov). Investigations with this spectrometer still continued, and Shapiro directed them until the end of his life. Even now, despite the huge progress achieved during the last decades in neutron spectrometry, the lead cube has not lost its importance, an example of which is the high-luminosity spectrometer PITON based on the neutron moderation time in lead[5] developed at the Moscow Meson Factory.

We may mention three fields of investigations that have been made using the moderation-time spectrometer. First of all, there was an extensive group of studies to measure the radiative cross sections of neutron capture for about 20 isotopes. An indication of the results, frequently unexpected, obtained using this spectrometer is provided by the following example. Investigation of the natural mixture of iron isotopes clearly revealed a resonance at neutron energy 1180 eV. Iron, a material that is widely used for constructional elements in reactors, had, of course, been previously investigated. However, the narrow resonance at 1180 eV is hardly manifested in the total cross section, and therefore it had not been noted. Its discovery in radiative capture was in its way a sensation. It should be mentioned that many constructional materials were investigated by means of the lead cube. For the measurement of the constants that are needed in reactor design, it is still a helpful facility today.

The measurements of the neutron cross sections made in wide energy ranges—from thermal energies to tens of kilo-electron-volts–enabled Shapiro and his collaborators to turn to the study of neutron–nucleus reactions with orbital angular momentum equal to unity: the so-called p resonances. At that time, data on the strength functions for p resonances were very sparse, and these measurements were the first systematic investigations in this field. They have still not lost their significance.

However, among the studies made by means of the moderation-time spectrometer, the investigations into reactions on light nuclei with emission of charged particles—protons and α particles—became most widely known. The publication of the results of these studies began in 1957. Investigating the energy dependence of the ratio of the effective cross section of the ^{3}He(n,p) reaction to the cross sections of the ^{6}Li(n,α) and ^{10}B(n,α) reactions, Shapiro and his collaborators discovered a strong deviation (up to 15% at neutron energy 27 keV) of the cross section of the first reaction from the $1/v$ law.

Analyzing these experimental data for the ^{3}He(n,p) reaction, Shapiro and his collaborators showed that, first, the reaction proceeds almost completely through the channel with spin and parity 0^+ and, second, the energy dependence of the reaction cross section can be well described by the Breit–Wigner formula for an isolated broad resonance level with spin and parity 0^+ near the neutron binding energy in ^{4}He. From this there followed the bold conclusion that in ^{4}He there exists an excited state with energy around 20–21 MeV and spin and parity 0^+. For several years, this prediction, important for the theory of light nuclei, was doubted. Physicists have a lively interest in the question of the excited states of helium. There were many indications of the existence of various energy levels of helium. However, these did not include the one found in the studies of Shapiro. Theoretically, the existence of such a state also appeared doubtful. Therefore, at the All-Union Conference on Nuclear Reactions at Low and Intermediate Energies in 1958 this result was received with more than skepticism. It was only several years later, at the Congress on Nuclear Physics in Paris in 1964, that it received general recognition, since it had been confirmed both here and abroad by other methods. Moreover, for several years after this the 0^+ level found by Shapiro was regarded as the only one reliably established.

As we have already noted, comparison of the energy dependences of the neutron cross sections obtained in the experiments with ^{3}He, ^{6}Li, ^{10}B, and ^{14}N revealed a significant departure from the $1/v$ law for ^{3}He, whereas the deviation for ^{6}Li, ^{10}B, and ^{14}N was not significant. Following Fermi's classical studies, the $1/v$ law was regarded as one of the most general relationships, with deviation from it being regarded as a manifestation specific to each nucleus of its resonances. In general form, the dependence of the effective cross section on the velocity can be represented in the form of a series expansion $\sigma=(\alpha/v)-\beta+\gamma v+\cdots$. The important result that Shapiro obtained was that in this expansion the second term β, which is, moreover, negative, is just as universal as the first term. The value of β is proportional to α^2 and depends on the spin of the channel through which the reaction proceeds and is uniquely determined by them [*sic*]. In the majority of cases, the presence of the negative correction to Fermi's law is masked by the following terms of the expansion, γv, etc. Thus, Shapiro's studies led to a generalization of the $1/v$ law, which has considerable fundamental importance and has now entered textbooks on quantum mechanics.

The foundation of the method of moderation-time spectrometry required the development of the theory of nonstationary neutron moderation (Shapiro, M. V. Kazarnovskiĭ, A. V. Stepanov, and I. M. Frank), and also several experimental studies.

Closely related to this are investigations on the diffusion of thermal neutrons by the pulsed method (the idea of this method of nonstationary diffusion was proposed by I. M. Frank), to the theoretical and, especially, experimental establishment of which a major contribution was made by Shapiro. A first report on this method was contained in Shapiro's lecture at the International Conference on the Peaceful Uses of Atomic Energy in Geneva in 1955.

In 1958 Shapiro began to work not only at the Lebedev Physics Institute but also, in parallel, at the Joint Institute for Nuclear Research (in Dubna), where the first periodic pulsed fast reactor IBR had been constructed at the recently established Laboratory of Neutron Physics. In 1959, Shapiro became the scientific deputy of I. M. Frank, the director of the Laboratory. He gradually concentrated his entire scientific work in this Laboratory. The sphere of his creative work was greatly expanded.

Besides studies using beams of the IBR reactor, about which we shall speak later, at the beginning of the sixties he made a significant contribution to the development of a new approach in nuclear spectroscopy—resonant scattering of γ rays (Mössbauer effect). Soon after the discovery of this effect, Shapiro in collaboration with Barit and Podgoretskiĭ demonstrated the possibility of using the effect to test one of the consequences of the general theory of relativity, namely, the red shift, which had previously been regarded as inaccessible to a laboratory experiment. Such an experiment was then performed by the American physicist Pound, who had independently arrived at the same idea (it was later shown that the red shift can also be explained in the framework of the special theory of relativity). Shapiro developed a semiclassical theory of the Mössbauer effect, giving a physically transparent interpretation of it. He and his collaborators made delicate experiments to investigate the Mössbauer effect in several nuclei, including ^{67}Zn, which has the narrowest line width. Shapiro's talented student Yu. M. Ostanevich was awarded the degree of doctor of the physical and mathematical sciences for his defense of a candidate's dissertation on the results of these investigations.

In 1960, the IBR pulsed reactor was commissioned. The new program of investigations made using this reactor was in large part based on the ideas of Shapiro. Among his numerous studies during the Dubna period of his life, the most important are the following.

In neutron physics, as in nuclear physics quite generally, experiments with polarized targets are very important. There existed several methods for polarizing slow and fast neutrons. However, for an extensive range of neutron energies, from several tens to several hundreds of thousands of electron volts, an adequate method did not exist. In 1960, Shapiro proposed and developed (together with the present author) a new method of polarizing neutrons by filtering them through a polarized proton target.[6] The proton-filter method completely closed the "white" region of neutron energies. At the same time, in several countries there was intensive development of the method of dynamic polarization of nuclei, and this led in 1962 in France (Saclay) and in 1963 in the United States (Berkeley) to the development of a polarized proton target for nuclear experiments. At the JINR, under the leadership of Shapiro, a group of scientists of the Laboratory of Neutron Physics (V. I. Lushchikov *et al.*) in collaboration with colleagues from the Laboratory of Nuclear Problems (B. N. Neganov and L. B. Parfenov) mastered comparatively quickly the method of dynamic polarization of protons in a target, and already in 1964 a beam of polarized resonance neutrons with energy up to 10 keV was obtained by means of such a target in the IBR reactor. The further development of this method made it possible for the Laboratory of Neutron Physics to have in 1966 a target with 70% proton polarization, record volume 35 cm^2, and, accordingly, a high-intensity beam of resonance neutrons with 70% polarization.

During 1965–1968, a polarized-neutron time-of-flight spectrometer, which had been constructed and was repeatedly improved, was used to perform several experiments on the interaction of polarized neutrons with polarized nuclei. In experiments of this kind, two possibilities can be realized: determination of the spins of neutron resonances and of the spin components of the neutron–nucleus scattering lengths. Both approaches were developed at the Laboratory of Neutron Physics.

The first of these was not original, since several years earlier two groups of physicists in the United States had begun to make such measurements using the crystal-diffraction method to polarize resonance neutrons. The limitations of this method with respect to the energy (not above 15–20 eV), the laborious nature of the measurements due to the low intensity (the reflectivity of the crystal is inversely proportional to the neutron energy, and in conjunction with the Fermi form of the spectrum of resonance neutrons this leads to a quadratic decrease of the intensity of the reflected beam with increasing energy), and the need to scan the Bragg angle for the energy analysis made it inevitable that only sparse information could be obtained by this method, and this subsequently led to the curtailment of these studies.

The advantages of the new polarization method were demonstrated in experiments using a polarized holmium target developed by the group of V. P. Alfimenkov. The spins of several tens of neutron resonances were determined. In these experiments there occurred an episode that somewhat resembled the discovery of the neutron resonance in iron at 1180 eV mentioned earlier. After analysis of the first series of measurements, a peak with an energy at about 8 eV was found in the energy dependence of the transmission effect, which is the difference of the two time-of-flight spectra with parallel and antiparallel orientations of the polarizations of the neutrons and holmium nuclei, respectively. Examination of the literature showed that at a similar energy already in 1955 American physicists had observed a resonance, but they had ascribed it to a small admixture of ^{152}Sm, which has a very strong resonance at 8.01 eV. Since no such effect should be observed in ^{152}Sm, which is an even–even isotope with zero spin, it was suggested that this resonance in reality belonged to holmium. Measurements of the transmission spectra of samples of holmium and samarium oxides made by A. B. Popov with a high-resolution time-of-flight spectrometer showed that the energies of the holmium and samarium resonances were different. Thus, the resonance in holmium at energy 8.1 eV had been rediscovered by means of the polarization method.

Another approach was the determination of the spin components $a_\pm$ in the well-known operator $\hat{a}$ of the scattering length for neutron scattering by a nucleus with spin I:

$$\hat{a}=(I+1)(2I+1)^{-1}a_+ + I(2I+1)^{-1}a_- + 2(a_+ - a_-)\times(2I+1)^{-1}\hat{\mathbf{I}}\hat{\mathbf{S}},$$

the study of which was begun at the Laboratory of Neutron Physics under the leadership of Shapiro for the example of the neutron–deuteron system. The doublet ($a_- \equiv a_2$) and quartet ($a_+ \equiv a_4$) neutron and deuteron scattering lengths are among the fundamental constants of the three-nucleon interaction that are used in the first place to test the adequacy of any solution of the nuclear three-body problem.

Already in 1951, experiments with unpolarized neutrons and deuterium nuclei had led to the determination of two possible sets of scattering lengths, in the first of which $a_2 < a_4$ while in the second $a_2 > a_4$. During these years, many theoretical studies were made, and the result of these was selection of the first set. Nevertheless, there was a clearly felt need for experimental choice of the true set, since all theoretical constructions were based on approximate models of nuclear forces and on approximate mathematical methods of solution. Moreover, a paper by A. M. Baldin published in 1965 contained some strong arguments in favor of the second set. Approximately at this time investigations were begun at the Laboratory of Neutron Physics on the dynamic polarization of deuterons in the famous lanthanum–magnesium nitrate, in which ordinary crystallization water was replaced by heavy water.[7] These investigations culminated in the creation of the first polarized deuteron target in the world, and this was soon used in a neutron experiment. The issue was resolved in favor of the first set. From the methodological point of view, the experiment had a unique nature: Two dynamically polarized targets—proton and deuteron—were used simultaneously in the neutron beam.

Concluding this survey of polarization investigations with slow neutrons made at the Laboratory of Neutron Physics under the leadership of Shapiro, I should like to mention one of the competent estimates of the place of these studies in world science. Speaking at the Second International Conference on Polarized Targets (1971), the well-known American physicist J. Dabbs noted three achievements in the preceding years that had led to a radical change of the bleak outlook that had developed in investigations into the interaction of polarized neutrons with polarized nuclei: 1) the proposal to use a polarized proton target as a neutron polarizer;

2) the development of the technology of superconducting magnets with high field intensity and ultra-low-temperature refrigerators with solutions of helium-3 in helium-4 in order to obtain a high nuclear polarization; 3) the creation of pulsed neutron sources based on high-current linear electron accelerators.

Further use of the proton-filter method led to a number of outstanding results. For example, resonant enhancement of P-odd effects in the interaction of neutrons with nuclei was discovered at the Laboratory of Neutron Physics (V. P. Alfimenkov, L. B. Pikel'ner, *et al.*).

Although the IBR reactor had initially been planned mainly for neutron-spectroscopy studies in nuclear physics, it also proved to be an extremely effective instrument for investigating the physics of the condensed state. In this field, Shapiro and his collaborators made several pioneering investigations.

Together with Polish physicists, Shapiro established experimentally a neutron-diffraction method for structural investigations that was based, not on measurement of the diffraction angle, but on time-of-flight measurement of the neutron energy at a given diffraction angle. This method proved to be extremely fruitful. An indication of this can be seen in the "park" of time-of-flight diffractometers operated in the pulsed fast reactor IBR-2.

Shapiro's name is associated with the development of investigations of the dynamics of matter by means of inelastic neutron scattering in the IBR reactor. In collaboration with him, a group of physicists (V. V. Golikov, E. Yanik, and others) created a facility for investigating cold-neutron scattering in direct geometry and carried out a large series of studies on the dynamics of molecules in different liquids.

Independently of foreign physicists, Shapiro had proposed in 1961, and then used in several studies, an original inverted-geometry method to study inelastic interactions of slow neutrons with matter. These studies brought Shapiro, a specialist in nuclear physics, wide recognition too among specialists in solid-state physics.

The development of pulsed neutron sources on the basis of linear electron accelerators in several nuclear centers made it important to raise the resolution of the neutron spectrometers in the IBR reactor. From 1963, under the direct leadership of Shapiro, unique tandem systems of the IBR reactor with electron injectors were developed and constructed. In them, an electron source with a suitable target serves as a pulsed injector of photoneutrons, while the IBR reactor plays the role of a pulsed subcritical breeder. The electron injector was initially a microtron (1964–1968), and then the linear accelerator LUÉ-40. For these developments, Shapiro, together with the other participants, was awarded the State Prize in 1971. Shapiro made a large contribution to the development of the powerful new reactor IBR-2, the work on which was begun in 1965 at the Laboratory of Nuclear Physics.

Shapiro also advanced an entire cascade of original ideas in other branches of nuclear physics: measurement of the asymmetry of the β decay of nuclei formed by the capture of slow neutrons and extraction from the asymmetry of information about the nucleus and matter; a method of increasing the intensity in time-of-flight measurements by expanding a beam of charged particles around a helical target, which serves as a neutron source (the so-called Shapiro method), a method for measuring the phases of structure amplitudes, and other proposals. Some of these ideas were realized by Shapiro himself and his collaborators, and others were developed in Soviet institutes and abroad.

One of these original ideas, which was realized by Shapiro and his collaborators, was the measurement of the magnetic moments of neutron resonances of nuclei excited by neutrons on the basis of the shift of their energy in a magnetic field. The first results of these experiments were published not long before Shapiro's death.

The final period in Shapiro's life was devoted to a completely new field—the physics of ultracold neutrons. The fact is that after the discovery of the violation of CP parity in the decay of the neutral K meson, the issue of the possible existence of an electric dipole moment of the neutron became very topical. Measurement of this moment would have made it possible to advance significantly in the understanding of this problem. However, the electric dipole moment of the neutron, if it is nonvanishing, is so small that as yet it cannot be discovered and measured.

In 1968, at the International Symposium on Problems of CP Violation, which was held in Moscow, Shapiro suggested in his review lecture the original idea of the possibility of using ultracold neutrons for this purpose. According to an idea that was based on theoretical notions and had been put forward by Ya. B. Zel'dovich in 1959, neutrons of sufficiently low velocities (meters per second) must possess the capability of being almost completely reflected by the surface of many materials. Therefore, one could expect that such neutrons could be kept for a long time in closed regions with walls of these materials. As Shapiro pointed out, this circumstance offered the hope, through the use of such neutrons, of significantly raising the accuracy in the measurement of the electric dipole moment by going over from a beam experiment (for which the time during which the neutrons remain in the facility is about 10^{-2} s) to a storage version, in which the neutrons can be confined for hundreds of seconds. However, it was believed that it would be so difficult a problem to obtain ultracold neutrons that up to that time no attempts to discover them had been made. Indeed, in a flux of thermal neutrons their fraction does not exceed about 10^{-11}.

In 1968, Shapiro together with a group of Dubna physicists (V. I. Lushchikov, A. V. Strelkov, Yu. N. Pokotilovskiĭ) made an attempt at the experimental extraction of ultracold neutrons from the IBR reactor. Despite the extremely low average power of the reactor (10 kW), it proved possible to observe reliably ultracold neutrons. In this experiment, the pulsed nature of the reactor played an important role, since the ultracold neutrons were detected between the reactor pulses under conditions of a very low background.

After the discovery of the ultracold neutrons, the question of the quantitative investigation of their properties arose. For this purpose, the groups of Shapiro and L. V. Groshev created a channel for ultracold neutrons in the reactor IRT-M at the I. V. Kurchatov Institute of Atomic Energy, and this was used for a series of beautiful and very clear experiments that received world recognition. Among these, we must undoubtedly mention the first realization of the old dream of Fermi of creating a "neutron bottle," in which neutrons would live for thousands of seconds. Twenty years later, this approach was used to obtain experimental estimates of record accuracy for the electric dipole moment and another fundamental characteristic of the neutron—its lifetime with respect to β decay.

In 1972, Shapiro prepared a major review lecture on ultracold neutrons for the Conference on the Investigation of Nuclear Structure by Neutrons at Budapest.[8] In particular, this described the investigations to obtain and confine ultracold neutrons made under Shapiro's leadership during 1969–72. The lecture outlined an extensive program of applications of ultracold neutrons in the physics of elementary particles (the neutron), nuclear and reactor physics, solid-state physics, physical chemistry, and a number of other, as he expressed it, "more exotic" applications of ultracold neutrons (neutron targets, neutron microscope, etc.). Much of this program had been implemented, and some of the goals could be realized at the present level of the technology of neutron experiments, while the realization of other ideas was evidently something for the more distant future (for example, the achievement of ultralow temperatures by inelastic scattering—and heating—of ultracold neutrons).

Unfortunately, Fedor L'vovich was not able to give his lecture himself at that conference (V. I. Lushchikov stood in for him). He was already seriously ill. He died on January 30, 1973, two months short of his 58th birthday. He died at the height of his creative powers. There are so many beautiful studies that he would have made had fate granted him even 10–15 years.

Concluding this review of the scientific legacy of Fedor L'vovich Shapiro,[1)] I must not omit to mention his talent as a teacher. Already when he started work at the Lebedev Physics Institute, he began his pedagogical activity at Moscow State University. Seminars for students, active participation in the development of practical courses in nuclear physics, lecture courses, the writing of textbooks, the supervision of diploma students and graduate students—all these constituted the ladder that he rapidly ascended by virtue of a remarkable ability to present material clearly, accurately, and economically. These qualities also distinguished his lectures at seminars and conferences and interventions in debates.

The scientific and pedagogical achievements of Shapiro were recognized by state awards and prizes. In 1967, he was made a professor, and in 1968 he was elected to be a Corresponding Member of the Academy of Sciences. His name is firmly established in the history of physics.

1)In accordance with a resolution of the Presidium of the Academy of Sciences, a two-volume collection of the works of Shapiro was published in 1976.[9,10]

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