Seminar dedicated to the seventieth anniversary of the date of birth of F. L. Shapiro

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April 6, 1985 was the seventieth anniversary of the date of birth of corresponding member of the Academy of Sciences of the USSR Fedor L'vovich Shapiro. A scientific seminar dedicated to this anniversary was held on April 4, 1985 in the Laboratory for Neutron Physics (LNP) of the Joint Institute for Nuclear Research (Dubna, Moscow region), with which the scientific activity of F. L. Shapiro had been associated from the foundation of the laboratory in 1957 right up to the days of his illness and death on January 30, 1973.

In his introductory remarks I. M. Frank briefly recounted the principal stages in the scientific activity of F. L. Shapiro. Between 1945 and 1965 he worked in the P. N. Lebedev Physics Institute of the Academy of Sciences of the USSR. His first investigations, including his candidate's dissertation in 1949 were devoted to reactor physics. Out of them in a natural manner arose his interest in neutron physics which became his principal specialty, and in neutron spectroscopy in particular. In the Laboratory for the Atomic Nucleus of the Lebedev Institute, which had for a source of neutrons only neutron generators utilizing the $D+T$ reaction, investigations in this field were not a simple problem. The bringing of the neutron generator into a pulsed regime turned out to be fruitful (the study of processes of nonsteady state diffusion and slowing down), but in combination with the traditional methods of spectroscopy of resonance neutrons such a source of radiation was not very promising. A great achievement was the development under the guidance of F. L. Shapiro of the method of spectrometry utilizing the slowing down time in lead (the theory of this method was given by L. E. Lazareva, E. L. Feĭnberg and F. L. Shapiro). A number of interesting results were obtained by this method, including some on the study of the cross sections for radiative capture. The most widely known one is the discovery of the deviation from the $1/v$ law in the absorption of neutrons and its interpretation. This led Shapiro to discover the excited state of helium-4 ($E=2.5$ MeV, $J^{\pi}=0^{+}$), which was universally acclaimed. It was quite natural that with the beginning of the construction in the LNP in 1957 of the first periodically pulsed reactor—IBR specially dedicated to neutron spectrometry, Shapiro evinced a keen interest in this work. He accomplished a lot to make IBR have the best equipment for physics research, and made a large contribution in developing a research programme for it.

Since 1959 the scientific activity of F. L. Shapiro in Dubna began, the many aspects of which are reported in papers which are abstracted below. Shapiro was characterized by the breadth of scientific interests, coupled with a great insight in evaluating the promise of various directions of research. For example, he had a keen interest in the problems of elementary particle physics. Thus, to him belongs the idea of utilizing ultracold neutrons in order to observe the electric dipole moment of the neutron. It served as a stimulus for beginning of work on obtaining ultracold neutrons which until that time had not been experimentally observed. Outstanding experimental technique was needed in order to observe these neutrons with the aid of the IBR reactor which operated only at moderate mean power. At present research with ultracold neutrons has become an independent field of neutron physics. As regards the dipole moment of the neutron excellent work in this field has been carried out in recent years at the B. P. Konstantinov Leningrad Institute of Nuclear Physics of the Academy of Sciences of the USSR.

The method of obtaining polarized resonance neutrons with the aid of which a number of results essential for the study of neutron resonances developed under the guidance of F. L. Shapiro is widely known. Recently it became clear that it is also fruitful for the solution of fundamental problems in physics. With its aid the discovery was made of the resonance enhancement of nonconservation of parity in the interaction of neutrons with nuclei.

The foundations of the methods for the study of condensed media with the aid of neutrons using the IBR reactor were laid by F. L. Shapiro and his collaborators at the beginning of 1960s. At present wide opportunities for such research have opened up using neutron beams from the IBR-2 reactor.

Many of the scientists at present working actively in the Laboratory for Neutron Physics of the JINR regard F. L. Shapiro as their teacher. The research carried out in the laboratory during the last decade in many cases is closely associated with the directions of the research of F. L. Shapiro or with ideas expressed by him. This was reflected in the papers presented at the seminar.

The paper by Yu. S. Yazvitskiĭ "Development of the experimental base for research on nuclear physics using the IBR reactors" was devoted to the subject of the development of neutron spectroscopy utilizing these reactors. By the beginning of preparation for research using the IBR reactor, i.e., towards the end of the 1950's, already an understanding had been reached that neutron spectrometry is a powerful instrument for the study of atomic nuclei. At the same time its principal direction was the measurement of total cross sections for the interaction of neutrons with nuclei. It required a further increase in the resolving power of time-of-flight neutron spectrometers in order to obtain more detailed information on total cross sections and an extension of the accessible range of neutron energies. As regards partial cross

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sections, here the information was fragmentary and was restricted primarily to data on fission cross sections. A notable advance into this region was achieved in the Lebedev Institute using a spectrometer based on the slowing down time. The IBR reactor used as a neutron spectrometer with a high relative aperture and medium resolving power appeared to be particularily promising specifically for the study of partial cross sections for the interaction of neutrons with nuclei. With direct participation by F. L. Shapiro this direction of research was selected as the basic one and its development was started. A number of high-efficiency detectors intended to be used for these purposes was constructed. Already at the beginning of the 1960's at the LNP of the JINR a complex approach to the study of neutron resonances was realized for the first time (for each of the nuclei σ_t, σ_γ, σ_n, σ_f were studied). Somewhat later investigations began utilizing polarized neutrons. The improvement of the pulsed neutron source (increase in the power of the IBR and the construction of a pulsed booster) made it possible already in the 1960s to lay the foundations for the creation of a number of new directions—study of the α decay of neutron resonances investigation of γ ray spectra accompanying neutron capture in individual resonances, and then also investigations of the effects of hyperfine interactions. All these directions are being successfully developed up to the present time.

The paper of E. I. Sharapov "Neutron investigations of light nuclei" was devoted to the problem of the lightest nuclei. Investigation of the reactions with slow neutrons in ^{3}He, ^{6}Li, ^{14}N, ^{10}B, ^{37}Cl nuclei were carried out beginning in 1957 by F. L. Shapiro and collaborators with the aid of a spectrometer based on the slowing down time in lead. These investigations led to significant results. In particular, the problem of the nature of the excited level of ^{4}He, the existence of which was proved in these investigations, became the subject of fruitful theoretical investigations. In the Laboratory for Neutron Physics F. L. Shapiro with collaborators carried out an experiment on the scattering of polarized neutrons by a polarized ^{2}D target and made a choice of a set of nd scattering lengths. This result is very important for the theory of few-nucleon systems.

In subsequent years the theory of few-nucleon systems underwent intensive development and posed a number of new problems for the experimenters.

During 1977–1982 a series of spectrometric measurements of neutron cross sections for the lightest nuclei was carried out at the LNP in the range from thermal energies to 200 keV. A set of scattering lengths for n ^{3}He scattering was determined; a strong spin dependence was observed for the scattering cross sections of neutrons scattered by ^{3}He, ^{6}Li, and ^{7}Li; a study was made of the radiative capture of neutrons by deuterons and helium-3 with an experimental estimate being made of the admixing of states with mixed permutational symmetry for the ^{4}He nucleus. For the product nuclei ^{7}Li and ^{8}Li the characteristics of excited states were determined with a significantly greater precision.

Experimental investigations of the lightest nuclei are very necessary to check the principle of charge invariance of nuclear forces, for determining the role played by exchange meson currents in processes of radiative capture, for an estimate of the manifestation of the quark degrees of freedom in light nuclei and for the solution of a number of other problems of present day theory of few-nucleon systems.

The paper by V. P. Alfimenkov "Investigations with polarized neutrons and nuclei at the LNP of the JINR" contained a review of investigations with resonance neutrons that were begun in the 1960s under the guidance of F. L. Shapiro. The basis for these investigations was the apparatus for polarizing neutrons by means of passing a neutron beam through a polarized proton target (the method of F. L. Shapiro and Yu. V. Taran). Using this apparatus the first investigations were made of the spin dependence of the interaction of neutrons with nuclei.

Towards the mid 1970s a new significantly modernized variant of the apparatus was constructed which continues to be improved in the course of operations up till the present. The presently operating apparatus enables one to obtain a beam of polarized neutrons with a cross sectional area of 5×6 cm^2 with a polarization of $P_m = 60\%$ in the neutron energy range of 0.1 eV–100 keV. Using this apparatus three methods of reversing polarization have been realized, including the very rapid one (~ 10 s) which enables one to alternate frequently measurements with opposite neutron polarization and to realize the search for sufficiently small polarization-sensitive effects over the whole range of neutron energy.

Another essential part of the apparatus—a polarized nuclear target utilizing a cryostat based on the solution of helium-3 in helium-4. This cryostat enables one to obtain at the target a steady low temperature of 20–30 mK in a magnetic field of up to 15 kOe. Under these conditions the polarization of nuclei using the Gorter-Rose method for polycrystalline rare-earth metals approaches 50–60%. The nuclei of Ho, Er, Tb, Dy, Tm and others have been successfully polarized. It should be emphasized that until very recent time this assembly of polarizing apparatus did not have any analogs or serious competitors anywhere in the world.

Scientific investigations carried out using polarized neutrons and nuclei led to many essentially new results. For a large number of nuclei the spins of resonances have been determined and the spin-dependence of average total neutron cross sections has been investigated in the region of neutron energies up to 100 keV. As a result of these investigations the spin-dependence of s-wave force functions has been obtained and an experimental estimate has been made of the imaginary part of the spin-spin potential in the optical model of the nucleus.

For the first time the magnetic moments of a number of nuclei have been determined at excitation energies close to the binding energy of the neutron (~ 7 MeV). Sets of scattering lengths for ^{2}H and ^{7}Li have been determined. They play an important role for checking theoretical models of the lightest nuclei.

Starting in 1981 the polarization apparatus has been used to investigate the P-odd dependence of total neutron cross sections of nuclei on the helicity of the neutron near the low lying p-wave resonances of complex nuclei. The phenomenon of the resonance enhancement of the P-odd effect in the total cross section was discovered, with the enhancement in the case of the 0.75 eV resonance of the ^{139}La nucleus attaining a value of 10^5–10^6, while the experimentally observed dependence of the cross section on the neutron helicity attains a value of 15%, or ~0.1 b. By now approximately 15 resonances have been investigated, and in four of them the P-odd effect has been observed. The resonance nature of the effect confirms the validity of model concepts according to which the weak interactions in nuclei can lead to a mixing of the wave functions of the excited states of the nuclei differing in parity.

The paper of L. B. Pikel'ner "Hyperfine interactions in neutron resonance spectroscopy" was devoted to investigations of the manifestation of hyperfine interactions in neutron resonances.

The idea concerning the possibility of measuring magnetic moments of nuclei in states close to the neutron binding energy by utilizing the energy shift of neutron resonances in a magnetic field was expressed by F. L. Shapiro in 1966. He also noted the difficulties of the experimental solution of this problem. However, the development of the methodology of investigations utilizing polarized neutrons and polarized nuclei made it possible already in the 1970s to undertake investigations of hyperfine interactions in neutron resonances. Such investigations are strongly impeded by the fact that the energy of the interactions being investigated is much less than the width of the neutron resonances, and therefore the observed effect reduces to the shift of the energy of a neutron resonance by a quantity amounting to 10^{-3}–10^{-4} of its width. Nevertheless the precision methodology both of measurements and of mathematical treatment of the results made it possible to observe and investigate the effect.

In the case of the interaction of the magnetic moment of a nucleus with the intraatomic magnetic fields the energy shift of the resonance is determined by the difference in the population of the Zeeman levels of the ground state of the nucleus at low temperature in a polarized nuclear target. The energy shift of a resonance arising as a result of the polarization of the target is $\Delta E \approx f_N H\ (\mu_{\rm exc} - \mu_{\rm gr})$, and enables one to obtain the magnetic moment of the excited state of the nucleus $\mu_{\rm exc}$. Magnetic moments of a number of levels for five isotopes of rare-earth elements were determined by this method.

Another type of hyperfine interaction manifests itself in neutron resonances when the nucleus under investigation is placed in different chemical compounds. Its analog is the so-called chemical shift in nuclear gamma-resonance (NGR) spectroscopy. This shift is proportional to the product $\Delta\rho_e(0) \cdot \Delta\langle r^2\rangle$ where $\Delta\rho_e(0)$ is the difference between the electron densities at the position of the nucleus in the case of the pair of chemical compounds being disucssed, while $\Delta\langle r^2\rangle$ is the difference in the mean square charge radii of the nucleus with mass A in the ground state and $A+1$ in the excited state formed as a result of resonance capture of a neutron. The chemical shift was experimentally investigated for 10 resonances of ^{235}U, ^{238}U and ^{234}U. From these investigations the changes in $\langle r^2\rangle$ associated with the excitation of the nucleus have been obtained. A previously unknown correlation has been observed: for compound states with low fission probability the mean-square radius decreases somewhat as the nucleus is excited, while for states with a high fission width $\langle r^2\rangle$ practically does not change as the nucleus is excited.

The developed methodology for determining small shifts in neutron resonances made it possible, also for the first time, to carry out experiments on observing yet another similar effect—the temperature shift of neutron resonances which also has an analog in NGR spectroscopy. It is interesting that the neutron analog of the temperature shift is smaller by a factor of three than in the case of nuclear γ-resonance.

V. I. Lushchikov in his paper "Ultracold neutrons" noted that for the physics of elementary particles in addition to moving into the region of ultrahigh energies, it was doubtless of interest to "break through" into the region of ultralow energies as occurred in 1968 when F. L. Shapiro with collaborators experimentally observed ultracold neutrons (UCN) of an energy of ~100 neV. This has also been achieved independently by A. Staerl in the FRG. The UCN have a number of remarkable properties among which is their ability to be retained in closed vessels for a long time. The yield of ultracold neutrons from reactors is unusually small, in the first experiments experimenters obtained only 1 neutron per minute. At the present time the technique of obtaining UCN has moved forward significantly, and the yield of UCN from steady state reactors reaches values of 10^3–10^4 neutron/s, and various physics experiments are carried out using them.

Thus the storing of a UCN gas in closed vessels has been demonstrated. The greatest storage time obtained is ~700 s and is restricted both by the period of the β-decay of a neutron (1000 s), and, apparently, also by the heating of the UCN as they collide with the walls of the vessel. At first glance it is surprising that a UCN gas that has an effective temperature of only 0.001 K, can remain cold for 10 minutes in a vessel with walls at room temperatures. However, this result is in quite reasonable agreement with the theoretically expected one and is qualitatively associated with the low neutron velocity (~5 m/s) and by the small value of the amplitude of the neutron wave penetrating into the wall of the vessel.

The possibility of a lengthy observation of the neutron in an experimental apparatus opens up a path for the precision investigations of the characteristics of the neutron itself with an accuracy which is limited only by the Heisenberg indeterminacy principle. In particular, this possibility can be effectively utilized in the search for the electric dipole moment of the neutron (F. L. Shapiro, 1968), for the measurement of the neutron half-life and for the search for an electrical charge of the neutron. The first of the above experiments has been successfully carried out by the group of V. M. Lobashev (Leningrad Institute for Nuclear Physics) which has already obtained the lowest estimate of a possible electric dipole moment of the neutron $d < 3 \cdot 10^{-26}$ cm/e.

The possibilities of carrying out research on UCN extend far beyond this brief list. Thus, for example, both in the USSR and abroad work is in progress on the construction of a neutron microscope which would use ultracold neutrons as "neutron light".

The topic of the report of Yu. M. Ostanevich was "The origin and the development of research on the physics of condensed media in the Laboratory for Neutron Physics of the JINR". The end of the 1950's—the beginning of the 1960s have been associated with the wide spread throughout the world of two nuclear-physics methods of research in the physics of solid state and of liquids—the Mössbauer effect and the scattering of slow neutrons. Both these methods have been adopted in the LNP already in 1960 on the initiative of and with the direct participation of F. L. Shapiro. Investigations using the ultranarrow gamma-emitter ^{67}Zn carried out at the beginning of the 1960s remained for a long time the record holder with respect to the observed ratio Γ/E—of the line width to the energy of the gamma quantum, while the classical theory of the Mössbauer effect (F. L. Shapiro, 1960) has not lost its relevance up till the present time. Investigations at the LNP with the aid of the Mössbauer effect were continued for quite a long time and very effectively and only in 1974 the participants in this work have shifted over entirely to the preparation of investigations in the physics of condensed media using the IBR-2 reactor.

The development of neutron investigations in the physics of condensed media at the LNP began practically simultaneously with the commissioning of the first pulsed IBR reactor (1960). At that time the problem was substantially more complicated from the methodological point of view since at that time there was no accumulated experience on the use of pulsed neutron sources for such investigations, while a direct comparison of the average powers of the IBR reactor (3 kW) and a typical steady-beam reactor [(10–20) 10^3 kW] might seem to have made competition in this field for the pulsed reactor entirely hopeless. One had to have the insight, the talent and the enthusiasm of F. L. Shapiro in order that in the course of two-three years with the participation of a number of members of the LNP (V. V. Golikov, I. Yanik, A. Baïorek, N. Sosnovska, E. Sosnovski, and others) it was possible to create a practically complete arsenal of methods of neutron investigation of condensed media (time-of-flight diffraction, inelastic scattering with a beryllium filter in front of the detector, etc.). As a result the LNP rapidly achieved a world-wide reputation also as the possessor of a new type of a highly effective neutron source. The successes of the work carried out at the IBR reactor and the IBR with an injector both in the field of nuclear physics, and in the physics of condensed media were convincing. They led to the appearance of a number of projects for periodic pulsed reactors for physics research. Only IBR-2 of all these was actually realized. As regards the competition between pulsed and steady-state neutron sources for the physics of condensed media, it continued for a number of years. It led to an understanding of the differences between them and of their advantages, and also to an understanding of the promising possibilities of pulsed sources for the further progress of research in the physics of condensed media.

From the point of view of subject matter neutron research in the Laboratory for Neutron Physics embraces problems in atomic structure and dynamics. At the same time appropriate attention was paid to the fundamental object—the quantum liquid He II, to the research on which a separate paper is devoted. Structural investigations quite rapidly attained a level sufficient for the investigation of biological objects—IgG immunoglobulin, ribosome particles, biological membranes, and also very complicated representatives of the inorganic world—superionic conductors, magnetic materials of the type of $\mathrm{Ba\,(TiCo)_{2x}Fe_{12-2x}O_{19}}$ with a long period magnetic structure, etc. An independent direction of considerable practical interest is the texture neutron diffraction technique using a pulsed neutron source which was for the first time developed at the LNP.

Neutron research on the physics of condensed media after the IBR-2 reactor was commissioned obtained new excellent possibilities and are accompanied by a rapid growth of international scientific cooperation. By 1985 sixty-seven scientific organizations from the 10 member-states of JINR are participating in these investigations in different ways, and this number continues to grow rapidly.

The report by I. Natkants "The origin and development of the method of inverse geometry for neutron investigations of condensed media using pulsed reactors of the JINR" was devoted to the investigations of the inelastic scattering of neutrons influenced by the atomic and molecular dynamics of the objects being studied. This method is based on the time-of-flight measurements of the energy of the neutrons incident on the sample, and on the determination of the final energy of the scattered neutrons with the aid of a beryllium filter. This method was created in 1963 with the direct participation of F. L. Shapiro. A further development of the method was carried out by a group of physicists from the Institute for Nuclear Physics in Krakow (Poland) and included the use of a single crystal analyser for the neutron energy after the Be-filter, an increase of the number of simultaneously operating detectors up to 8, a simultaneous recording of the diffraction spectra and the elastic scattering spectra, the use of a rotating collimator for suppressing the background and other improvements.

The principal topic for the investigations using the Krakow-Dubna inverse geometry spectrometer (KDIGS) was the dynamics of molecular crystals. These investigations yielded many interesting results. As an example we can cite the work (together with the Institute for Solid State Physics of the Academy of Sciences at Chernogolovka) which studied harmonic vibrations and anharmonic effects in typical molecular crystals (benzene, naphthalene, anthracene and others) in the course of which a complete understanding was obtained of the harmonic oscillations in complex crystals, and also anharmonic shifts of frequencies were discovered induced both by the thermal expansion of the lattice, and also by the intrinsic anharmonic nature of the molecular interactions.

The inverse geometry method was also used successfully to investigate the local levels of light impurity atoms, the splitting of electronic levels of paramagnetic ions in crystal-line electric fields in metals and alloys, the oscillations of hydrogen adsorbed on the surface of catalysts, etc. At the present time two inverse-geometry spectrometers are in operation at the LNP. In addition to the set of topics enumerated above they are also used to develop new directions, for example, the investigation of vibrational spectra of amorphous materials, molecules adsorbed on zeolites, investigation of electronic structure of rare-earth metals, etc. Work is in progress on the construction of a variant of a spectrometer with a resolving power of several microelectron volts.

The report by Zh. A. Kozlov "Investigations of helium-II by the method of neutron scattering" was devoted to the experimental observation and study of the quantum effect of Bose-condensation in superfluid helium. Experiments along this line were begun in the early 1970s on the suggestion of F. L. Shapiro and were carried out together with group of physicists from the JINR and the Physics and Power Institute. In the course of these investigations which make it possible to obtain experimentally the momentum distribution of helium atoms it was shown for the first time that there exists a Bose-condensation temperature (2.24 ± 0.04) K which coincides with the temperature of transition of liquid helium into the superfluid state. Below this temperature as the temperature is lowered an increase in the number of helium atoms with zero momentum (Bose-condensate, BC) is observed. At $T > 0.6$ K the temperature dependence of the density of BC coincides with the similar dependence for the superfluid component of helium. Present-day theoretical descriptions of superfluidity do not make use of concepts of Bose-condensation, as a result of which the observed correlation between the BC densities and the superfluid component does not for the time being have a clear interpretation.

The seminar that was held at Dubna dedicated to F. L. Shapiro evoked considerable interest among the scientists of the JINR and from other institutes. The participants in the discussions noted the high scientific significance and timeliness of the investigations carried out at the LNP.

Translated by G. M. Volkoff