HISTORY REVIEW OF NEUTRON RESEARCH IN PNPI

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Introduction

One of the oldest research reactors was launched over forty years ago. The WWR-M reactor started operating in December, 1959 at Petersburg Nuclear Physics Institute (PNPI) in Gatchina. Ever since it has been normally operating without replacement of the tank. Russia’s concern for this reactor as a stationary neutron source was significantly increased, when many research reactors were shut down after USSR break-up. The construction of a new high-flux reactor PIK is currently in progress at PNPI. According to expert estimations 70% of the works has already been done. However, the economical situation in Russia makes it difficult to estimate the date of launch. In connection with this the institute has made a decision to change the capabilities of the WWR-M reactor so that they comply with new standards of security requirements, and to prolong its operation.

The WWR-M reactor is located in the Neutron Research Department (NRD) of PNPI. The institute has a large mechanical workshop for manufacturing the experimental equipment and the developed infrastructure. A cryogenic station for production of liquid nitrogen and helium is located 800 m away from the reactor. The institute is situated in a wood region about 3 km away from Gatchina and 50 km away from St. Petersburg. The institute facilities are: a dining place, a hotel (100 places), a sport complex with a swimming pool, bus and railway lines to St. Petersburg. The institute welcomes science visitors and collaborates with many institutes of Russia and foreign countries.

1. WWR-M reactor

Already during reactor construction the initial project of WWR-S for 2 MW was changed and the upgraded project of WWR-M for 10 MW was actualized. In 1979 the reactor power capacity was increased to 18 MW, however, as a rule, it uses 14-16 MW. The WWR-M is the reactor of a pool type with a beryllium reflector. The flux of thermal neutrons in the reflector is $0.8 \times 10^{14} \text{ cm}^{-2} \text{ s}^{-1}$.

The initial project had 9 horizontal channels and a “thermal graphite column”. However, quite soon the graphite column was replaced with a concrete inset. In this sector 5 additional horizontal channels were made to provide installation space for 6 additional beams of thermal neutrons. Also a through-channel was drilled for experiments with secondary radiation. At the bottom of this additional channels the flux of thermal neutrons is less than abovementioned that in the reflector, that have the flux of $(2-3) \times 10^{13} \text{ cm}^{-2} \text{ s}^{-1}$. In spite of a less neutron flux these channels are successfully exploited and used to conduct a considerable part of solid studies. The reactor has 13 vertical channels for radiation of samples and low temperature helium loop for the studies of materials during their radiation by thermal (and/or fast) neutrons. In 1969 an over-reactor chamber with remote control manipulators was created on the reactor cover. The chamber makes it possible to conduct the visual observation and simple operations with the samples and the fuel elements recovered from the active reactor zone. Hot cells connected with the storages of radiated samples are located in the sub-reactor space. This makes it possible for a customer to get containers with the radiated samples.

In 1986 a universal channel of polarized cold and ultra cold neutrons was installed at the reactor, and in 1996 a solid deuterium source of ultra cold neutrons was installed in the horizontal channel 10.

Normally, the reactor works in 2 week cycles with 2–3 day pauses between them, with a 2 week pause in every 3 months and a 2 month summer pause for a maintenance.

The exact schedule of reactor operation is determined by the Science Council of NRD PNPI.

The WWR-M reactor has been operating for 40 years without a single crash. The level of reactor ejection (90% of which is $^{41}$Ar) is much less than the admissible standards and creates a radiation dose for citizens of Gatchina, which is about 1000 times less than the natural radiation. Ever since the reactor was built there have been no single case of over-radiation of personnel, which is mainly a merit of high-qualified personnel and its leader R.G. Pikulik.
2. 60s – 70s. Scientific studies in nuclear physics, fundamental physics and physics of condensed state

Scientific studies at the WWR-M reactor began in 1960 under leadership of Lev Ilyich Rusinov, the pioneer in the isomerism of atomic nucleus, the disciple of I.V. Kurchatov, who was the initiator and the director of the reactor construction. He gathered around himself young talented scientists, who subsequently headed various directions of activity at the reactor. The direction of fundamental studies was developed by V.M. Lobashev, the studies of nuclear and roentgen spectroscopy were formed under the direction of O.I. Sumbaev, and I.A. Kondurov, the studies of physics of fission were headed by G.A. Petrov. G.M. Drabkin initiated studies solid state physics. The development of reactor technology and construction of PIK reactor is managed by K.A. Konoplev. The project of the new reactor was prepared by Yu.V. Petrov and K.A. Konoplev.

After Lev Ilyich Rusinov the laboratory heads were: Prof. D.M. Kaminker, Prof. O.I. Sumbaev, Prof. A.P. Serebrov. Since 1992 the laboratory of neutron research has the status of Department consisting of 3 scientific divisions:

- Neutron physics division (Prof. A.P. Serebrov);
- Condensed state studies division (Prof. A.I. Okorokov);
- Reactor physics and engineering division (Dr. K.A. Konoplev)

and 3 scientific-technical divisions:

- Division of semiconductor nuclear detectors (Dr. A.H. Khusainov);
- Division of reactor research automation (Dr. V.V. Marchenkov);
- Division of neutron optics (Dr. A.F. Schebetov).

Director of Neutron Research Department is Prof. V.A. Nazarenko, also the Institute director.

There can be defined three historical stages in development of scientific studies at WWR-M reactor, determined by both internal and external circumstances. The first stage is the stage of formation and development of main scientific directions, taking place during 60-s and the beginning of 70-s. The second stage is an active preparation for the scientific studies at PIK reactor covering the end of 70-s, 80-s and the beginning of 90-s. And, at last, the stage of science saving which began in 90-s and has lasted till today.

The initial stage of studies at the reactor is the most memorable for physicists of elder generation. And to pay a tribute to them it should be noted that it was at their time, when the foundations of scientific activity were established and the primary spiritual values were formed, which is, first of all, a devoted attitude towards science and democracy of communication. All of this played the main role in the process of formation of Gatchina School of neutron studies.

Nuclear-spectroscopic studies

The first experiments at the reactor were devoted to the measurement of lifetime (I.A. Kondurov, D.M. Kaminker, Yu.E. Loginov). Soon after the reactor launch the crystal-diffraction focusing gamma-spectrometer was put into operation. The spectrometer was created by O.I. Sumbaev and A.I. Smirnov and subsequently modernized by V.L. Alexeev and V.L. Rumyantsev. Now this spectrometer successfully operates and allows to measure the $\gamma$-ray energies with accuracy of units electronvolt in the range $40 - 1000$ keV.

One of the first experiments (O.I. Sumbaev, D.M. Kaminker, A.I. Smirnov, V.A. Shaburov, 1963) conducted at this spectrometer showed the results which still remain a mystery and call for explanation. This experiment was concerned with the studies of rhodium gamma spectrum, in which the energy distribution of gamma lines was first discovered to be non-statistical. Instead of a well-known random distribution of levels on account of their “repulsion”, their “attraction”, i.e. the level grouping was discovered. Moreover, the distances between the groups occurred to be divisible. The nature and even the evidence of the phenomenon itself are still argued.

The measurements of spectra of electrons of internal conversion from the (n,$\gamma$) reaction became a reality after installation in 1968 of magnetic beta-spectrometer (B.A. Emelianov, V.S. Gvozdev, Yu.L. Khazov, S.L. Sakharov). Subsequently employment of inner-channel transport solenoid allowed to increase sensitivity by 7 times, which helped to approximate the spectrometer characteristics to the parameters of BILL spectrometer at ILL. The availability of the complex of nuclear spectroscopic installations at the WWR-M reactor and the possibility to work at other spectrometers of the world (in Grenoble, Geidelberg, Garching) allowed
to level schemes of a large number of nuclei (I.A. Kondurov, P.A. Sushkov, V.V. Martyinov, V.L. Alexeev and others). The considerable part of nuclear spectroscopic studies was devoted to the creation of a nuclear data bank (Yu.V. Sergeenkov and others).

**Weak interactions and Neutron EDM studies**

In the end of 50-s it was shown that one of the laws of the fundamental physics does not work, the law of parity conservation in the weak interactions. The hypothesis of universality of weak interaction predicted the effects of the violation of P-parity in nuclear electromagnetic transitions. The studies of such effects were started by V.M. Lobashev together with V.A. Nazarenko in the beginning of 60-s. Employment of the unique methods by combining the integral method of registration of γ-quanta with resonance discrimination of a signal by means of a high-quality contour (pendel of astronomic clock) allowed to measure exceptionally small effects of the circular polarization of γ-quanta equal to $10^{-5} - 10^{-7}$. As a result of studies, the effects of parity violation were found in a great number of γ-transitions of radioactive nuclei, which were the first firm proof of the hypothesis of universality of weak interaction. Measurement of circular polarization of γ-quanta in np→dγ reaction has become in principle important. The experiment on the search for electric dipole moment of neutron, realized at the WWR-M reactor by V.M. Lobashev together with a collective of physicists enrolled in PNPI in 70-s, became the most significant for both the laboratory and fundamental physics. The main feature of this experiment was employment of ultra cold neutrons. The preparations for this experiment were started in 1968. The techniques of work with UCN were developed actually from nothing, starting from the UCN production, that is, the creation of UCN sources, and further on to the creation of magnet-resonance spectrometer with energy resolution of $10^{-17}$ eV (see fig. 1).

Already in the beginning of 80-s a principally important for the theory result was obtained: the upper limit for EDM of neutron $d_n \leq 3 \cdot 10^{-25}$ e·cm (V.M. Lobashev, A.P. Serebrov, G.D. Porsev, V.F. Ezhov, S.N. Ivanov, Yu.V. Borisov and others).

This experiment has become one of the most principal for physics of elementary particles. It is connected with the search for the effect of violation of CP or T-parity basal for the Universe formation. Determination of a new upper limit for EDM of neutron in practice allowed to completely close the model of CP-violation of Weinberg and make comments about the advantages of other models of CP-violation: super-symmetric, left-right and the model of Kobayashi-Maskawa. The UCN method in the experiment on the search for EDM of neutron, which showed its advantages, was also realized at a high-flux reactor in Grenoble. In the end of 80-s in the course of the following measurements at the universal channel the accuracy was improved by 3 times. The same accuracy was obtained at the experiment in Grenoble.

**Studies on physics of nuclear fission**

A scientific program on physics of heavy nucleus fission, emphasizing on dynamic effects of this reaction, started with the first days of reactor operation (G.A. Petrov). For the first decade a new physical phenomenon in fission reaction of heavy actinides was thoroughly studied namely the angular anisotropy of γ-quantum emission in case of fission of undirected compound-nuclei formed as a result of thermal neutron capture. A strong pronounced dependence of the anisotropy coefficient on γ-quantum energy was first discovered (G.A. Petrov, G.V. Valsky, Y.S. Pleva). At the suggestion of G.V. Valsky a linear polarization of $235\text{U} \gamma$-quanta in the range of 0.1 – 1.5 MeV was measured, and the dependence on mass and energy of fragments was thoroughly studied.

The effect of anisotropy of γ-quantum emission relative to the axis of fragments fly apart was explained by V.M. Strutinsky. It occurred to be connected with considerable angular moments of fragments oriented in the plane perpendicular to the axis of fragment separation. Experiments, carried out in Gatchina, allowed to estimate the values of these moments ($\approx 5 – 7 \ h$), and also to determine the prevalent E2 multipolarity of γ-quanta in the range of 0.1 – 0.7 MeV.
Fig. 1. The scheme of the magnet-resonance spectrometer with electric field for the search of EDM of neutron: 1 – liquid hydrogen UCN source, 2 – beryllium reflector, 3 – active reactor zone, 4 – lead shield, 5 – UCN neutron guide, 6 – helium tubes, 7 – hydrogen tube, 8 – vacuum tube, 9 – polarizer, 10 – UCN storage chambers with high-voltage electrodes, 11 – magnetic shields, 12 – solenoid of magnetic field (incoming), 13 – a coil for gradient of magnetic field (outcoming) 14 – coils for homogeneous magnetic field, 15 – magnetometer of the system of stabilization of external magnetic field, 16 – Cs-magnetometer of the system of stabilization of magnetic field in shields, 17 – coils for demagnetization of magnetic shields, 18 – analyzers, 19 – flipper of the system of double analysis of polarization, 20 – UCN detectors.

About at the same time the yields and the main properties of isomeric delayed $\gamma$-radiation in the fission reaction were thoroughly studied (L.A. Popeko, G.A. Petrov, D.M. Kaminker).

At the suggestion of A.A. Vorobyev a series of experimental studies of triple fission of $^{233, 235}\text{U}$, $^{239}\text{Pu}$, $^{241, 242m}\text{Am}$ was carried out at the WWR-M reactor (V.T. Grachev, I.A.Kondurov, D.M. Seliverstov, N.N. Smirnov, etc.). As a result, the yields and the energy spectra of light nuclei from hydrogen isotopes to oxygen ones were precisely measured for the first time.

A deep insight into the perspectives of studies of the fission process with resonance neutrons resulted in enthusiastic attempts to build a pulse neutron source in Gatchina. In 1971, these attempts successfully turned into a start of the neutron spectrometer GNEIS created on the basis of synchrocyclotron with the energy of 1 GeV. This installation, built at the initiative of G.A. Petrov and his colleagues, G.Z. Boruhovich, V.I. Yurchenko, T.K. Zvezdkina, E.N. Teterev, still operates with success today. A priceless contribution to the transformation of the GNEIS spectrometer into a modern physical device was done by O. A. Scherbakov. Exactly due to his efforts at the end of 70-s and beginning of 80-s a very good series of works concerned with the studies of $(n\gamma f)$ reaction in fission of $^{238, 235}\text{U}$ and $^{239}\text{Pu}$ was carried out at this spectrometer.

Two original experimental works were carried out at the same time. The first one was concerned with the probability evaluation of ionization of a fissionable atom shell by fluctuating electromagnetic field of a
fissiable nucleus (L.A. Popeko, E.F. Kochubei, G.A. Petrov), and the second one was connected with the studies of possibility of a fission cross-section change by thermal neutrons under conditions when fissiable isotopes are placed into different gas molecules (A.V. Derbin, A.B. Laptev, G.A. Petrov, Y.S. Pleva, M.A. Yamschikov).

Beginning with 1976, the fission physics direction changes orientation of its scientific interests and starts to realize a great number of scientific studies devoted to the phenomenon (just discovered at ITEPh) of the space parity violation in the process of heavy nuclei fission by thermal and resonance polarized neutrons. Along with this phenomenon other P-even interferential phenomena in angular distribution of fission fragments were also thoroughly studied due to a certain similarity of their origination mechanisms. As a result of these integrated studies, carried out for a wide range of fissiable nuclei from $^{229}$Th to $^{245}$Cm, the experimental basis for the modern theory of P-odd and P-even phenomena in fission of heavy actinides was created.

**Solid state physics**

Studies of the solid state physics were started at the WWR-M reactor in 60-s too. Right after the reactor launch G.M. Drabkin and S.V. Maleyev organized experimental and theoretical groups for neutron studies of the physics of condensed state (PCS). This theoretical-experimental tandem is still at work, providing a high level of studies. Polarized mirrors and other equipment required for depolarization and small-angle scattering experiments were created already in 2 – 3 years after the reactor launch. It was just then when the main feature of solid state studies in Gatchina was defined; it was work with polarized neutrons. The method of neutron spatial spin resonance proposed and developed by G.M. Drabkin is widely known. Actively working physicists from G.M. Drabkin’s sector later on chaired the laboratories and groups, their names being: A.I. Okorokov, V.A. Trunov, V.P. Plakhty, A.F. Schebetov.

Studies of this period at beams of polarized neutrons are characterized by creation in principle new techniques, which base upon the obtained experimental data and also result from development of the polarized neutron scattering theory. The cross-section of magnetic scattering depends on mutual direction of the initial polarization $P$, magnetization of sample $M$ (or $m=m|M|$, the scattering vector $q$ (or $e=q/q$) and neutron velocity vector (or wave vector $k$).

In addition to one well known pseudo-vector of magnetic interaction $M_{||}=m-(em)e$ (Halpern and Johnson), describing the magnetic-nuclear interference, S.V. Maleyev discovered a new one for purely magnetic interaction in 1961, $M_{||}=(em)e$. In 1978 it was discovered that pseudo-vector $n=[k',k]/|k',k|$ gives an opportunity to study 3-spin (chiral) correlations (A.V. Lazuta, S.V. Maleyev and B.P. Toperverg). This fact was immediately verified through experiment (A.I. Okorokov, A.G. Gukasov, V.V. Runov).

All the mentioned vectors and the relation $P=-e(eP_{e})$ became a basis for the polarization methods and the interpretation of experimental data. One of the main methods is 3-dimensional (3-d) analysis of the polarization. It appeared that for small-angle scattering the function $P=-e(eP_{e})$ gives the possibility, by measuring only $P$ vector, to find out everything about the process of magnetic scattering including its elastic and inelastic components. Using 3-d analysis techniques a large cycle of studies of ferromagnetic phase transition in Fe (A.I. Okorokov, V.V. Runov and others) and in PdFe (4 at. %) (G.P. Gordeev, L.A. Aksel’rod, and others) and magnetic texture was performed.

In principle new thing in the studies of phase transitions was that 3-d analysis allowed us to investigate the asymptotical region with energy transfer $\omega$ and half-width of the dynamic form factor $\Gamma$: $\omega << \Gamma$ and $\omega >> \Gamma$. In other words, it allowed to obtain results adequate to the asymptotical theories of phase transition. For instance, the dynamic characteristics were obtained in the range of $\omega = (7 - 100) \Gamma$, where the asymptotic of dynamic form-factor $F(q,\omega) \sim \omega^{13/2}$ was found to be within the limit of $\omega >> \Gamma$, and not the Lorentz one, as it had been assumed earlier. That kind of results can not be obtained by other techniques. On the basis of Maleev’s pseudo-vector $M_{||}$ the techniques of left-right asymmetry of scattering was developed. This scattering is connected with dynamic correlations described by a 3-spin Green function Im$G^{(3)}$, spin z-projection fixed by magnetic field. These techniques allowed to first study the critical dynamics by triple spin correlations in the field, to answer a series of in principle important questions of theory and to measure
with high accuracy the parameters of spin waves in ferromagnetic phase. A two-dimensional picture of asymmetric scattering on spin waves is shown in the fig. 2.

The neutron diffraction studies of magnetic structure and the exchange interaction were primary questions of the science of magnetic crystals (V.P. Plakhty, I.V. Golosovsky, O.P. Smirnov, Yu.P. Chernenkov). The following studies gave experimental data for development of a method of symmetry analysis of magnetic structures: the determination of spin configurations and exchange links in seignette-magnetics, e.g. in perofskites, determination of magnetic ordering in multi-sublattice antiferromagnetic garnets with 3d-ions and detection of atom chains (taking part in formation of exchange links) in them.

The same period is characterized by studies of more sophisticated features of exchange interaction in crystals. One of them is a polarization analysis of neutrons after scattering in yttrium orthoferrite. It revealed a weak antiferromagnetic component caused by antisymmetric exchange interaction of Dzyaloshinsky-Moriya $H_D = \sum_{ij} D_{ij} [S_i \times S_j]$ The ratio of the weak AF component of the Fe$^{3+}$ spin to the main one was found to be $1.93(18) \cdot 10^{-2}$.

3. Preparations for research at the PIK reactor

In 1976 the construction of a new reactor (PIK reactor) was started in PNPI. At that stage the main role belonged to O.I. Sumbaev who was then director of the Institute and head of the Neutron Research Laboratory (NRL). In the end of 70-s at the WWR-M reactor an active preparation for the experiments at the reactor being constructed was started. O.I. Sumbaev took a decision to call for help of physicists of the next generation, in order to develop the scientific programme and the physical equipment. A.P. Serebrov was assigned the NRL head. A new sub-division for development of experimental installations under leadership of V.A. Trunov was added to the structure of NRL. The creation of a new experimental base became the aim of all sub-divisions of the laboratory. It was required not only to develop scientific programme of studies but to build experimental installations for its realization as well. It was decided to equip the WWR-M reactor with new installations or with prototypes of those meant for the PIK reactor and to use them simultaneously for current measurements. This tactics allowed to activate scientific studies, to prepare the operating equipment and the real scientific program. Under conditions of undefined dates for the launch of the new reactor this tactics proved to be optimal. As a result by the end of 80-s practically all the beams of the WWR-M reactor were equipped with new experimental installations (see fig. 3 and table 1) and the liquid helium source of cold and ultra cold neutrons (see fig. 4) was installed in the centre of the active zone.
Fig. 3. Beam and instrument layout at the reactor WWR-M.

<table>
<thead>
<tr>
<th>Instruments</th>
<th>Ch. No</th>
<th>I (sample), n/cm².s</th>
<th>Parameters</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>UCN – ultra-cold neutron</td>
<td>1</td>
<td>$6 \times 10^4$</td>
<td>$\lambda = 700\text{Å}$</td>
<td>Fundamental physics</td>
</tr>
<tr>
<td>PCN – polarized cold neutrons</td>
<td>1</td>
<td>$6 \times 10^5$</td>
<td>$\lambda = 4\text{Å}$</td>
<td>Fundamental physics</td>
</tr>
<tr>
<td>PD – Powder diffractometer</td>
<td>1</td>
<td>$10^6$</td>
<td>$\lambda = 1.38 - 2.52\text{Å}; \Delta d/d = 0.01$</td>
<td>Structure study</td>
</tr>
<tr>
<td>MRPN – Monochromator of resonance Polarized neutrons</td>
<td>1</td>
<td>$5.10^4$</td>
<td>$\lambda = 0.34\text{Å}, \Delta \lambda/\lambda = 0.1$</td>
<td>P,T-parity, fission physics</td>
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Table 1 (continued)

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<tbody>
<tr>
<td>BSGS GSK-2M – Bend crystal γ-spectrometer (Cauchois-type)</td>
<td>2</td>
<td>$6.10^{15}$</td>
<td>E=40-1000 keV, FWHM=6-120 eV</td>
<td>Precise γ-spectroscopy</td>
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<tr>
<td>IN NEUTRON-3 – Three-axis spectrometer</td>
<td>3</td>
<td>$10^6$</td>
<td>$\lambda=1-4 \text{ Å}; \Delta \omega=0.5 \text{ meV}$</td>
<td>Inelastic scattering</td>
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<td>SAPNS-VECTOR – SANS instrument of Polarized neutrons</td>
<td>4</td>
<td>$1.7\times10^4$</td>
<td>$\lambda=7-12 \text{ Å}; \Delta \lambda/\lambda=0.1-0.3$</td>
<td>Spin correlations</td>
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<td>SANS-MEMBRANA – small angle diffractometer</td>
<td>5</td>
<td>$10^6$</td>
<td>$\lambda=2.2-5 \text{ Å}; \Delta \lambda/\lambda=0.1-0.3$</td>
<td>Supra structure</td>
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<td>CSPN – correlation spectrometer of polarized neutrons</td>
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<td>$10^6$</td>
<td>$\lambda=2.5 \text{ Å}; \Delta \lambda/\lambda=0.3$</td>
<td>Magnetic diffraction,</td>
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<tr>
<td>MRN – Monochromator of resonance neutrons</td>
<td>7</td>
<td>$5.10^2$/eV</td>
<td>E=15 eV, $\Delta E/E=0.1$</td>
<td>Physics of fission</td>
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<td>RCN – radiation neutron capture instrument</td>
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<td></td>
<td></td>
</tr>
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<td>RTOF Mini-SFINKS – Time of flight powder diffractometer</td>
<td>9</td>
<td>$2.10^7$</td>
<td>$\lambda=0.9-5 \text{ Å}; \Delta d/d = 2.5\times10^{-3}$</td>
<td>Atomic structure</td>
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<td>CD UCNS – Solid deuterium UCN source</td>
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<td>$5.10^2$</td>
<td>$\lambda=400 \text{ Å}$</td>
<td>Fundamental physics</td>
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<td>MSES – Modified spin-echo spectrometer</td>
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<td>L-f - dynamics</td>
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<td>RPN – Reflectometer of polarized neutrons (under construction)</td>
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<td>Surface of liquids</td>
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<td>TOFRPN – Time of flight reflectometer of polarized neutrons</td>
<td>13</td>
<td>$10^1$</td>
<td>$\lambda=1-4 \text{ Å}; \Delta \lambda/\lambda=0.1-0.25$</td>
<td>Neutron optics</td>
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<td>SCD – Single crystal diffractometer</td>
<td>13a</td>
<td>$2.10^5$</td>
<td>$\lambda=0.7-1.73 \text{ Å}$</td>
<td>Single crystals</td>
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<td>3DAPN – 3-d analyzer of polarized neutrons</td>
<td>14</td>
<td>$3.10^9$</td>
<td>$\lambda=2.3 \text{ Å}; P&gt;0.95$</td>
<td>Magnetic texture</td>
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<tr>
<td>LTHel – Low-temperature He-loop</td>
<td>1013(f)</td>
<td>$7.10^{11}$/t</td>
<td>T=20-400K</td>
<td>Radiation physics</td>
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<td></td>
<td>1.1013(f)</td>
<td>$\Delta T=0.1K$</td>
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<td></td>
<td>200 Cu</td>
<td>$\lambda=0.03 \text{Å}; \Delta \lambda/\lambda=10^{-6}$</td>
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<td>Perfect crystals</td>
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</tbody>
</table>

Fig. 4. The liquid hydrogen source of cold and ultra cold neutrons and a complex of experimental installations for studies of β-decay of neutron

The asymmetry of β-decay was measured at a vertical polarized cold neutron beam by means of the electron detector and the proton detector located along the axis of installation which oriented along the vector of the neutron beam polarization. For the measurements of neutron lifetime the original techniques were used: the storage of ultra cold neutrons in a trap with the gravitational shutter. Ultra cold neutrons fill the spherical trap when its hole looks down, afterwards the sphere turns in the state when the hole looks up and neutrons with low kinetic energy can not leave the trap because of the gravitational field.
**Fundamental and Nuclear Physics**

The reactor obtains new quality after it was fit up with new physical equipment. Especially effective was the launch of cold and ultra cold neutron source (A.P. Serebrov, I.S. Altarev, B.G. Erozolimskiy, I.A. Kuznetsov, A.F. Schebetov, B.G. Peskov, N.V. Borovikova, and others). The flux of polarized cold neutrons at the exit of vertical neutron guide amounted to $3 \times 10^{10}$ n/s at the density of $6 \times 10^{9}$ n/cm$^2$s, what appeared to be 5 times greater than that at the reactor in Grenoble. It can be said that the liquid helium source of cold and ultra cold neutrons changed the status of the WWR-M reactor, in any case, it put it into one line with a number of modern reactors. A series of the remarkable world-level results was obtained with this source. The upper limit for electrical dipole moment of neutron was brought to the value of $1.1 \times 10^{-35}$ e⋅cm (V.M. Lobashev, A.P. Serebrov, I.S. Altarev, Y.V. Borisov, N.V. Borovikova, A.I. Egorov, C.N. Ivanov, E.A. Kolomensky, M.S. Lasakov, V.A. Nazarenko, A.N. Pirozhkov, Y.V. Sobolev, E.V. Shulgina, and others).

Precise measurements of neutron $\beta$-decay were started at this source. Beta-decay of neutron is one of the problems of elementary particle physics which should and must be decided at reactors. This process is exceptionally important for the theory. Axial and vector constants of the weak interaction can be determined more strictly from $\beta$-decay of neutron. A high accuracy of the parameters of this process verifies unitarity of Kobayashi-Maskawa matrix and is very important for the cosmology and the model of the Sun. The results of $\beta$-decay of neutron obtained at the WWR-M reactor are of the world-level accuracy and are in good competition with the results obtained at ILL high-flux reactor. An asymmetry of antineutrino escape relative to the neutron spin in its $\beta$-decay was measured with the best accuracy in the world (A.P. Serebrov, I.A. Kuznetsov, I.V. Stepanenko, A.V. Alduschenkov, M.S. Lasakov, and others). The asymmetry of antineutrino escape of electron relative to the neutron spin was measured with accuracy of 1.2 % (B.G. Erozolimskiy, I.A. Kuznetsov, I.V. Stepanenko, Y.A. Mostovoi, O.V. Rozhnov, N.F. Maslov, and others). The neutron lifetime was measured by means of UCN storage with accuracy of 0.3 % (A.P. Serebrov, A.G. Kharitonov, R.R. Taldaev, V.V. Nesvizhevskiy, A.V. Strelkov, V.N. Shvetsov, V.P. Alfimenkov, and others). The loss probability during UCN storage accounted for only 3% of the probability of $\beta$-decay, therefore it was almost a direct measurement of the exponent for the decay of neutron. The complex of installations for studies of $\beta$-decay of neutron is presented in the fig. 4.

The effects of parity violation (with the accuracy that was not achievable before) were studied by means of a number of modern reactors. A series of the remarkable world-level results was obtained with this source. The upper limit for electrical dipole moment of neutron was brought to the value of $1.1 \times 10^{-35}$ e⋅cm.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Correlation</th>
<th>Result</th>
</tr>
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<tbody>
<tr>
<td>$^2$H(n, $\gamma$)$^2$H</td>
<td>$P_7$</td>
<td>$(1.8 \pm 1.8) \times 10^{-7}$</td>
</tr>
<tr>
<td>$^3$He(n,p)$^3$Li</td>
<td>$\rightarrow$</td>
<td>$(-0.38 \pm 0.49) \times 10^{-7}$</td>
</tr>
<tr>
<td>$^6$Li(n,α)$^4$He</td>
<td>$\rightarrow^0$</td>
<td>$(3.4 \pm 0.7) \times 10^{-7}$</td>
</tr>
<tr>
<td>$^7$Li(n,α)$^4$He</td>
<td>$\rightarrow^1$</td>
<td>$(-2.5 \pm 1.6) \times 10^{-7}$</td>
</tr>
<tr>
<td>$^{14}$N(n,p)$^{13}$C</td>
<td>$\rightarrow$</td>
<td>$^{35}$Cl(n,p)$^{35}$S</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\rightarrow_{11}$</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Correlation</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{35}$Cl(n, $\gamma$)$^{35}$Cl</td>
<td>$P_7\rightarrow_{11}$</td>
<td>$(6.5 \pm 0.6) \times 10^{-7}$</td>
</tr>
<tr>
<td>$^{39}$K(n,$\gamma)$</td>
<td>$P_7\rightarrow_{11}$</td>
<td>$(2.6 \pm 2.1) \times 10^{-7}$</td>
</tr>
<tr>
<td>$^{34}$Se(n,$\gamma$)</td>
<td>$P_7\rightarrow_{11}$</td>
<td>$(-0.8 \pm 0.9) \times 10^{-8}$</td>
</tr>
<tr>
<td>$^{59}$Fe(n,$\gamma$)</td>
<td>$P_7\rightarrow_{11}$</td>
<td>$(25.3 \pm 4.2) \times 10^{-6}$</td>
</tr>
<tr>
<td>$^{59}$Co(n,$\gamma$)</td>
<td>$P_7\rightarrow_{11}$</td>
<td>$(0 \pm 0.12) \times 10^{-6}$</td>
</tr>
<tr>
<td>Br(n,$\gamma$)</td>
<td>$P_7\rightarrow_{11}$</td>
<td>$(3.0 \pm 0.2) \times 10^{-5}$</td>
</tr>
</tbody>
</table>
Studies of the effects of parity violation in fission were successfully advanced by G.A. Petrov at horizontal beams of reactor. The mass dependence of P-violation effects (fig. 5) was studied for a series of fissionable nuclei by means of a beam of thermal polarized neutrons at a neutron guide (G.A. Petrov, A.K. Petukhov, G.V. Val’sky, Yu.S. Pleva).

In order to study the energy function a crystal-diffraction spectrometer of polarized hot neutrons was used. These measurements showed that the effect arises due to interference of s- and p-waves and changes the sign at the point of p-wave resonance. (fig. 6) (G.A. Petrov, G.V. Val’sky and others). Resonance character of the precession of neutron spin caused by the weak interaction was demonstrated with the use of a special polairemeter at the same spectrometer (fig. 7) (A.P. Serebrov, A.K. Petukhov, G.A. Petrov, G.V. Valsky, Y.S. Pleva, and others).

Fig. 5. P-odd asymmetry as a function of fragment mass.

Fig. 6. P-odd (on the left) and P-even (on the right) asymmetries as a function of descending neutron energies in $^{233}\text{U}$ fission.

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
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<tbody>
<tr>
<td>Cd(n,γ)</td>
<td>$\rightarrow_{\gamma}$</td>
<td>$-(1.3\pm1.4) \times 10^{-6}$</td>
</tr>
<tr>
<td>Sn(n,γ)</td>
<td>$\rightarrow_{\gamma}$</td>
<td>$(1.5\pm0.45) \times 10^{5}$ $\rightarrow_{\gamma}$</td>
</tr>
<tr>
<td>$^{133}$Cs(n,γ)</td>
<td>$\rightarrow_{\gamma}$</td>
<td>$-(2.4\pm0.8) \times 10^{-8}$</td>
</tr>
<tr>
<td>$^{139}$La(n,γ)</td>
<td>$\rightarrow_{\gamma}$</td>
<td>$-(15.4\pm2.3) \times 10^{-5}$</td>
</tr>
</tbody>
</table>

\[ 1^{67}\text{Ho(n,γ)} \rightarrow_{\gamma} P_{\gamma} \rightarrow_{\gamma} (1.5\pm1.2) \times 10^{-6} \]

\[ 2^{33}\text{U(n,f)} \rightarrow_{\gamma} (3.60\pm0.34) \times 10^{4} \rightarrow_{\gamma} (0.75\pm0.12) \times 10^{4} \]

\[ 2^{35}\text{U(n,f)} \rightarrow_{\gamma} (0.75\pm0.12) \times 10^{4} \rightarrow_{\gamma} (1.65\pm0.11) \times 10^{4} \]
As the reactor PIK was supposed to become the National centre for neutron studies, the preparation of scientific studies and experimental equipment was organized in collaboration with other institutes of the country. For instance, the rotor monochromator, was developed at ITEPh (Yu.G. Abov, S.I. Kalebin). Studies of $\beta$-decay of neutron were performed in collaboration with JINR (A.V. Strelkov) and Kurchatov Institute (Yu.A. Mostovoi).

Just few years ago (1996–97) a crystal-diffraction device was modernized (V.L. Alexeev, V.L. Rumiantsev) in collaboration with the laboratory of B.G. Turukhano. For the first time in the world the spectrometer was equipped with interferometer on high-frequency holographic arrays, in order to improve accuracy of relative measurements of $\gamma$-rays diffraction (energy) angles. With this spectrometer an angular resolution of 0.34′′ of the full aperture and 0.2′ of the central part of the crystal aperture were obtained. This is the record resolution for the focusing gamma-spectrometers.

The unique resolution of this device gave the opportunity for the first time in the world to carry out the direct measurements of $\gamma$-spectrum of the active reactor zone and thus to obtain the new data about $\gamma$-decay of uranium fission nuclides (about a hundred of well resolved $\gamma$-lines in the energy range of 95 – 250 eV (V.L. Alexeev, V.L. Rumiantsev, 1998). Such a high resolution of the spectrometer allowed, in particular, to discover a new phenomenon. The main point of the phenomenon is that many intense $\gamma$-peaks are close doublets (triplets) well resolved in these measurements.

It was demonstrated (V.L. Alexeev, V.L. Rumiantsev, V.V. Fedorov, 1999) that the crystal-diffraction method of studies of $\gamma$-activity of fragments of uranium (plutonium) fission can be used in solution of the transmutation problem, namely, for research and control of isotope and element composition in the process of nuclear waste burning.

Beginning with 1986 the dynamic diffraction of neutrons in perfect bent and plain crystals has been intensively researched in O.I. Sumbaev’s laboratory. The gravitational effect on one crystal, that was predicted by O. I. Sumbaev, was measured for the first time. It was done by measuring the change in Pendellosung contrast caused by rotation of the setup for neutrons diffracted by a bent crystal (V.L. Alexeev, E.G. Lapin, E.K. Leushkin, V.L. Rumiantsev, O.I. Sumbaev, V.V. Fedorov, 1988).

The existence of a strong (~ $10^8$ V/cm) electric field affecting a neutron in case of diffraction in a non-centre-symmetrical crystal was theoretically predicted (V.V. Fedorov). This field was discovered and measured in the experiment on the dynamic diffraction of polarized neutrons (V.L. Alexeev, V.V. Voronin, E.G. Lapin, E.K. Leushkin, V.L. Rumiantsev, O.I. Sumbaev, V.V. Fedorov, 1989). The experimentally obtained result matched with the one that was theoretically calculated.

Fig.7. P-odd neutron-optical dichroism (on the left) and neutron spin precession (on the right) in vicinity of resonance 0.74 eV $^{139}$La. The solid and dashed lines correspond to the real and ideal energy resolution, respectively.
A new experiment on a search for neutron EDM in case of diffraction in non-centre-symmetrical crystal with the accuracy level of \( \approx 10^{-25} \text{ e-cm} \) was proposed and developed in details (V.V. Fedorov, V.V. Voronin, E.G. Lapin).

A significant time delay of diffracting neutron inside the crystal with the Bragg angles close to 90º, that had been theoretically predicted, was experimentally discovered on the setup model located in the horizontal channel of the WWR-M reactor.

**Condensed state physics**

For solid state physics 12 devices have been built, 7 of which are fit up with polarizing equipment. Some setups and their parts are the prototypes of the PIK reactor instrumental base. The layout of equipment in the reactor hall is shown in the fig. 3, and some equipment properties are presented in the table 1.

Small-angle polarized neutron scattering experiments (SAPNS) have been performed on the SAPNS-VECTOR installation equipped with 3-d (vector) analyzer of polarization (A.I. Okorokov, V.V. Runov, C.V. Grigoryev, G.P. Kopitsa, C.A. Klimko). The beam is formed by a mirror filter in the reactor channel, then it is polarized due to reflection from a small assembly of Si plates with Fe/Al supermirror coating (A.F. Schebetov and others), and then is monochromized by a space spin resonator with the ability to smoothly change neutron wave length from 7 to 12 Å and to change width of spectral line from 10 to 30%. The range of transmitted pulses is \( 5 \cdot 10^{-3} \leq q < 10^{-1} \text{Å}^{-1} \). Two adiabatic radio-frequency flippers are used. The installation has a 20-channel detector with a mirror-analyzer in front of each counter.

A substantial part of experiments on the SAPNS VECTOR installation is connected with the studies of magnetic phase transitions. Firstly they were studied only with the purpose of similarity hypothesis verification. However, along with the development of polarized neutrons method, the critical scattering has become the subject of inquiry of unique aspects of magnetism physics. The critical scattering in Ni, Fe, Pd, Fe (4 at. %), amorphous alloys, spin glasses, invar alloys, etc. was measured. Within concise frame of this review we will mention the contribution of polarized neutrons only to obtaining unique results by means of 3-d analysis of polarization:

1. Curie point \( T_c \) for Fe was measured with the accuracy of \( \tau = (T-T_c)/T_c = 10^{-5} \), which allowed to study the range of \( \tau < 10^{-4} \).
2. T-behavior of magnetostriction in Pd Fe(4 at. %) within the range of \( \tau = (3-30) \cdot 10^{-3} \) was studied.
3. Critical indexes of high accuracy for Fe: \( \nu = 0.67(1) \), \( z = 2.627(4) \) were obtained.
4. Co-existence of two scales of critical fluctuations, and Gauss distribution of local \( T_c \) with dispersion of \( \approx 3\text{K} \) were discovered in invar alloys Fe\(_{70}\)Ni\(_{30}\) (0.1 at. %) (S.V. Grigoryev and others).

These results have been obtained through research of pair spin correlations, which are usually researched exactly in neutron scattering. In 1979 the effect of left-right asymmetry of polarized neutrons scattering in a non-magnetized sample was experimentally (A.I. Okorokov, A.G. Gukasov, V.V. Runov) and theoretically (A.V. Lazuta, S.V. Maleev, B.P. Toperverg) discovered. This effect is connected with an antisymmetric part of the scattering cross-section, that is described by Green \( G^{(3)} \) 3-spin function, and, under certain (inclined) geometry of the experiment, allows to study 3-spin dynamic correlations. With the help of this method the spin dynamics in Fe in magnetic field for the critical scattering higher than \( T_c \) was studied:

1. Coefficient of spin diffusion in paramagnetic area was defined. \( D = 80 \pm 6 \text{ meV Å}^{5/2} \).
2. “Freezing” of critical dynamics at a dipole pulse \( q_0 \) in the form of \( \Omega_d \sim q_0^{3/2} \) was found, where \( \Omega_d \) is the energy of critical fluctuations, and \( q_0(\text{Fe}) = 4 \cdot 10^{-2} \text{ Å}^{-1} \).
3. The method of precise measurement of spin-wave (SW) parameters was developed for ferromagnetic area \( T < T_c \). The picture of scattering on spin waves for amorphous alloy Fe(50)Ni(22)Cr(10)P(18) (V.V. Deriglazov, A.I. Okorokov, and B.P. Toperverg) is shown in the fig. 2. The table 3 shows the obtained SW parameters for amorphous alloy Fe(40)Ni(40)B(20) and their change under the action of load (tension) of 270 MPa and annealing at the temperature of \( T = 300 \text{oC} \). Parameters: \( D \) is SW rigidity, \( \Gamma_0 \) is SW damping, \( \omega_0 \) is dipole constant.
Table 3

<table>
<thead>
<tr>
<th>Sample state</th>
<th>Parameters</th>
<th>( \omega_0 &lt;S_z&gt;^* ), ( \mu \text{eV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>182.7±0.2</td>
<td>110.3±0.9</td>
</tr>
<tr>
<td>With load</td>
<td>191.0±0.4</td>
<td>121.0±1.4</td>
</tr>
<tr>
<td>3 hour annealing</td>
<td>195±0.3</td>
<td>107.7±1.2</td>
</tr>
<tr>
<td>3 hour annealing</td>
<td>206.5±0.2</td>
<td>121.4±0.9</td>
</tr>
</tbody>
</table>

* \( <S_z>^* \)– averaged atom spin

At the present time in the field of magnetism interests of physicists are focused on the problem of chirality. PNPI has always been a monopolist in the field of experimental research of chiral (3-spin) correlations. For the first time chiral correlations were theoretically (A.V. Lazuta, S.V. Maleev, B.P. Toperverg) and experimentally (A.I. Okorokov, A.G. Gukasov and others) discovered and studied in 1977 in critical scattering on Fe in a zero magnetic field at \( T - T_c = 4 – 55 \) K. The left-right asymmetry of scattering, following from the above-mentioned pseudo-vector \( n = [k_1, k]/|k_1, k| \), was measured. The maximum asymmetry effect was observed at the level of \( P_A = 1.5 \cdot 10^{-4} \), which complicated its further research. In 1992 the chirality problem acquired a new, more fundamental development after the Kavamura’s idea about the existence of a new universal class of phase transitions with chiral parameter of order. As a result of experimental (V.P. Plakhhy and others) and theoretical (S.V. Maleev) studies, firstly, interaction of torsion deformation with spin chirality in Ho was discovered, secondly, in the course of triangle antiferromagnetics (CsMnB\(_3\)) research the chiral critical index was experimentally defined for the first time. This index matched with the Kavamura’s calculations.

3DAPN installation is equipped with 3-d analyser of polarization in passed beam and allows to determine direction of \( P \) in the space with 1% accuracy by \( P_i \) components. The studies of magnetic texture of magnets, ferroliquids are currently performed on the installation. The distribution of induced and trapped magnetic fluxes in HTSC samples is studied with the help of polarization vector precession. The data obtained from a sample scanned by a narrow beam (~ 0.1 – 0.5 mm) (Fig. 8) gives information about image currents inside the sample and thus longitudinal and transversal currents are visualized.

![Fig. 8. Visualization of magnetic flux in Y-Ba-Cu-O ceramics in case of a switched-on external magnetic field (curves 1, 2, 3 for \( H = 2.2, 3.1 \) and 4 Oe, respectively) and a switched-off one (trapped flux) for a series of \( H \)-field values varying from 0.45 to 7.2 Oe](image)

Small-angle diffractometer SANS-MEMBRANA (G.A. Evmenenko, V.L. Alexeev) is designed for studies of super-atom structure of condensed mediums of 20 – 1000 Å scale (polymers, colloid systems, materials-science objects). Similarly to SANS-VECTOR installation the beam is formed by a polarizing system with a magnetic monochromator on the basis of space spin resonance and is detected by a multi-counter system SNM-50 with a diameter of 12 mm and an operating height of 80 mm. There is a protective mask in front of the detector. It is made of Cd and has vertical slots with adjustable width. The employment of the mask and the scanning within the range of 12 mm allow to change angular resolution of the detector part of installation from \( 1.5 \cdot 10^{-3} \) to \( 1.5 \cdot 10^{-4} \) radian. On this diffractometer the structure of T7 phage was finally determined (M.M. Agamalyan). For the recent years structural studies of polyacrylate super-increasing hy-
droplets at different degrees of increasing have been conducted, and the role of polyelectrolyte influences on conformation of polymeric chains in the junction areas has been analyzed.

The low-frequency dynamics of magnetic (and non-magnetic) systems, such as ferroliquids, superconductors, etc., is studied on the modernized spin-echo spectrometer MSES (V.T. Lebedev), which is the spectrometer of a quasi-elastic scattering of polarized neutrons with the modulation of the spectrum by the phase of neutron spin precession. The spectrometer uses neutrons with the average wave-length of \( \lambda = 6.5 \text{ Å} \) and polarization \( P > 95\% \), the range of elastic transmitted pulses is \( 0.01 < q < 0.3 \text{ Å}^{-1} \), energy resolution is \( 10^{-7} \text{ eV} \), the beam dimensions at the sample location are \( 10 \times 60 \text{ mm}^2 \), the neutron flux on the sample is \( 10^2 \text{ n/cm}^2 \cdot \text{s} \). The device operates in modes of “scattering” and “tomography”, i.e. Fourier-analysis of passed beam.

With the purpose to study a free surface of liquids, a reflectometer of polarized neutrons RPN with a reflection in the vertical plane is to be built at the channel 12. In particular, there are some experiments planned to be carried out. They are concerned with studies of the structure and dynamics of ferroliquids under external magnetic field which changes surface stability. PG-monochromator, mirror polarizer, 20-channel detection system with aperture of 16° and angular resolution of 0.01° are planned to be installed on the reflectometer.

PD, CSPN and SCD devices make up a complex for studies of magnetic ordering and spin dynamics with analysis of polarization (the laboratory of V.P. Plakhty).

High-luminosity multicounter powder diffractometer PD (I.V. Golosovsky), with which the majority of neutron-graphical studies is carried out, has 48 counters with soller membranous collimators placed in front of them. It has a good resolution in the range of average transmitted pulses, that is, where magnetic scattering reaches its maximum. For the recent years a large number of works has been performed with this diffractometer. These works were concerned with the determination of magnetic structures in two-sublattice cuprates, known as “green” \( \text{R}_2\text{BaCuO}_5 \), “blue” \( \text{R}_2\text{Cu}_2\text{O}_5 \) and “brown” \( \text{Nd}_2\text{BaCu}_2\text{O}_5 \) phases, where \( \text{R} \) are rare-earth elements. A magnetic structure of \( \text{Er}_2\text{BaCuO}_5 \) compound, obtained from a neutron-graphical experiment, is shown in the fig. 9.

The correlation spectrometer of polarized neutrons CSPN (O.P. Smirnov) has been created for studies of the spin dynamics and the diffraction experiments with polarization analysis. The employment of polarizing neutron guide (A.F. Schebetov, A.I. Okorokov), time-of-flight techniques with the pseudo-random modulation of neutron beam polarization and the scheme of reverse geometry (for which spectrum analysis is done after scattering on sample) allowed to obtain the device parameters comparable with the best analogues at high-flux reactors: the neutron intensity in case of Heusler crystal used as analyzer, \( 10^5 \text{ n/cm}^2 \cdot \text{s} \) (\( \lambda = 2.5 \text{ Å}, \Delta \lambda / \lambda = 0.04 \)), in case of TOF-analysis \( \Delta \omega = 0.5 \text{ meV} \). The techniques of a complete polarization analysis with the measurement of scattering with the spin flip (SF) and without the spin flip (SNF) for 3 directions of polarization of descending neutrons \( P_{x,y,z} \) is used in experiments.

In order to study magnetic and crystal structure, a normal type four-circle diffractometer SCD (Yu.P. Chernenkov) with monochromators Cu, Ge, PG is used. The detector moves in a vertical plane within the angle range of 5 – 30°.

Together with neutron devices rontgenographic equipment has also been built. From the end of 80’s the research was conducted in a close contact with Institute of Laue-Langevin. The main topic of research with this complex of equipment is connected with the studies of the magnetic structure and the exchange interaction, two-sublattice antiferromagnetic systems, rare-earth cuprates, oxygen ordering in HTSC systems.

The main results obtained on this complex of equipment are as follows (V.P. Plakhty, S.V. Gavrilov, I.V. Golosovsky, A.G. Gukasov, I.A. Zobkalo, E.V. Moskvin, O.P. Smirnov, V.I. Fedorov, Yu.P. Chernenkov and others):
1. A gap was discovered in the system \((\text{Ca}_3\text{Fe}_2\text{Ge}_2\text{O}_{12})\) in spectrum of spin waves. This gap is caused by the dynamic interaction of sublattices (zero fluctuations), not interacting with each other in the vicinity of molecular field. The gap size is 0.003(4) THz. A similar quantum gap was measured on an isomorphous garnet \((\text{Ca}_3\text{Fe}_2\text{Si}_2\text{O}_{12})\).

2. Magnetic properties of rare-earth cuprates \((\text{R}_2\text{CuO}_4)\) \((\text{R} = \text{La}, \text{Nd}, \text{Pr}, \text{Sm}, \text{Eu}, \text{Gd}, \text{Sr}, \text{Ce})\) were studied in order to define the role of \(\text{Cu}_2\) planes in the HTSC effect. The spin reorientations were studied. It was also shown that cerium dope results in transition suppressing.

3. A cross-over in the critical behavior of orientation of \(\text{Pr}_2\text{CuO}_4\) antiferromagnetic sublattices in external magnetic field in the vicinity of spin-flop transition was discovered. This is a consequence (and the first experimental proof) of Bose-condensation of spin waves in \(\text{Cu}_2\) layers, which was predicted by S.V. Maleev.

4. By means of neutron and roentgen structural analysis the existence boundaries were determined for ortho-II and ortho-III phases in \(\text{Yb}_2\text{Cu}_3\text{O}_{6+x}\) compound, which, as it was shown, are in close agreement with typical areas of dependence of \(T_c\) on oxygen contents \(x\).

The structural features and their connection with physical properties of various compounds are studied with the use of diffractometer RTOF Mini-SFINKS (V.A. Trounov, V.A. Kudryashev, D.Yu. Chernyshev) and \(\gamma\)-diffractometer GD (A.I. Kurbakov, A.E. Sokolov, E.E. Rubinova). The powder diffractometer RTOF Mini-SFINKS was built in 1984 in collaboration with the Centre of Technical Research (VTT) of Finland. It uses reverse time of flight method (RTOF) with Fourier chopper that produces resolution of \(\Delta d/d = 0.25\%\). Reverse scattering detector has an aperture of 0.1 sr and consists of 4 slim plates of scintillation glass (with photomultipliers with diameter of 110 mm), located on the surface with an intermediate focusing. The optimized track source-collimator-neutron guides allows to obtain on a sample a flux of \(1.5 \times 10^7 \text{n/cm}^2\cdot\text{s}\) for spectrum of \(\lambda = 0.9 – 5\) Å.

At this diffractometer:

1. 18 HTSC experiments were performed at this diffractometer. Among them there was one of the first in the world determination of the structure of 1-2-3 HTSC compound and the study of phase transition in \(\text{La}_{1-x}\text{Sr}_x\text{CuO}_4\) systems.

2. By means of isotope contrasting the position of the Ca atom was defined. It replaces \(\text{Y}\) in \(\text{Y}_{0.9}\text{Ca}_{0.1}\text{Ba}_2\text{Cu}_4\text{O}_8\) compound. The temperature dependence of the “b” lattice parameter in this compound was studied. As a result, the structural phase transition at \(T \approx 150\) K was discovered (fig. 10).

3. In Fe doped 1-2-3 HTSC systems the data about Fe atoms distribution in crystal lattice was obtained.

4. High possibilities of the RTOF diffractometer in the determination of temperature parameters, Debye-Waller factors, were demonstrated in the course of the structural studies of rare-earth hexaborides \(\text{ReB}_6\) \((\text{Re} = \text{La}, \text{Ce}, \text{Pr}, \text{Nd}, \text{Sm}, \text{Y})\). A series of phenomena was discovered, some of which are: the vacancy availability in boric sublattice, the decrease of characteristic Einstein frequency with the increase of the atom number of the rare-earth element, effects of intermediate valency.

Studies of the real state of perfect single-crystals and of their natural and induced defects are conducted at \(\gamma\)-diffractometer GD. Golden foil \((0.1 \times 5 \times 18 \text{ mm}^3)\) activated by thermal neutrons serves as a source of \(\gamma\)-radiation \((200 \text{ Ci})\). High monochromatisation of the beam \(\Delta\lambda/\lambda \approx 10^{-6}\) at \(\lambda = 0.03\) Å and angular resolution of 4” provides for precise diffractometer measurements. For instance, in the course of studies of quartz monocrystals with dislocation density from 0 to 200 dislocations/cm it turned out to be possible to measure their density with the accuracy of several pieces.

Inelastic scattering (of classical type) is studied with a 3-axis spectrometer IN NEUTRON-3 (the laboratory of N.M. Okuneva, Physical-Technical Institute named after A.F. Ioffe, St.-Petersburg). It has a twin monochromator.
and analyzer from monocrystals Cu(220) with $2d = 2.556 \, \text{Å}$, Cu(200) with $2d = 3.608 \, \text{Å}$ and PG(002) with $2d = 6.71 \, \text{Å}$. The wave-length of incident neutrons varies from 1 to 4 $\text{Å}$, the maximum flux on the sample is $10^6 \, \text{n/cm}^2 \cdot \text{s}$, energy resolution is better than 0.5 meV. The spectrometer is used to study the inelastic and quasi-elastic scattering of neutrons in disordered structurally unstable crystals. The features of phase transitions in relax or ferroelectrics ($\text{Na}_5\text{Bi}_5\text{TiO}_3$, $\text{PbMg}_{1/3}\text{Nb}_{2/3}\text{O}_3$, (PMN) and others) have been recently studied.

The time-of-flight reflectometer TOFRPN (A.F. Schebetov, V.A. Ulyanov, V.G. Syromyatnikov, N.K. Pleshakov, V.M. Pusenkov and others) is used for testing the optical equipment manufactured by efforts of Neutron Optics Division of NRD (NOD). The main reflectometer components are: the polarizer is a mirror with CoFe coating and TiGd subcoating, the chopper is Cd disk with slots, the flipper, the sample, the analyser and the detector. The wave-length range used is $\lambda = 1 – 4 \, \text{Å}$, the wave-length resolution of the time-of-flight spectrometer is $\Delta \lambda/\lambda = 0.1 – 0.025$, the angular width of the beam incident on the sample is 0.1 mrad, the flux on the sample is $10^5 \, \text{n/cm}^2 \cdot \text{s}$, the polarization is $\mathcal{P} > 0.98$. NOD designs and produces polarizing and non-polarizing mirrors and super-mirrors, single- and multi-slot neutron guides on the basis of these mirrors, collimators, mirror monochromators, and other equipment required for researchers at the WWR-M reactor and other neutron centres.

Besides testing of neutron elements, the installation is used for studies of magnetic and non-magnetic multi-layer structures with the purpose of determination of its real parameters and perfection.

The WWR-M reactor is equipped with a low-temperature helium loop LTHel (R.F. Konopleva, I.V. Nazarkin, V.A. Chekanov), which allows to study quasi-stationary disordered states, various stages of defect-formation, influence of neutron radiation on low-temperature processes and phase transitions, and low-temperature radiation resistance of materials. The “effect of small doses” was discovered during the studies of changes in electrophysical properties of HTSC materials (YBCuO ceramics and films) in the process of low-temperature (20 K) neutron irradiation in the range of fast ($E > 0.1 \, \text{MeV}$) neutron fluences $F = 10^{17} – 10^{18} \, \text{cm}^{-2}$. This effect is connected with the increase of critical temperature $T_c$ from 92.3 K to 95.3 K. During the studies of critical current in YBaCuO films the temperature and dose dependences were defined. These dependences can be explained by pinning with flat boundaries of grain.

4. Research done without use of WWR-M reactor

However strange may be, in the course of preparations for the studies on the PIK reactor, a number of different studies, not connected with neutrons, were developed and formed independent directions. These were the neutrino physics (L.A. Popeko) and the molecular beam physics (V.F. Ezhov). Intention for development of neutrino studies was based on the possibility to build powerful neutrino sources on the PIK reactor and on the possibility to build a unique silicon detector of neutrino using PNPI detector manufacturing technologies. Such a neutrino detector was successfully built (L.A. Popeko, G.A. Shishkina, A.V. Derbin, S.V. Bakhlanov, A.V. Cherniy) and was used in studies carried out in the underground laboratory of Solotvino, and also in the neutrino laboratory at Rovenskaya Atomic Power Station.

These studies gave a remarkable result: the upper limit of the neutrino magnetic moment $\mu_\nu \leq 1.8 \cdot 10^{-10} \, \mu_B$ (L.A. Popeko, A.V. Derbin). This result is exceptionally significant for neutrino physics.

Molecular beam studies were stimulated by the interest in CP-violation effects. V.F. Ezhov and his colleagues formed a unique experimental base which allows to conduct a wide scope of studies with atoms and molecules. It is assumed that results of these studies will make it possible to observe the effects of the weak interaction in atomic and molecular physics, and will also become the instrument for the Standard Model verification.

The direction of roentgen spectroscopy, that was developed by O.I. Sumbaev along with $\gamma$-spectroscopic studies on the WWR-M reactor, is classified as a non-reactor one. By means of the roentgen line shift method the unique studies of electron structure of the rare-earth elements and actinides in chemical compounds, crystals and HTSC ceramics were carried out (O.I. Sumbaev, E.V. Petrovich, V.A. Shaburov, A.S. Rylnikov, Yu.P. Smirnov, A.E. Sovestnov, A.V. Tyunis), as well as the studies of charge nucleus radii and measurements of multipole nuclei moments (O.I. Sumbaev, A.F. Mezentsev, A.S. Rylnikov, A.A. Rodionov, V.A. Shaburov). The laboratory of O.I. Sumbaev put a start for the following directions: the studies of roentgen spectra of hadronic atoms, subsequently developed by A.I. Smirnov and the studies of...
elementary particle channeling in bent monocrystals, subsequently developed by V.M. Samsonov and A.I. Smirnov.

Finally, achievements of A.I. Egorov’s group of isotope chemistry and physics should be mentioned. This group contributed to a number of successful physical studies, being responsible for chemical provision of works. Sources, target materials of the highest purity, analytical standards, chemical technology procedures, all these were provided in time and with quality. A single example is enough: during the "superconductivity" boom about 300 of various HTSC samples were synthesized. However, the main achievement of isotope chemistry and physics group is a series of scientific works: the radiochemical cycle of neutrino detector similar to Gallex, the ammoniac detritiation of light water, the azeotropic detritiation of heavy water, the separation of zirconium and hafnium, the vapometalurgical refining of thorium fuel, the separation of lithium and boron isotopes, the regeneration of nuclear zirconium, etc. The main scientific achievement (together with O.I. Sumbaev) is a study of anomalous valences of rare-earth elements. This is the most important question still has no satisfactory scientific explanation.

In the studies of condensed state physics, in addition to neutron beam installations complementary methods of studies are effectively used: radio-frequency measurements of linear and non-linear dynamic induction in the range of $10^2 – 10^6$ Hz with the sensitivity not lower than $10^{-5}$ Oe (I.D. Luzyanin, V.P. Havronin) and the fluctuation spectroscopy with the sensitivity not lower than $10^{-17}$ V$^2$/Hz in frequencies up to 100 kHz. The following phenomena are also studied: the critical phenomena in ferromagnetics, scaling behavior of sensitivity in ferromagnetic phase, phase division phenomenon in manganites having enormously high magnetoresistance and the penetration of weak magnetic field in granular and polycrystal superconductors (low-pole electrodynamics of multi-linked superconductors). These studies are conducted in cooperation with the Theoretical Physics Department (TPD) (S.V. Maleev, S.L. Ginzburg, and A.G. Yashchenkin).

A fluctuating spectroscopy method is used to study noises in granular superconductors (O.V. Geraschenko, A.I. Sibilev), “super-sensitivity” phenomenon (O.V. Geraschenko, M.A. Pustovoit, and S.L Ginzburg), and also stochastic resonance in biological membranes (S.M. Bezrukov). M.A. Pustovoit in cooperation with S.L. Ginzburg and N.E. Savizkaya (TPD) conduct a successful research on self-organized criticality in Josephson environment by the method of computer simulation. V.I. Sbitnev uses the same method for theoretical studies of determined chaos in biological objects (neural networks, etc.). Common laws of the electric low-frequency noise in materials with low conductivity are successfully studied by B.I. Yakubovich. The texture and magnetic properties of films in comparison with their crystal structure are studied by A.V. Kovaliev with the help of rontgen methods.

The laboratory of chemistry and spectroscopy of materials was one of the first in Russia to start research of fullerenes, and also to synthesize and isolate them (Yu.S. Grushko, M.F. Kovaliev, S.N. Kolesnik). The laboratory preparatory facilities became the basis for the regional research program in the north-west of Russia: “Fullerenes and Atomic clusters”. At present the laboratory can produce fullerene C$_{60}$ of 99.9% purity, in quality of hundreds of grams, and C$_{70}$ (98%) in quantity of dozens of grams (V.P. Sedov, O.N. Vavilova, V.V. Kukorenko).

Within the frame of methods of Moessbauer spectroscopy a flexible modern spectrometric system was created, which made it possible to study different class objects (M.F. Kovaliev, V.S. Kozlov, L.I. Molkovanov). A wide range of Doppler velocities of the spectrometer +/- 300 mm/s allows to work with any of the known Moessbauer isotopes and to independently adjust the temperature of the source and absorber in the range from 1.5 to 300 K.

Achievements of the last years are concerned with the studies of organic superconductors, superionic glasses and intercalation compounds of fullerenes. The Moessbauer spectra were first observed on nuclei of metallofulleren molecules localized inside a carbonic cage (Yu.S. Grushko, V.S. Kozlov, L.I. Molkovanov). Dy@C$_{80}$ and Dy@C$_{82}$ were studied, the phenomenon of paramagnetic relaxation, the transition of three electrons from metal onto carbonic cage, and the strong temperature dependence of Debye-Waller factor were found.

Finally, one of the achievements important to experimenters should be mentioned, namely, invention and production of the required quality of elastic and paste-like protective materials (I.M. Lazebnik, 2 patents). These are almost hydrogen-less (lower than 2%) materials, made on the basis of a plastic synthetic stuff, with a wide scope of absorbing fillers (filling degree from 60 to 96 mass percents) for protection of ob-
jects with complicated geometry. Fillers from heavy metals (Pb, U, Bi, etc.) are used for protection from γ-radiation. Fillers from elements and isotopes with the large neutron capture cross-section are used for neutron protection. $^6$Li material is the most popular, as it has a large neutron capture cross-section and produces in practice no secondary γ-radiation.

5. Characteristics of last decade studies

Finally the stage of the studies of last decade should be mentioned. It was marked with considerable difficulties in connection with a sharp reduction of financing of science in Russia and, as a consequence, with a partial migration of the scientific personnel.

The main problem of that period was to provide opportunities for study conduction and preservation of creative potential of laboratories. In this fight for the existence of science the main components of success were the following. At first, the systematic efforts to keep the budget financing at an acceptable level, to provide heating system and electricity and saving of institute infrastructure. The director of the Institute V.A. Nazarenko plays the most important role in this. Second, by international contacts, integration of Russian science with the world one are of considerable importance at present time. The existence of various funds (ISF, INTAS, etc.) considerably helps to preserve the creative potential of science.

An entry of Russia in international centre (Institut Laue-Langevin, Grenoble, France) and financial support of this international collaboration by Russian Ministry of Science and Ministry of Atomic Energy were of exceptional significance for the neutron studies. Quite a high level of studies reached at PNPI allows to successfully compete and proudly introduce Gatchina school in this international centre. In 90-s PNPI employees performed the following studies at ILL reactor: the studies of β-decay of neutron and the studies with ultra cold neutrons (A.P. Serebrov, A.G. Haritonov, L.A. Kuznetsov, I.V. Stepanenko, A.V. Alduschenkov, M.S. Lasakov, A.V. Vasilyev and others), the studies of fission physics (G.A. Petrov, A.M. Gagarsky), the studies of neutron-optic effects caused by the weak interaction (A.P. Serebrov, A.K. Petukhov, G.V. Valsky, G.A. Petrov and others), the magnet-crystal material structure studies (V.P. Plakhty, S.V. Maleev and others). PNPI widely collaborates with Hahn-Meitner-Institute in Berlin, Max Plank Institute, Munich University and a series of other international research centres.

The third primary factor helping to keep scientific activity is the activity connected with development and manufacturing of physical equipment for foreign scientific centres. A considerable potential of intellectual and technological character accumulated in connection with development of experimental equipment for PIK reactor appeared to be exceptionally important under current conditions. Polarizing neutron guide systems has been developed and manufactured for JINR (Dubna), IPM (Ekaterinburg), IRI TU Delft (Holland), GKSS (Geesthacht, Germany), for KAERI reactor (South Korea) and others, (A.F. Schebetov, V.A. Trounov et. al.); diffractometer for JINR (Dubna), LLB (Saclay, France), GKSS (Germany), ETRR-2 reactor in Cairo (Egypt), KFKI (Hungary) and others, (V.A. Trounov, V.A. Kudryashev, A.P. Bulkin and others).

The cold neutron source was designed, manufactured and is being installed at the reactor of KFKI institute in Budapest, Hungary (A.P. Serebrov, V.A. Mityukhlyaev, A.A. Zakharov and others). Semiconductor detectors for Europe and America are successfully developed and manufactured (A.H. Khusainov).

At the present time a series of projects for cold neutron sources, neutron guide systems and physical equipment for HANARO reactor (South Korea), ETRR-2 reactor in Cairo (Egypt), reactor in Delft (The Netherlands) are developed (A.P. Serebrov, A.F. Schebetov, V.A. Mityukhlyaev and others).

In summer 1999 a polarizing neutron guide system and polarization analysis system were installed at PSI. These systems were created and installed by PNPI employees (A.F. Schebetov, A. P. Serebrov, B.G. Peskov, M.S. Lasakov, V.M. Pusenkov, A.V. Vasilyev, E.N. Medvedev and others). As a result, a beam of polarized cold neutrons with a flux density of $2 \times 10^5$ n/s cm$^{-2}$ and the total flux higher than $10^{10}$ n/s was obtained. This beam is required for studies of β-decay of neutron. The intensity obtained is equal to the intensity of polarized cold neutrons of the PF1 beam on the high-flux ILL reactor. This result was obtained due to a high transmission of the neutron guide system.

During the last years at the WWR-M reactor the studies of solid deuterium UCN source and a UCN source on the basis of heavy ice at 5K were performed (A.P. Serebrov, V.A. Mityukhlyaev, A.A. Zakharov, M.S. Lasakov, A.V. Vasilyev, A.G. Kharitonov, V.E. Varlamov, P.P. Taldan and others). These studies have been performed within the frame of international collaboration with the aim of development of so-
called UCN factory on the basis of high-current accelerators in LANL (USA) and PSI (Switzerland). All these works are actually aimed at the experiment for the search of neutron EDM with the accuracy of $10^{-27}$ e·cm.

The Neutron Research Department holds Russian and international conferences.

To make a conclusion, in spite of all the difficulties of the present period, the scientific studies at the WWR-M reactor continue, and we would like to hope that their level in future will as high as in the past.

**From authors**

This article is a brief review of the milestones of our more than 40-year path displaying certain selected results.

We would like to apologize to those who were unintentionally omitted and whose successful work is undoubtedly a contribution to scientific achievements of Neutron Research Department (NRD).

The Gatchina School of neutron research would never see the light without conscientious and sometimes self-sacrificing efforts of engineers, technicians and operative personnel of the reactor and research laboratories. On behalf of all the scientific team of NRD, we would like to express our sincere thanks to them.