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Setup for the study of the paramagnetic resonance of neutrons of the first kind

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The experimental setup KOLKHIDA has been designed to study the interactions of polarized neutrons with polarized nuclei, in particular to study the neutron nuclear precession (nuclear pseudomagnetism) and also for studying magnetic properties of crystals.
The investigation has been performed at the Frank Laboratory of Neutron Physics, JINR.

Keywords: polarized neutrons, polarized nuclei, nuclear precession of neutrons, nuclear pseudomagnetism

Introduction

The "KOLKHIDA" experimental setup [1] designed for studies of neutron-optics phenomena in interactions of polarized neutrons with polarized nuclei, in particular to study the neutron nuclear precession (nuclear pseudomagnetism), has been constructed in JINR, at the IBR-2 pulsed reactor. The setup also makes it possible to investigate magnetic properties using polarized neutrons.

In the paper [2], which marked the beginning of a new research area – neutron optics of polarized media, it has been theoretically shown that the dependence of the refractive index of a neutron wave on mutual orientation of spins of the neutron and nucleus determines the neutron spin rotation around the direction of the target polarization. The precession frequency ω depends on nuclear spin I, density of nuclei N and difference f^+ f^- of amplitudes of neutron scattering by this nucleus corresponding to the states with total momentum of the neutron and nucleus $I+\frac{1}{2}$, $I-\frac{1}{2}$:

$$\omega = \frac{4\pi N\hbar}{m_n}\frac{I}{2I+1}(f^+ - f^-)P_n, \tag{1}$$

where m_n is the neutron mass, P_n is the degree of nuclear polarization. The nuclear field, which causes the neutron spin precession, is generally called the effective magnetic field or pseudomagnetic field. The value of the effective magnetic field is

$$H_{ef} = \frac{\omega}{\gamma_n}, \tag{2}$$

where γ_n is the gyromagnetic ratio for neutrons.

The authors [2] have suggested three types of experiments on neutron nuclear precession: pseudomagnetic neutron resonance [3], measurement of rotation angle of the spin of the neutron passing through a polarized nuclear target [4], and paramagnetic neutron resonance of the first kind. Two of them were carried out by the Abraham (Saclay, France) and Forte (Ispra, Italy) group.

The experiment on paramagnetic resonance with polarized neutrons passing through a polarized nuclear target has not been carried out yet. The essence of this experiment is as follows: if in a polarized nuclear target a variable magnetic field rotating around the direction of polarization is created, then there occur transitions between neutron energy levels at the rotating field frequency equal to the neutron nuclear precession frequency ω. In a constant magnetic field the introduction of a polarized nuclear target will result in algebraic addition of the constant magnetic field H and pseudomagnetic field H_{ef}. This leads to a shift of resonance frequency ω. The phenomenon is analogous to neutron paramagnetic resonance at this frequency. Such an experiment has not been realized yet.

All the above-mentioned experiments were performed for one fixed neutron wavelength.The energy dependence of the effect of neutron nuclear precession has not been studied either. The projected studies on neutron nuclear precession will be performed in the neutron energy range from 0.062 eV to 2.3 eV.

The extension of neutron energy range to neutron resonances is of special interest. It is known that the amplitude of neutron scattering by a nucleus is $f = f^0 + f^R$, where f^0 is the amplitude of potential scattering and f^R is the amplitude of resonance scattering. In the case of slow neutrons $(\lambda \gg R)$:

$$f^0 = R, \tag{3}$$

and

$$f^R = \frac{\lambda \Gamma_n/2}{2\pi[(E - E_0) + i\Gamma/2]}. \tag{4}$$

Here Γ_n is the neutron width, Γ is the total resonance width, E is the neutron energy, E_0 is the resonance neutron energy value, R is the nuclear radius. Thus,

$$f = R + \frac{\lambda \Gamma_n/2}{2\pi[(E - E_0) + i\Gamma/2]}. \tag{5}$$

Away from neutron resonances in the region of thermal neutron energies the scattering amplitude f is independent of neutron energy and, correspondingly, the nuclear precession frequency ω does not depend on neutron energy. As the resonance is approached, the absolute value f^R increases at the expense of a decrease of the difference $E - E_0$ and changes its sign when passing through the resonance. It might be good to point out that such behavior is expected from the general consideration of the neutron spin precession effect, but has not been observed in the experiments. Therefore the detection of this effect, which would support the predictions of the theory, is undeniably of much interest.

The KOLKHIDA setup is ready for these investigations and its consists for the following components:

- Spectrometer of polarized neutrons;
- Polarized nuclear target;
- Experimental setup control and operation system;
- System for study of the process;
- Experimental setup software.

In this paper presented the description of the setup components and key parameters after its last modernization.

Spectrometer of polarized neutrons

The polarized neutron spectrometer is located on the tangential channel 1 of the IBR-2 pulse reactor of Frank Laboratory of Neutron Physics, JINR. The detailed description of the spectrometer, in particularly, detailed description of experimental setup control and operation system as well as software for the experimental setup is given in [2,7].

The schematic view of the spectrometer is shown on Figure 1.

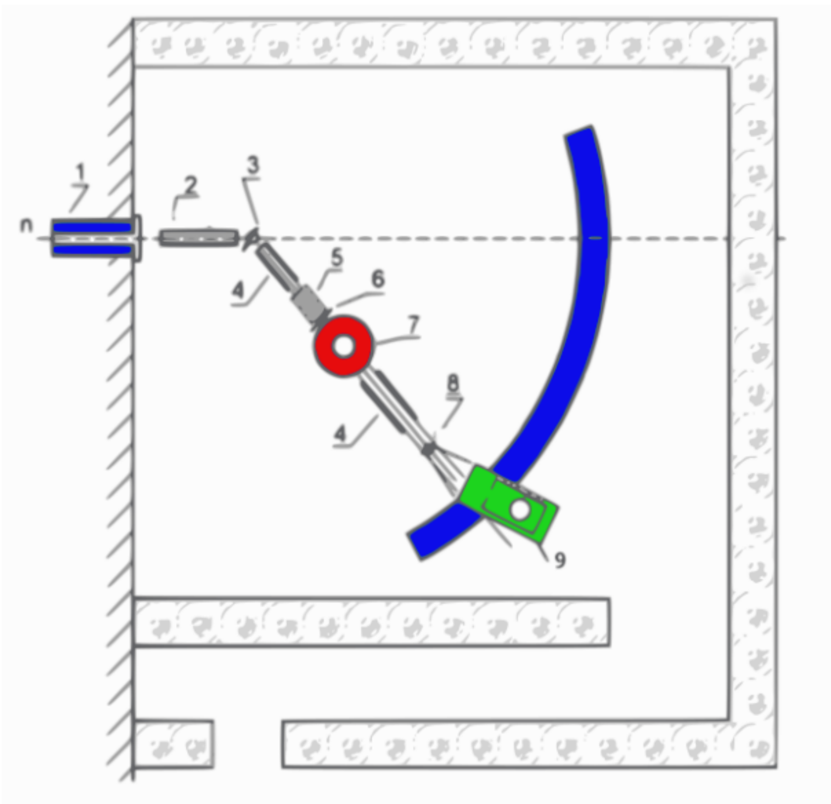

Figure 1. Schematic view of the spectrometer: 1 — primary collimator; 2 — Soller collimator; 3 — polarizer crystal; 4 — leading magnetic fields; 5 — Mezei flipper; 6 — shim; 7 — cryostat; 8 — analyzer crystal; 9 — detector.

The primary-neutron spectrum is formed in a moderator. The neutrons emerging from the moderator go through the biological shield by the channel with a primary collimator 1. Prior to entering the polarizer, the neutrons go through Soller collimator 2.

In order to polarize neutrons and to analyze their polarization Co-Fe single crystals are used. A SNM-17 counter filled with ^{3}He to a pressure of 10 atm is employed as a neutron detector. The detector entrance window has horizontal and vertical sizes of 10 and 50 mm. A ^{235}U fission chamber with uranium layer thickness of 100 μg/cm^2 is used as a monitor.

The flight distance from the moderator in the reactor radiation zone to the detector is 15.9 m and comprises the following distances: moderator – polarizer, 12.4 m; polarizer – analyzer, 2.5 m; and analyzer – detector, 1.0 m.

The intensity and energy spectrum of the primary neutron beam incident on the polarizer, measured by the time-of-flight method in the energy range from 10 to 200 meV, is shown in Figure 2.

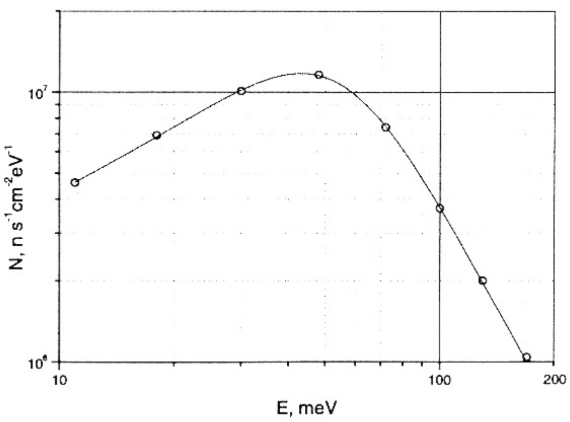

Figure 2. Dependency of the neutron beam density on the energy of neutrons hitting the polarizer

For the single crystal $Co-Fe$ in Laue geometry, neutron diffraction was measured for various angles θ of neutron incidence on the (200) plane within range from $(3\ \text{-}\ 19)^\circ$. Table 1 shows the values of the angles θ for which the measurements were made and, correspondingly, the wavelengths and neutron energies. As a result of scanning the angle θ, there was a maximum of the reflected beam. The counting rate n_1, the intensity I_1, taking into account the detector efficiency and the area of the reflected beam $(s \cong 4sm^2)$, are given in Table 1.

Table 1.
Parameters of polarized neutron beam

Angle θ, (deg)	19	12	6	4	3
Wavelength λ, $(\dot{A})$	1.15	0.74	0.37	0.25	0.19
Energy E_n, (eV)	0.062	0.15	0.6	1.3	2.3
The detector count rate after polarizer n_1, (sec^{-1}),	800	270	65	33	22
Polarized beam intensity I_1, (n/cm^2sec)	430	200	80	60	50
The detector count rate after analysis n_2, (sec^{-1})	70	23	3.1	0.6	0.2

Depending on the collimation of the neutron beam and the intensity of leading magnetic fields between the magnets of the polarizer and the analyzer, the neutron polarization measured in our experiments ranged from P = 0.9 to 0.98.

Polarized nuclear target

The most universal method is used for the polarization of the nuclei in the KOLKHIDA setup: the "brute force" method, when the target is cooled in a strong constant magnetic field [5]. In this case the nuclear polarization is achieved due to the orientation action of the magnetic field on nuclear magnetic moments.

As thermal equilibrium between the system of nuclear spins and the substance of the nuclear target is attained, the polarization is given by the Brillouin function

$$f_1 = \frac{2I+1}{2I} cth(\frac{2I+1}{2I}\frac{\mu H}{kT}) - \frac{1}{2I} cth \frac{\mu H}{kT}, \quad (6)$$

where I is the nuclear spin, μ is its magnetic moment, T is the target temperature, k is the Boltzmann constant. For small $\frac{\mu H}{kT}$ a simplified expression holds true

$$f_1 \approx \frac{I+1}{3I}\frac{\mu H}{kT}. \quad (7)$$

Because of smallness of nuclear magnetic moments μ , to achieve a noticeable rate of polarization requires very low temperatures and very strong magnetic fields. So, for a hypothetical nucleus with spin $I = 1$ and magnetic moment equal to one nuclear magneton, at achievable fields $H \approx 10\ T$ and temperatures $T \approx 10^{-2} K$, the calculations give $f_1 \approx 0.25$.

For this purpose, a (^{3}He $-^4$ He) dilution cryostat with replaceable superconducting solenoids was made [5,6] (Figure 3). It is also possible to dynamically polarize the nuclei.

The cryostat is preliminary cooled by filling all volumes with liquid nitrogen, which is removed before the beginning of helium filling. Nitrogen cooling of the cryostat is controlled by TVO type carbon resistors. It takes $80l$ of liquid nitrogen and $8h$ to cool the cryostat down to nitrogen temperature. Liquid nitrogen consumption in the operating mode of the cryostat is 0.8 l/h. It takes $40l$ of liquid helium and $6h$ to cool the cryostat down to helium temperature. Liquid ^{4}He consumption in the stationary operating mode of the cryostat is 0.8 l/h. He exchange gas under the pressure of 20 Pa is used to cool the dilution stage down to helium temperature and the process takes $15h$. The exchange gas is removed from VS before the beginning of ^{3}He/^{4}He mixture condensation. The temperature in one-degree helium bath is determined using McLeod compression pressure gauge and also by the PKR251 gauge with a TPG256A controller. The level of liquid ^{4}He in helium baths is determined by superconducting sensors and a two-channel controller LM-510.

The target is placed into a dilution bath of the ^{3}He $-^4$ He refrigerator, in which the temperature is T = 23 mK at ^{3}He circulation speed $\dot{n} = 1.07 \times 10^{-3}$ mol/s. The temperature is measured by a low-noise resistance bridge and temperature controller 372 AC with 16-channel scanner model 3726 from LakeShore. The dilution bath with the target is located in the center of the superconducting solenoid [7], where the maximal magnetic field is $H = 7\ T$, and the field uniformity in a 14 mm diameter sphere $\triangle H/H = 2.4 \times 10^{-4}$.

For neutron studies of samples in strong magnetic fields at room temperature, the dilution cryostat was equipped with a removable "warm sluice" (Figure 4). Before the cryostat is cooled, the sample is placed in the vacuum cavity 1, the

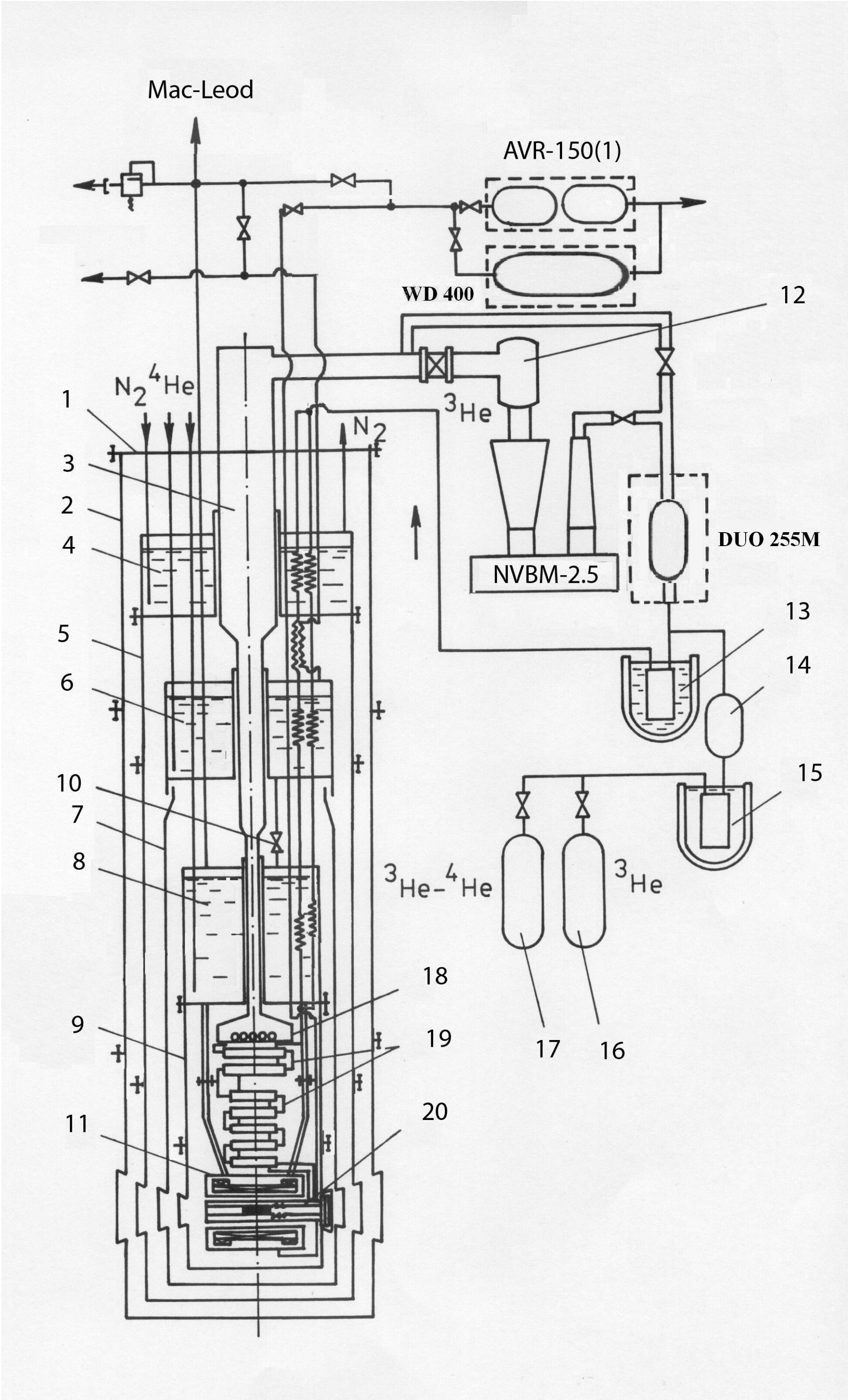

Figure 3. Schematic view of the ($^3He - ^4He$) dilution cryostat with superconducting solenoid: 1 – main flange; 2 – vacuum jacket; 3 – central pipe of the ^3He pumping line; 4 – nitrogen bath; 5 – nitrogen screen; 6 – helium bath; 7 – helium screen; 8 – pumped helium bath; 9 – helium screen of the dilution step; 10 – cryo valve; 11 – superconducting solenoid; 12 – nitrogen trap of the NVBM-25 booster pump; 13 – oil filter; 14 – NVG-2 pump; 15 – angular trap; 16 – ^3He storage reservoir; 17 – ($3He - ^4He$) storage reservoir; 18 – vaporization bath; 19 – heat exchanger; 20 – dilution bath.

plug 2 is hermetically sealed, and with the valve B2 closed, the sluice is pumped to 10^{-2} Torr through valve B1. In order to exclude frosting of the sluice 1 and sample 3 (due to the proximity to the helium temperature), the valve B2 opens before changing the sample and, with closed valve B1, helium gas is fed into the sluice. After the sample is replaced, B2 and the plug 2 are closed and the system is pumped through the valve B1.

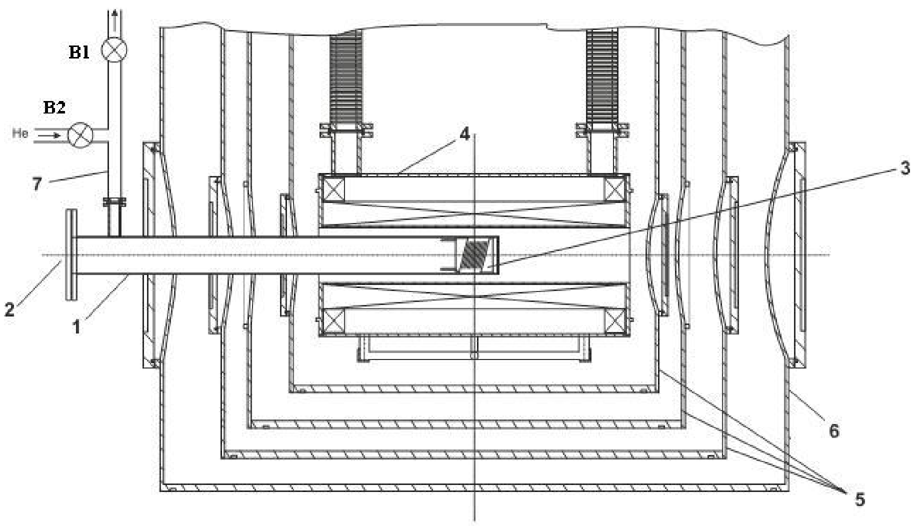

Figure 4. «Warm sluice» scheme: 1 — sluice; 2 — vacuum flange; 3 — sample; 4 — superconducting solenoid; 5 — cold screens of cryostat; 6 — vacuum casing of the cryostat; 7 — tee; B1, B2 — vacuum valves.

Ferromagnetic resonator of neutrons

For an experimental investigation of paramagnetic resonance of the first kind, when polarized neutrons pass through a polarized nuclear target, in addition to polarized neutrons and polarized nuclei, a device is needed to observe the resonance shift. For this purpose, a ferromagnetic neutron resonator was chosen.

The basic scheme of the resonator (the configuration of its magnetic fields) is shown in Figure 5. It is known [8,9] that a neutron, passing through a spatially periodic pulsed magnetic field and a constant (leading) magnetic field H_0 perpendicular to it, overturns its spin for certain values of the neutron velocity and the step of the spatially periodic field. If a spatially periodic magnetic field is created by magnetized films before saturation with ferromagnetic films, then such a resonator of neutron spins is called ferromagnetic. The leading field H_0 is created by solenoid, and spatially periodic magnetic field is created by magnetized to saturation with permalloy foils.

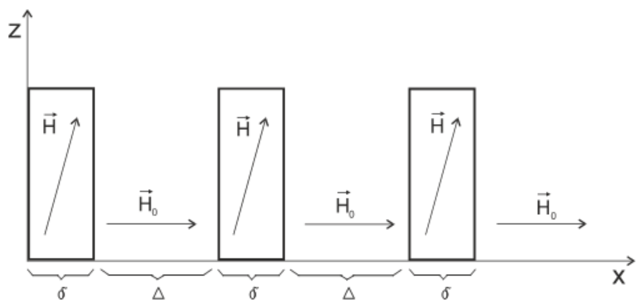

Figure 5. Scheme of the configuration of the magnetic fields of a ferromagnetic neutron resonator: δ — thickness of the permalloy foil; H_0 — constant magnetic field directed along the direction of neutron motion; Δ — distance between the permalloy foils; H — sum of the field H_0 and the field of magnetization of the permalloy foil.

The design of the resonator is shown in Figure 6. One section of the resonator is formed with a permalloy foil 4, 1.5 μm thick and an aluminum gasket 3, 0.2 mm thick. Such sections are placed between plates of stainless steel 2, 1 mm thick and are tightened by fixing bolts 5. Aluminum spacers 3 create a constant step $\triangle$ between the foils of permalloy 4, and stainless steel plates 2 prevent permalloy foils and aluminum liners from deformation during their assembly.

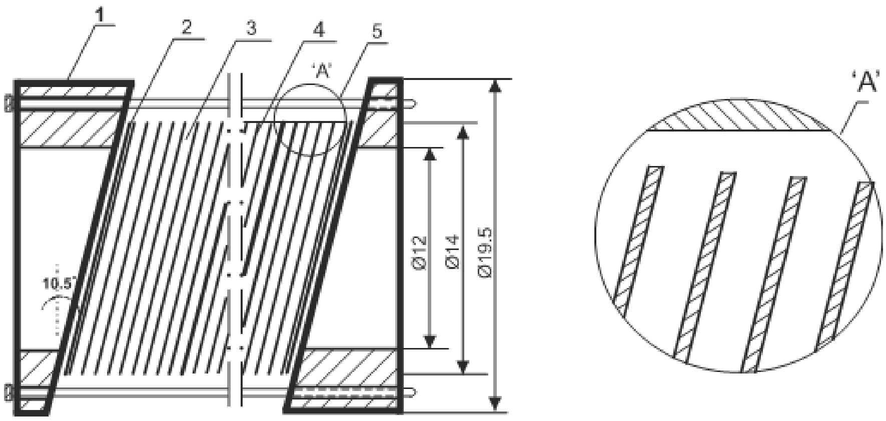

Figure 6. The design of ferromagnetic neutron resonator: 1 — dampers; 2 — stainless steel plates; 3 — aluminum gaskets; 4 — permalloy foils; 5 — fixing bolts.

The flaps 1 provide an inclination of 10.5 degrees of the permalloy foil 4 relative to leading magnetic H_0. Such a slope creates a component of the field H_0 magnetizing before the saturation of the permalloy foil along their surface. The field H_0 is created by a solenoid and, simultaneously, it is the leading magnetic field and the field creating a spatially periodic magnetic field. The efficiency of the resonator revolution K_{ef} depends on the neutron energy, the number of sections and the magnitude of the leading magnetic field H_0.

In the neutron nuclear precession experiment the aluminum sheets will be replaced by samples of the nuclear target. As a target, it is planned to use various nuclei. It is planned to study the dependence of nuclear precession (nuclear pseudomagnetism) on neutron energy in the neutron energy range 0.062 eV-2.3 eV. Resonators for neutron energy of 0.062 eV and 0.15 eV have been created and tested. Resonators for neutron energy of 0.6 eV and 2.3 eV are assembled.

Experimental setup control systems and software

For rotations of various components of the setup (for changing angular positions of the shoulder, the detector platform, the polarizer and the analyzer) computer-controlled system is used. It uses an algorithm, which implements selection of gaps. The angles are set with the precision of <0.1 deg (the resolution of sensors is 0.0055 deg).

The computer also controls the precise source of current. It allows us to set the current in the superconducting magnet on up to 110 A with the precision of 5 mA, which is required for investigation of the nuclear precession of the neutron spin.

The software consists of an experiment automation system (EAS) and a group of programs for the experimental setup adjustment.

The existence of the neutron and nuclear polarization equipment – which is part of the KOLKHIDA setup – gives a flexibility to choose from wide range of problems and research methods. The number of specimen conditions control devices is expected to grow and this puts specific requirements on the software architecture, which should flexibly adapt to the changes in experimental methods and at the same time allow to reuse already developed programs. According to the principles described in the paper [10] a component system with service-oriented structure was developed. The components of this system depend neither on the experimental methodology nor on the construction of the spectrometer. They are built in executable format and their descriptions are stored in a database. The user describes methodology of a concrete experiment with the help of an universal dialogue application, which does not depend on the spectrometer construction and which uses component descriptions stored in the database. The EAS is assembled automatically in accordance with the current description of the experiment methodology. A specialized distributed software environment – which uses dynamic "remote linking" method – allows different components to interact with each other. There are two groups of components within EAS: basic components, which allow execution of main tasks (specimen conditions control, data registration and archiving), and helper components (data visualization, express data analysis etc).

The EAS architecture and its working principles allow to extend the number of the basic components and to develop new helper components without changing the already developed code. The users can exploit the system and extend its functionality with new components (provided such components already exist) without a help from software developers.

Conclusion

Experiments have been prepared in order to study paramagnetic resonance of neutrons of the first kind and the dependence of the nuclear precession of neutrons on neutron energy. Scheduled:

- measurement of nuclear quadrupole splitting;
- measurement of pseudomagnetic moments and effective magnetic field for different nuclei.

The main experiment is planned for 2018.

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