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At the initiative of S.P. Kruglov at the PNPI synchrocyclotron, a muon channel was also created; Laboratory staff also actively participated in the implementation of this project.

Initially, the laboratory was assigned the study of the magnetic properties of various substances using the µSR method conducted on the muon channel of the PNPI synchrocyclotron.

At the PNPI, the muon method for studying matter began to develop in 1976, when the muon channel at the synchrocyclotron was put into operation. In 1977, the **"MUONIY"** facility was created to study local magnetic fields in matter by the method of muon spin rotation, and then experimental studies of the magnetic properties of the substance began using the µSR method. Currently, in Russia there is the only working µSR setup on the muon beam of the PNPI synchrocyclotron. **µSR at PNPI for over 40 years!**

Work on the "**MUONIY**" facility at the Leningrad Institute of Nuclear Physics of the USSR Academy of Sciences began in 1978. This was a period of rapid development of the µSR method at meson factories in Switzerland, Canada, and the USA. In our country, in connection with the reconstruction of the accelerator in Dubna, Leningrad NPP monopoly possessed a beam of polarized muons. The work experience of Moscow physicists (Kurchatov Institute, ITEP, MEPhI, MIPT, JINR) and the partial use of their equipment contributed to the development of the µSR method at Leningrad Nuclear Physics. However, a significant part of the work of this period was mainly of a methodological nature; a search was made for the directions of the most optimal use of µSR in scientific research.

By the beginning of 1987, when the high-temperature superconductivity (HTSC) was discovered, the Laboratory of Meson Condensed Matter Physics had accumulated extensive experience working in beams of polarized muons. However, the launch of the accelerator in Dubna significantly complicated the practical possibilities of working at PNPI. For an efficient study of HTSC by the muon method, it was necessary not only to understand the physical foundations of superconductivity as a research area in solid state physics, but also to create a new µSR installation based on the PNPI equipment. A new **µSR setup** for measurements in higher fields was created and experimental equipment was upgraded. This allowed us to reduce the required sample sizes and effectively use the integrated method of µSR studies developed at PNPI.

Between 1988 and 1991 the laboratory team conducted research in accordance with the PNPI research plan on the topic "Research of high-temperature superconductivity" within the framework of the "**SCALE**" and "**MUON**" projects of the State Program for the Study of HTSC. The experiments performed on the muon channel of the PNPI synchrocyclotron using the modernized MUONIY facility and the newly created µSR setup for research showed that a fairly regular vortex lattice of Abrikosov vortices is formed in high-temperature superconductors. For the first time, a deviation of the vortices from the direction of the external field due to the anisotropy of the HTSC was experimentally discovered. Independently and almost simultaneously with foreign groups, systematic experimental studies of the magnetic properties of monophase ceramic samples of the YBa2Cu3O6 +x compound (0.06 <x <0.95) were carried out. During this period of time, the properties of the textured monophasic superconductor Bi2Sr2CaCu2O8+x were first studied by the muon method. In ceramic YBaCuO superconductors (x> 0.40), the dependence of the measured characteristics of the distribution of local fields on the conditions of manufacture of the samples was found, the most probable reason being a change in the penetration depth under the influence of medium inhomogeneity. The question of the coexistence of superconductivity and magnetism in YBaCuO was investigated.

Since 1996, studies of manganese-containing compounds of the type Cu1-xMnx, La0.85Sr0.15MnO3, Pt3(Fe1-xMnx) and Pd0.95(Fe1-xMnx) were started at the MFKS laboratory. The peculiarity of these compounds is that due to the competing interaction in them, a complex phase diagram and a number of unusual effects are observed. For example, in the Cu1-xMnx alloy at high Mn concentrations (x> 0.7), a

6% shape memory effect is observed. At lower concentrations (x <0.7), this effect is significantly reduced, but nevertheless remains at the level of 0.1%. At these concentrations, the Cu1-xMnx compound at temperatures of 100–150 K changes from the paramagnet (PM) state to the spin glass (SG) type state. However, below the percolation threshold (x = 0.25–0.4), large uncertainties are observed in determining the phase transition temperature, indicating the appearance of some features. For the first time, the µSR method was used to study the magnetic characteristics of homogeneous Cu1-xMnx alloys. In samples with 0.2 <x <0.7, the appearance of a specific magnetic phase was detected, which is apparently characterized by the absence of long-range order and strong spin dynamics in the temperature range from 10 K to 330 K. Thus, the data obtained make it possible to significantly supplement the magnetic phase diagram of homogeneous Cu1-xMnx copper-manganese alloys, which takes the form characteristic of systems with competing exchange interactions. An analysis of the obtained experimental data suggests that two phases of a magnetically ordered state can be realized in binary Cu1-xMnx alloys at relatively high concentrations of magnetic Mn (x) atoms in the temperature range from 250 K to 20 K. At higher temperatures (above 100 K), a state with increased spin dynamics with fluctuating random fields arises. In this phase, the parameters ▯D and ▯ are of the same order. At a temperature of ~ 70 K, for all studied concentrations, a transition to the spin glass phase is observed without fluctuating random fields, i.e. in the phase of ordinary spin glass.

In compounds of the PdFeMn and PtFeMn type, at concentrations near the triple point in the ferromagnetic region, strong irreversibility effects are observed, indicating a possible transition inside the ferromagnetic phase to the state of an asperomagnet. The main studies of these materials were carried out either macroscopically or by the neutron method, and measurements by the µSR method were completely absent. As for the compounds (Pd0.984Fe0.16) Mn0.05, in accordance with neutron studies in this alloy, a transition to the ferromagnetic phase is observed at 40 K, and strong irreversible effects were found at temperatures below 35 K, but no additional phase transitions. Nevertheless, the phenomenon of irreversibility at temperatures (25–30) K indicates the possibility of a transition to an asperomagnet at these temperatures. Based on the studies of transitions to the asperomagnetic state in FeNiCr and PdFeMn alloys that we previously performed with µSR, we can conclude that the µSR method is uniquely sensitive to such transitions.

Therefore, at the end of 2002, the first trial µSR studies of the sample (Pd0.984Fe0.16) Mn0.05 were carried out, which confirmed the prospect of studying this alloy. A study was made of the alloy (Pd1-xFex)0.95Mn0.05 with a random competing interaction. A study of the dependence of the dynamic relaxation rate λ and the distribution characteristics of local static fields made it possible to clarify the phase states of the sample under study. In particular, it was shown that, below 25 K, two phase states simultaneously coexist in the sample: ferromagnetic and spin glasses. With a decrease in temperature, a spin glass fraction appears in the sample against the background of a collinear ferromagnet, long before the transition of the sample to the spin-glass state. Joint studies of the sample with the µSR method and the neutron depolarization method made it possible to determine the magnitude of magnetic inhomogeneities equal to 2–6 µm.

Intensive studies are still being carried out at the µSR installation, in particular, the following studies are underway: magnetism in materials with shape memory; alloys with random competing interactions; the interaction of ferroelectricity and ferromagnetism; research of nanostructured materials; multiferroic research and more.

In particular, at present, the traditional µSR technique is used to study nanodispersed magnets in order to determine the influence of the size factor on the internal structure. Thus, the µSR installation on the muon channel of the PNPI synchrocyclotron makes it possible to increase the efficiency of research in the field of condensed matter physics. This, in turn, is a good circumstance for NRC “Kurchatov Institute” - PNPI, because He is, of course, the world leader in the field of the study of matter using neutron methods, which will soon receive a powerful impetus in connection with the upcoming commissioning of the PIK reactor complex in Gatchina.

In recent years, with the help of this µSR installation, the following studies were carried out and new results were obtained:

Interaction of ferroelectricity and ferromagnetism (rare-earth manganites and manganates, doped manganites, multiferroics with close temperatures of magnetic and ferroelectric ordering). Using the µSR method, it was shown that a $HoMnO_3$ sample at a temperature of $T_N = 74$ K undergoes a transition from the paramagnetic to the antiferromagnetic state (P → AFM). It was proved that $HoMnO_3$ manganite undergoes a spin-rotational transition at a temperature of $T_{SR} = 42$ K, i.e. manganese spins undergo a turn of 900 at this temperature. Using the µSR method, it was determined that at paramagnetic temperature $T_N = 66$ K a paramagnet – antiferromagnet phase transition occurs. For the first time, features were discovered for $YMnO_3$ manganite near a temperature of ~ 50 K, which may correspond to a partial rotation of the spins of manganese ions. It has been shown that in manganites there are two localization sites of the muon with different internal magnetic fields, with the second magnetic field being approximately two times smaller in magnitude than the first.

When studying the $EuMn_2O_5$ and $GdMn_2O_5$ manganates by the µSR method without an external magnetic field, it was found that below the magnetic ordering temperature of 40 K, 20–25% of the muon polarization is lost. This can be explained by the fact that separate ferromagnetic pairs are formed in the antiferromagnetic matrix, in which the exchange of eg electrons through the ligand (oxygen) between Mn ions is possible.

Research is being conducted into the magnetic properties of nanostructured materials. The ferromagnetic fluid based on Fe_3O_4 nanoparticles dispersed in D_2O heavy water was studied using the µSR method. It was found that along with the precession signal from the muon (diamagnetic) component, a distinct signal from the muonium component is observed. It was found that the diamagnetic (muon) fraction is formed in ferrofluid in approximately the same proportion as in D_2O, however, the relaxation rate of the muon spin is much higher in ferrofluid compared with D_2O at temperatures $T > 150$ K. The fraction of the muonium fraction at these temperatures is much smaller in ferrofluid than in D_2O.

Investigations of ferritic-martensitic steels (Fe-Cr). In this paper, we obtained the magnetic properties of ferritic-martensitic steel EK-181 with various heat treatment modes. When studying the dependences of the dynamic polarization relaxation rate λ, the asymmetry coefficient, and the characteristics of the distribution of local static magnetic fields on the sample temperature, their irregular behavior in the brittle-viscous transition region was discovered, which can be explained by the transition of a part of the material to the state of spin glass.