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ON THE μSR ACTIVITY AT LNP JINR PHASOTRON

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Гуревич И.И. и др. E14-92-574
О работах в области μSR на фазотроне ЛЯП ОИЯИ

В работе представлено современное состояние μSR экспериментов на фазотроне ЛЯП ОИЯИ и краткое описание экспериментальных установок. Обсуждаются возможные направления будущих исследований. Приведен список основных публикаций 1987—1992 гг.

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On the μSR Activity at LNP JINR Phasotron

The current state of μSR activity at LNP JINR phasotron is presented, including short description of experimental facilities. The possible trends of μSR investigation for future work are outlined. The list of main publications (1987—1992) is included.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna, 1992

THE EXPERIMENTAL COMPLEX "MUSPIN"

The μSR technique (muon spin rotation, relaxation or resonance)/1/ is a nuclear-physics method of measuring local microscopic magnetic fields, which is based on the possibility of tracking the orientation of the magnetic moments of muons implanted in the objects being studied. Violation of the space parity conservation low in $\pi \Rightarrow \mu \Rightarrow e$ decay processes permits obtaining beams of polarized muons and observation of the time evolution of the polarization of ensembles of muons, arising because of magnetic interactions with the environment. All physical quantities of interest are derived by comparison of experimental time dependencies of muon polarization (time histograms) with theoretical models. For obtaining a standard μSR histogram about $5 \cdot 10^6$ muons are implanted in the sample.

Muons, which combine the properties of a simple magnetometer and of a probe charge with Z=1, make possible the solution of a wide range of problems starting from those relevant to purely quantum diffusion aspects of light impurity particles in a heavy crystalline matrix and problems of phase transitions involving changes of magnetic order to the chemistry of molecules, that are of interest from a biological point of view. The information obtained by μSR bears many similarities with NMR spectroscopy, while the actual implementation is close to that of the method of perturbed angular correlations. The figure represents a lay-out of a typical experimental μSR arrangement pertaining to the transverse field technique. The μSR method is applied for investigating the dynamics of distributions of local magnetic fields in real time. The μSR measurement technique allows obtaining information which is often unattainable by other nuclear-physics methods. The μSR method is not hindered by difficulties related to the skin-effect, or to the problem of interaction between probe particles. μSR studies may be carried out in the total absence of external fields, since

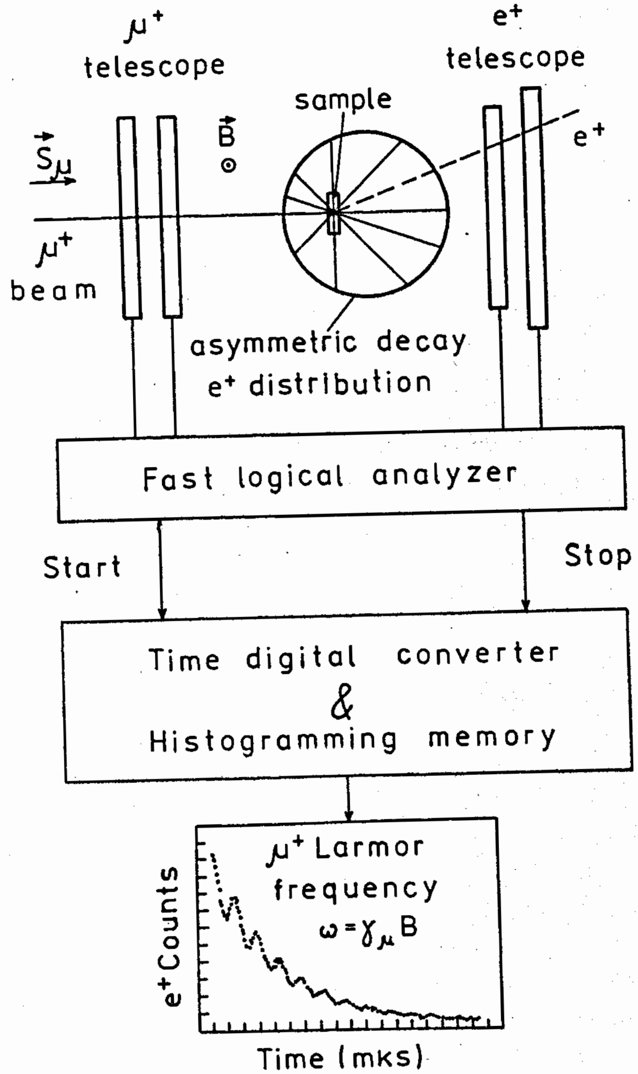

Fig. Scheme of the transverse field μSR technique. The initial muon polarization is perpendicular to the applied magnetic field and the muon spin will perform a Larmor precession.

the initial muon polarization depends only on the law of parity non-conservation in the $\pi \Rightarrow \mu$ decay and on the formation system of muon beams. The μSR method applied in an external zero field permits one to obtain unique information relevant to magnetic phase transitions. It must be stressed that this method is particularly sensitive to weak magnetic phenomena (μSR reveals magnetic order in matter down to values of the magnetic moment of $0.01\mu_B$ per formula unit) and to studies of multiphase systems (μSR permits determination of the volume fraction of a sample, to which a given distribution of internal magnetic fields is related).

The unique possibilities provided by μSR have led to the method's widespread application throughout the World. Thus, for example, programs employing μSR spectroscopy occupy about half of the accelerator time at muon channels of the meson factories at PSI (Switzerland), TRIUMF (Canada) and at the pulsed source of KEK (Japan). Numerous institutions take part in the work, while newly constructed muon sources immediately attract the experimental groups - at RAL (Great Britain) the EUROMUON collaboration is initiating activities with scientists participating from Italy, England, France, Sweden, Germany.

The complex "Muspin"/2/ is created by JINR and Kurchatov Institute team at the phasotron of the JINR Laboratory of Nuclear Problems for implementing studies by μSR spectroscopy. "Muspin" permits solving of broad range of problems of solid state physics and chemistry. "Muspin" can technically (considering the range of magnetic fields and temperatures, the level of measurement automation) well compete with other installations, while exceeding them in certain characteristics. Thus, for example, a $3\cdot10^{-4}$ signal-to-background ratio has been achieved for conventionally used muon beams stretched in time (DC mode). The complex includes a set of cryostats operating within the 1.3-300 K temperature range, magnetic systems with a perpendicular (to the initial beam polarization) field of 5kG and a longitudinal field of 6 kG, standard spectrometer based

on coding of muon lifetimes (with a channel width of 1 ns and analyzing time intervals up to 10 μs). The control CAMAC based system is guided by IBM-PC/AT compatible computers. Data handling system is based on IBM-PC/486DX and VAX computers connected to Ethernet. Unique equipment is available for performing μSR experiments with cryocrystals. A refrigerator utilizing dilution of ^3He in ^4He, that has been assembled and is at the test stage, will permit operation within a range of temperatures between 50 mK and 4.2 K. There is a magnetic system based on a superconduction solenoid employed for creating longitudinal fields up to 60 kG. A stroboscopic measurement system is under development, that is intended for precision determination of the Larmor precession frequency of the muon spin, taking advantage of features peculiar to the time structure of the JINR phasotron beam. Work is also under way for developing a tracking analysis system of $\mu \Rightarrow e$ decay events, based on semiconducting strips. A μSR apparatus, constructed in the Kurchatov Institute and based on a dilution refrigerator and Helmholtz coils, will be placed in the new beam of surface muons.

It must be noted that at the phasotron, where a significant amount of the required equipment and much methodical experience has been accumulated, work is planned for preparing measurements at the Moscow meson factory; this concerns such essentially novel fields of research, which are close in technology to μSR, as the muon elemental tomography and real-time studies of decay positrons channeling processes from muons thermalized in monocrystals.

At present the main part of μSR experiments in the World is carried out on muon beams with momenta lower than 30 MeV/c (so-called surface muons) - see Table. The beam obtained in the DC mode at the JINR phasotron is good enough even compared to the DC muon beams of meson factories and exceeds in quality the beams, operating only in pulsed modes unsuitable for a broad class of μSR investigations.

Table. Beams of surface muons at operating accelerators

		Proton energy (MeV)	Proton intensity (μA)	Mode	Muon intensity ($1/cm^2\cdot s$)
TRIUMF	Canada	520	150	DC	$2\cdot 10^5$
PSI(SIN)	Switzerland	590	400	DC	$\geqslant 3\cdot 10^4$
JINR	Russia	650	2	DC	$1.3\cdot 10^4$
LAMPF	USA	800	500	Pulsed	$\leqslant 3\cdot 10^6$
RAL	Great Britain	800	100	Pulsed	$4\cdot 10^4$
KEK/BOOM	Japan	500	2	Pulsed	$4\cdot 10^3$

It must, also, be noted that μSR studies at the Moscow meson factory will become competitive only after the storage stretcher-ring comes into operation.

The traditional method of scintillation μSR spectroscopy, applied at present in all the World, imposes strong limits on the beam intensity for muons being implanted in a sample - only those $\mu \Rightarrow e$ decay events are submitted for time analysis which satisfy the condition that only one muon stops during the analyzed time interval (of the order of 10 μs) and that a single decay positron be detected ("1μ,1e"-rule). Therefore, high-current accelerators exhibit the sole advantage, as compared with the JINR phasotron, that they permit working with somewhat smaller samples. The essential restrictions on the data taking rate in the DC mode may be removed only when the method of tracking analysis will be introduced in μSR studies. Spatial identification of the $\mu \Rightarrow e$ decay event will permit discarding the "1μ,1e" selection criterion and, moreover, will permit simultaneous investigation of several small samples situated in a single cryostat. Such research studies, based on the utilization of track detectors with semiconducting strips have already been launched by JINR - Kurchatov collaboration.

After completion of the reconstruction of the LNP JINR accelerator in 1986 and adjustment of muon channels a lot of μSR investigations has been performed, mainly relevant to the

problem of high-temperature superconductivity (HTSC), to studies of magnetic phase transitions in pure rare-earth elements and to the behaviour of a muon and of muonium in cryocrystals and cryoliquids (see the List of publications).

Scientists from research centers of Russia (Kurchatov Institute, Institute of Experimental and Theoretical Physics, Institute of Structural Macrokinetics Academy of Science, Moscow Institute of Radioengineering, Electronics and Automation, Moscow Physical and Technical Institute, Lebedev Institute, Moscow State University), Czechoslovakia (Physical Institute, Institute of Inorganic Chemistry, Charles University) and Poland (Institute of Low Temperatures and Structural Studies) have taken part in experiments performed with the installation "Muspin". Current investigations are supported by the State programs "High-temperature superconductivity" and "Fundamental nuclear physics". In 1990-91 joint research of high-temperature superconductors (HTSC) and cryocrystals was performed together with scientists of PSI/ETH (Switzerland), TRIUMF (Canada) and KFA (Juelich, Germany).

In conditions, when the μSR research programs proposed by all the World μSR community require beam time significantly exceeding that available at operating accelerators, μSR studies still continue to go on with muon beams that are essentially inferior in intensity or quality to the beams of the JINR phasotron.

The time available at the phasotron being limited essentially hinders collaboration with foreign colleagues. If the μSR activities at the phasotron would receive financial support, it could be quite realistic to organize within a short period of time an international program of μSR research with the best specialists taking part, calculated to consume between 2.0 and 2.5 thousand hours per year. It would also be very reasonable to provide for much broader participation in the planning and performing of μSR experiments at the phasotron of staff members from Institutions undertaking investigation of magnetic phenomena in participant-countries of the JINR. The JINR - Kurchatov μSR collaboration could practically provide for all required technical support of the measurements. The Institutes of the JINR members - states would be required to take part in the development of scientific programs and to provide high-quality samples for research. In particular, the possibility must be pointed out of undertaking, already now, complex muon and neutronographic investigations together with scientists from the JINR Frank Laboratory of Neutron Physics.

The "Muspin" complex may be considered as an excellent experimental base for undergraduate and postgraduate students of the Educational-Scientific Center at the JINR. Within the framework of this experimental complex problems in solid-state physics are studied by typical nuclear-physics methods utilized at accelerators at a wide range of temperatures and magnetic fields. The level of automation of measurements is not inferior to the one of operating μSR complexes at meson factories. Handling of μSR spectra based on methods of multiparameter optimization, the support of data banks, the availability of computers (from PC to VAX), participation in the creation of a World-wide bank of accumulated μSR spectra and in standardization of the utilized software - all this contributes to the good schooling of staff for various branches of physics.

POSSIBLE FIELDS OF μSR INVESTIGATION AT THE JINR PHASOTRON

1. Investigation of the properties of superconductors [3,4]

1.1 Investigation of the temperature dependencies of penetration depths of the magnetic field λ in high-temperature superconductors (HTSC)

The main idea of measurements consists in precise measurement of the distribution of magnetic fields in the mixed state of the superconducting samples under study. Such studies are important for the following reasons:

a) the quantity $\lambda(T=0)$ determined by the effective mass

m and the concentration n_s of carriers taking part in the formation of Cooper pairs is one of the fundamental parameters characterizing a superconductor;

b) the precision of μSR measurements is sufficient for choosing from the theoretical models yielding differing temperature dependencies $\lambda(T)$. The μSR method is weakly sensitive to systematic errors, that arise when the quantity λ is derived from the experimentally measured dispersion of the magnetic field distribution, $\langle\Delta\omega_\mu^2\rangle$;

c) it is interesting to establish the relationship between T_c and λ for all known types of high-temperature superconductivity. Thus, for the case of samples with a low concentration of charge carriers Y.Uemura et al. have proposed a universal linear relationship between T_c and $1/\lambda^2 \propto n_s/m$, which testifies in favour of models differing from the weak coupling BCS theory with phonons as the mediating bosons. However, the latest experimental data obtained with high-temperature superconductors based on Bi have raised doubts concerning the universal nature of this relationship.

First of all, we propose to perform measurements with monocrystals of HTSC based on bismuth (the 2212 system) for different orientations of the crystallographic axes of the samples with respect to the external magnetic field.

1.2 Investigation of issues of magnetic ordering in HTSC-systems

The questions concerning the coexistence of magnetic order and superconductivity and the position of the region of a spin-glass state in between the clearly antiferromagnetic and superconducting phases in $La_{2-x}Sr_xCuO_4$ and $YBa_2Cu_3O_7$ remains open - the results obtained by different groups contradict each other. μSR investigations will help shed additional light on the above problem.

1.3 The search for anyons

Bearing in mind the particular sensitivity of μSR to weak magnetism, it would be worthwhile to plan an additional check of the HTSC-theories asserting the existence of exotic quasiparticles - of anyons obeying fractional statistics. The presence of anyons results in the appearance of magnetic fields, of the order of some parts of a Gauss, that are oriented in a direction perpendicular to the Cu-O planes. The presence of weak anyon fields in HTSC may be revealed by precision μSR measurements in a zero external field.

1.4 Investigation of irreversible and metastable processes occurring when samples are magnetized with the aim of obtaining information concerning the state of superconducting glass in HTSC and the dissipation mechanism of the magnetic flux in a crystalline lattice of a HTSC

We propose studying the evolution of the distribution of magnetic fields inside superconductors, including memory effects - the dependence of the μSR signal on the delay time between the moment the sample is cooled and the moment the external magnetic field is switched on. Besides this, we intend to perform measurements with monocrystals of compounds 1-2-3, submitted to preliminary irradiation, with the aim of studying the influence of monitored irradiation with neutrons on the formation of pinning centers. The obtained data will be compared with the predictions of existing theoretical approaches, for example, with the theory of "vortex dots".

1.5 Investigation of the influence of chemically bound states of the muon in HTSC on depolarization processes[5]

Formation of chemical bounds of muonium in HTSC with the maximum possible oxygen content (for instance, $YBa_2Cu_3O_x$ for x=7.0) proceeds like in a hydroxyl radical (-Cu-O-Mu), and in the case of oxygen deficit ($x < 7$) - like in a hydride (-Cu-Mu). The differing muon polarization relaxation rate in longitudinal magnetic fields in such conditions reflects the mechanism of physico-chemical interaction of one-electron atoms in a solid state lattice. Of special interest is the comparison of the data with results for oxygen-deficient, but saturated with hydrogen, HTSC (the muonium - model analog of atomic hydrogen), and also with positron - electron annihilation results.

2. Investigation of the magnetically ordered state of intermetallic compounds

The interest in intermetallic electronically nonstable compounds is due to these systems representing a sort of testing ground where simultaneous investigation is possible of such phenomena as intermediate valence, magnetism, superconductivity, anomalously high electron density on a Fermi surface, etc. The materials are basically composed of REM ions, 3d transition metals and of ions of the actinide group. The electron structure of such systems is extremely sensitive to such external factors as temperature and pressure. Recently, success was achieved at the Institute of Physics of High Pressures (IPHP) in synthesizing sufficiently stable intermetallides, in which a series of interesting electron transitions was induced[6]. For investigation of these transitions ZF μSR experiments[7] are to be performed for studying the temperature dependencies of hyperfine fields in cubic Laves phases synthesized both at high and normal pressures. First of all, the compounds $GdFe_2$, YFe_2 and $GdNi_2$ are to be studied. It must be noted that the process of obtaining intermetals exhibiting electronic non-stability, activated by pressure, in amounts sufficient for μSR measurements has, at present, been mastered only in IPHP. Samples are proposed to be investigated by other methods, such as X-ray structural analysis, macroscopic magnetic measurements, neutron diffraction, the Mössbauer effect, perturbed angular correlations (PAC) and NMR.

3. Investigation of quantum diffusion of positive muons in metallic superconductors

Investigation of the diffusion of light impurity particles in crystals is interesting because at sufficiently low temperatures the motion of the particles is influenced by the tunnelling process. The quantum-mechanical aspects of motion are manifested, in particular, in the case of positive muons, the mass of which is 9 times smaller than the proton mass. Investigation of the influence of conduction electrons on diffusion was always one of the main problems of theory. Therefore, the importance of the possibility of performing a straightforward experiment for comparing the diffusion velocities of muons in the normal and superconducting states cannot be overestimated. The quantum nature of diffusion is best seen in the muon spin relaxation rate decreasing with a drop in temperature. In the course of studying the diffusion of muons in Al in 1990/8/ a sharp rise of the diffusion coefficient was observed, when transition of Al into the superconducting state occurred. We propose to extend the scope of such studies and to take simple metals, which are sufficiently easy to purify and the transition temperature (T_c) of which to the superconducting state is sufficiently high, for instance, indium, vanadium and mercury and to perform μSR measurements at temperatures lower than the transition point. In the case of a zero external field (ZF) the diffusion properties of metals in the superconducting state will be determined, and when an external field higher, than the critical one at T=0, is applied, information on diffusion in the normal state will be obtained.

4. Comparative study of delocalization effects of muonium in ice crystals of light (H_2O) and heavy (D_2O) water

Till recently, most work on diffusion carried out by the μSR method was related to determination of the muon spin relaxation due to magnetic interaction of the muon spin with nuclei of the lattice during propagation through the crystal. From the theoretical point of view, muonium is preferable for observation of quantum diffusion than μ^+. Interaction of the neutral muonium with the environment is significantly weaker than that of μ^+, which provides for lower potential barriers and a significantly higher probability of tunnelling displacements, although the masses of Mu and μ^+ are equal. Not long ago, the group of J.Brewer et al. at TRIUMF observed

quantum diffusion of muonium in KCl/9/ and NaCl/10/ ionic crystals. A theoretical explanation of the observed phenomena was given within the framework of the quantum diffusion theory developed by Yu.M.Kagan and N.V.Prokofiev/11/. The main idea consists in that the hyperfine interaction of the electron of the muonium with the nuclei of the environment depends on the nuclear spin orientation and, therefore, as the muonium undergoes diffusion, the effective magnetic field at the electron site fluctuates and induces transitions between levels of the muonium, which results in a decrease of the observed muon spin relaxation rate. For observation of muon diffusion by the μSR method crystals are required, in which the nuclei of the lattice exhibit significant magnetic moments and the bound (μ^+e^-) state lives sufficiently long. Such requirements are satisfied, in principle, by the ice crystals of light and heavy water, which from the point of view of muonium differ only like the the proton and deuteron magnetic moments. Detailed μSR information for both types of ice was obtained by P.W.Percival et al./12/ in temperature region above liquid nitrogen. It will be of interest to widespread the experimental region down to helium temperature and also to study the parameters of the quadrupole effect for muonium within a broad range of temperatures.

5. Investigation of the magnetic properties of super-pure rare-earth metals

Compounds based on rare-earth metals (REM) are becoming more and more diffused in engineering. Their applications range from powerful constant magnets to ultrasonics emitters. The search for new materials continues. Significant success has been achieved in understanding the properties of REM at a microscopic level, but the investigation of fundamental issues related to the magnetism of REM still remains important/13/. It suffices to say that the question of the types of magnetic phase transition is still open in the case of many REM/14/. It would, therefore, be reasonable, together with representatives of other experimental techniques and making use of the same high-quality samples, to undertake complex studies of the magnetic properties of simple REM and of their double alloys. Local fields at the muon site in the region of magnetic order may be measured by the μSR method[15], and the temperature and magnetic hysteresis of the time dependence of the muon polarization can be studied in the vicinity of phase transition points. It must be stressed that we intend measurements with samples of really record purity: R(300 K)/R(4.2 K) > 200 (this ratio is very large in the case of REM). At present such metals can be obtained in the Baikov Institute of Metallurgy and in the State Institute of Rare-Earth Metals (GIREDMET).

6. Investigation of magnetically ordered states of HTSC related compounds (CuO, $Y_2Cu_2O_5$, $YBa_2Cu_3O_{6.5}$)

At present it is known that such compounds as CuO and $Y_2Cu_2O_5$ are antiferromagnetics with $T_N \propto 14$ K and $T_N \propto 230$ K, respectively.[16,17,18] There exist indications that at $T<T_N$ additional phase transitions occur, but the existence of such transitions remains to be clarified. It must be noted that a change of magnetic properties below Neel point was previously observed in $La_{2-x}Sr_xCuO_4$ compounds at $0.01<x<0.05$. The preliminary data obtained by us when studying polycrystalline samples of CuO and $Y_2Cu_2O_5$ confirmed the possible existence of the phase transitions at temperatures lower than T_N. The proof of the general character of processes changing the magnetic order in compounds akin to HTSC may turn out to be an important circumstance for comprehension of the nature of high-temperature superconductivity.

We plan to perform systematic μSR measurements of CuO, $Y_2Cu_2O_5$ and $YBa_2Cu_3O_{6.5}$ below the Neel point in zero fields (ZF measurements) and magnetic fields, perpendicular to the initial polarization of the muon beam (TF measurements).

7. Investigation of local magnetic fields in Bi_2O_3, Sb_2O_3 and $BaBiO_3$ compounds

The α-Bi_2O_3 compound is one of the components used in producing HTSC based on Bi, and it also serves as a reference point of the triple-valence Bi in various spectroscopic studies of the electronic structure of HTSC. At the same time this compound exhibits a series of properties that are unusual for substances, in the atoms of which only the s- and p- electrons serve as valence electrons. Thus, in the NQR spectra for α-Bi_2O_3, which is conventionally considered to be diamagnetic, the splitting of the spectral lines revealed a local field on the bismuth nuclei[19]. In experiments with a SQUID magnetometer a paramagnetic peak of unknown nature was observed in the same compound in the 50-80 K temperature range[20]. We have performed μSR measurements with a polycrystalline α-Bi_2O_3 sample in a zero magnetic field and in external fields of varying orientation with respect to the initial muon beam polarization[21]. A fast muon spin depolarization process was observed, that exhibited an unusually confused dependence upon the external field. The appearance of local magnetic fields significantly exceeding in value the dipole magnetic fields produced by the Bi magnetic moments, but smaller, than the magnetic fields characteristic of paramegnetics, was explained by the bonds in α-Bi_2O_3 being of a partially covalent nature. The appearance of a long-ranged magnetic order was not detected down to the temperature of 4.2 K. It seems to be quite important to extend the range of measurements down to lower temperatures and to perform complex measurements of such compounds akin to bismuth oxide, as Sb_2O_3 and $BaBiO_3$.

8. Investigation of systems with heavy fermions

After the discovery of systems with heavy fermions (HF), the group of A.Schenck at PSI undertook μSR studies of the magnetic properties of many compounds containing HF and obtained experimental information, which demonstrated the possibilities of the μSR method in this field[22].

One of the surprising experimental findings in systems with HF was the observation of very small oriented moments at the level of 10^{-3}- $10^{-2}\mu_B$. In spite of the effective moments being so small, the corresponding ordering temperatures are sufficiently high, for example, in the URu_2Si_2 (μ_{eff}=0.03μ_B) system the Neel temperature amounts to 17 K. This phenomenon has still not been understood, at all. Recently, members of the Department of Low Temperatures of the Moscow University discovered a new compound, $CeRuSi_2$, exhibiting ferromagnetic ordering at 10 K[23]. For experiments at the phasotron a unique sample has been prepared, which has been totally certified by macroscopic methods. We intend to carry out complete ZF and TF studies of this sample both in the ferromagnetic and in the paramagnetic regions.

9. Investigation of liquid ^{3}He at enhanced pressures

Condensed ^{3}He is one of the most outstanding representatives of quantum materials. The amplitude a_0 with which its atoms oscillate may be characterized by the de Bour parameter $\Lambda = a_0/a = 0.48$, where a is the distance between the atoms. This circumstance results in a series of specific effects related to intense exchange processes (here the word "exchange" is used in the direct sense - mutual tunnelling of atoms, or permutation of their sites, is intended). The "exchange" interaction energy expressed in units of frequency amounts to $10^6 \div 10^7 s^{-1}$. This quantity has the meaning of a tunnelling frequency and reflects the extent to which an object can be studied by the μSR method.

The properties of liquid and solid ^{3}He have been extensively investigated by the NMR method. At present a complete and consistent picture of its magnetic properties has already been developed (excluding, maybe, the temperature range below 1 mK). However, besides the properties of non-perturbed ^{3}He, there remain several problems that cannot

be solved by NMR. One of the most interesting of such issues is the problem of the immediate (1-2 coordinate spheres) structure of the surrounding of a charge, the so-called Atkins icicles. We note that the results of relevant experiments with magnetic resonances on charges in cryoliquids (EPR on implanted charges in ^{3}He-^{4}He solutions[24], μSR in liquid hydrogen[25]) are contradictory and require clarification.

In this connection muon studies of liquid ^{3}He seem very promising and important. Liquid ^{3}He exhibits an anomalously large compressibility ($k \approx 4\%$ bar^{-1}), which is a manifestation of its quantum nature. Already at moderate pressures of $p \approx 30 \div 40$ bar the wave functions of particles undergo essential variations owing to the compression of matter. Moreover, these pressures turn out to be comparable to the polarization pressure at a distance of the nearest neighbor. Thus, the possibility arises of studying the influence pressure has on the structure of the immediate surrounding of a charged particle. A more long-term problem could be the investigation of the influence of fermi-liquid effects on the magnetic relaxation.

10. Investigation of the formation process of muonium in cryoliquids and cryocrystals

Muonic experiments with superfluid ^{4}He[26,27] have revealed that the formation of muonium may essentially influence muon depolarization in matter. On the other hand, it has turned out that the process of muonium formation itself, which was for the first time observed in conditions of anomalously high charge mobility, is not at all trivial and deserves special investigation. At the same time, there are reasons for believing that the observed muon relaxation in solid hydrogen and in certain other cryoobjects may be related to the indicated processes. For studying such a possibility one may apply the same technique, that was already made use of in studies of solid ^{4}He, of measurements in an external electric field and various transverse magnetic fields. We intend to perform μSR experiments with such materials as solid and liquid hydrogen, neon, argon.

11. Investigation of the reactive capability of impurity non-organic ions in a crystalline chemically inert lattice[28,29]

Determination of the absolute reaction rates of muonium with ions in a solid state lattice represents both an independent significant problem pertaining to chemical kinetics and an applied method for determining the chemical and crystallographic purities of samples, which is of great importance, for instance, in the case of quartz, leucosapphire, refractory oxides. The processes of accumulating and annealing of radiation point defects in crystalline samples can be studied by the analogous way.

12. Investigation of muon depolarization in solutions of biochemical compounds[30]

Utilization of biological radioprotectors, applied for capturing and recombining free radicals produced under the action of ionizing radiation on aqueous systems (including live organisms) requires a quantitative basis for interpretation of the efficiency of the protectors. Measurement is planned of the rates of muonium chemical reactions with various radioprotectors and other, important from the biological point of view, compounds as well as comparison with data from positron and radiation-chemical investigations.

13. Investigation of radiation damage of ferromagnetic materials

The main purpose of this investigation is development of a method involving positive muons for studying defects of structural materials used in constructing reactors. The μSR method has been successfully applied for studying internal magnetic fields in simple ferromagnetics, such as Fe, Ni, Cr and their alloys[15,31]. Moreover, the method is known to be especially sensitive to distortions of the crystalline structure even at the level of several ppm.

It seems important to study the possibility of the μSR method for solving such "strategic" problems as the following:

- monitoring the metallurgic and mechanical state of critical parts of a reactor, including the prediction of possible emergency situations;
- optimization of the management of the reactor operation for prolongation of its operation life time;
- deciding upon criteria for choosing new types of structural materials for future reactors.

The main expenses are to be spent on construction of the special μSR installation at the new beam of slow muons of the JINR phasotron. This new setup is to be utilized for working with irradiated structural steels and films (amorphous and crystalline), that are applied as coatings. In principle, the setup can be employed in beams of "surface muons" at any accelerators, including the Moscow Meson Factory.

Preliminary μSR studies may be carried out on materials deformed mechanically (investigation of the dependence of μSR signals on the frequency, pulse height and number of stretching-compression cycles of Fe and Ni samples and of their alloys).

Investigations in this field of research have been initiated at the Laboratory of Lepton Spectroscopy of the French National Research Center (CNRS)[32].

14. Investigations with beams of negative muons

14.1. Investigations of hyperfine interactions of acceptor centers in semiconductors

Detailed investigation of acceptor centers in semiconductors with diamond structures (Si, Ge) by the EPR method is hindered by the high relaxation rate of the electron magnetic moment of a paramagnetic center. From this point of view μSR investigations employing negative muons seem to be quite promising. When a negative muon is captured, a muonic atom is produced, in which the muon substitutes one of the electrons. A muonic atom may be pictured as an atom consisting of a pseudonucleus, $(Z + \mu)$, and $(Z - 1)$ electrons, this atom representing an analog of the impurity acceptor atom in a semiconductor. In the case of Si the muonic atom is an analog of the impurity Al atom. Negative muons conserve part of the initial polarization before reaching the 1S state, and its variation may be followed experimentally during times of 10^{-8}–10^{-5}s. Consequently, it is possible to investigate scattering processes of charge carriers on paramagnetic centers and to study rapid physico-chemical processes occurring in semiconductors. Such experiments are just being initiated in foreign scientific centers[33].

We propose to carry out a complex study with silicon in transverse and longitudinal magnetic fields in the temperature range between 4.2 and 300 K.

14.2. Investigation of high-temperature superconductors

Negative and positive muons stopping in crystals are localized at different sites. Therefore it is very interesting to perform independent μSR studies with positive and negative muons in HTSC. Owing to the life time of a negative muon in the 1S state of oxygen being greater, by approximately an order of magnitude, than in other atoms composing HTSC, the electrons produced in muon decays in oxygen can be readily distinguished from the contribution of other atoms. Hence, with the aid of negative muons one can investigate the state of the oxygen atom in a HTSC.

The results of preliminary investigations[34,35] reveal that in HTSC of type 1-2-3 nearly all the polarization of negative muons in the 1S state of oxygen is lost at the precession frequency of the free muon spin. μSR investigations are proposed for clarifying the reason of the

total loss of polarization in the 1S state of oxygen, since it may be due to the same characteristic features of the crystalline structure, that are responsible for superconductivity.

In the $Bi_2CaSr_2Cu_2O_{8-\delta}$ compound at room temperature we have observed[34] a significant residual polarization of negative muons. We propose to continue μSR experiments with this sample at temperatures down to 4.2 K.

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