Investigation of superconductors by the muon technique

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Type-I and Type-II superconductors were investigated by measuring the magnetic fields at the μ^+ mesons. The internal magnetic fields and their degree of inhomogeneity in the normal metal of superconducting lead in the mixed state were measured. The volume of the normal phase was measured as a function of the intensity of the external magnetic field. The volumes of the Meissner phases in the mixed states of niobium and V_3Ga were measured as functions of the temperature and of the intensity of the external magnetic field. The magnetic fields that penetrate into the superconductor when the limit of the transition into the normal state is approached were measured.

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1. INTRODUCTION

The use of μ^+ mesons for the study of supreconductivity[1-4] is based on measurement, with the aid of these muons, of the internal magnetic fields that are directly connected with the properties of the metal in the superconducting field. Thus, in a type-I superconductor in the Meissner phase, the μ^+ meson is acted only by the local magnetic fields produced by the magnetic moments of the surrounding nuclei. A zero average of the local magnetic fields leads to relaxation of the μ^+-meson spin. The corresponding μ^+ signal will be named the relaxation signal. Of course, there will be no relaxation μ^+ signal if the metal nuclei have no magnetic moment.

Under certain conditions, an external magnetic field H penetrates into a type-I superconductor, as a result of which regions of the metal in the normal state are produced in the superconductor. This complicated state is called intermediate. If the field H is transverse, then in the intermediate-state normal regions the spin of the μ^+ meson precesses at the Larmor frequency $\omega = eB_\mu/mc$, where B_μ is the magnetic field that penetrates into the metal. In the general case, therefore, both relaxation and precession μ^+ signals are observed in the intermediate state, and their amplitude ratio is equal to the ratio of the volumes of the superconducting and normal regions of the metal. The inhomogeneity of the magnetic fields in the normal regions of the intermediate state leads to damping of the experimentally observed μ^+-meson precession, i.e., to relaxation of the precession μ^+ signal.

The magnetic structure of a type-II superconductor is more complicated. At low values of the temperature T and of the magnetic field H this superconductor is in the Meissner phase. With increasing H and T, however, the thermodynamically more stable state is one in which the magnetic field penetrates into the metal in the form of the so-called filaments that form an ordered lattice. This state is called the mixed or the Shubnikov phase. Obviously, in the mixed state, just as in the intermediate state, both relaxation and precession μ^+ signals can be observed. In contrast to the normal regions of the intermediate state, however, the magnetic field in the filaments of the mixed state is most inhomogeneous and the corresponding precession signal attenuates very rapidly.

2. EXPERIMENT

The work was performed with the JINR synchrocyclotron in Dubna. The μ^+ meson beam polarized opposite to the momentum direction was slowed down and stopped in the investigated sample. The sample was placed in a magnetic field transverse to the μ^+-meson spin direction and of intensity up to 6 kOe. A helium cryostate made it possible to set any sample temperature above 4.2 K. The relaxation and precession of the μ^+-meson spin in the sample were measured by a standard method in proportion to the number of registered $\mu^+ \to e^+$ decay positrons. The electron-recording apparatus was described earlier.[5]

The experimentally observed time dependence of the number $N(t)$ of registered positrons of the $\mu^+ \to e^+$ decay in the superconductor, after subtracting the background, was expressed in the general case as a sum of two terms corresponding to the relaxation and the precession of the μ^+-meson spin:

$$N(t) = N_0 e^{-t/\tau_0}[1 - a_0 P_0(t) - a_\perp P_\perp \cos \omega t]. \tag{1}$$

Here $\tau_0 = 2.2 \times 10^{-6}$ sec is the μ^+-meson lifetime; a_0 and $P_0(t)$ are respectively the experimental asymmetry coefficient of the angular distribution of the $\mu^+ \to e^+$ decay positrons and the time dependence of the μ^+-meson polarization in the superconducting state, and $a_\perp$ and $P_\perp(t)$ are quantities analogous to a_0 and $P_0(t)$ and describe the μ^+-meson precession in a transverse magnetic field B_μ penetrating into the superconductor, i.e., the precession μ^+ signal; $\omega = eB_\mu/mc$ is the frequency of the Larmor precession of the μ^+ meson. In the reduction of the experimental data, $P_0(t)$ and $P_\perp(t)$ were extrapolated by the functions $e^{-\Lambda t}$ or $e^{-\sigma^2 t^2}$. The parameters N_0, a_0, $a_\perp$, Λ (or σ) and ω were determined by the maximum-likelihood method in comparison of expression (1) with the experimental function $N_{exp}(t)$.

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3. INVESTIGATION OF INTERMEDIATE STATE IN LEAD

The intermediate state of a superconductor is produced when an external magnetic field H penetrates partially into the superconductor. This takes place at $H_1 < H < H_{cr}$, where $H_1 = H_{cr}(1-D)$, H_{cr} is the critical magnetic field, and D is the sample demagnetization coefficient. In the intermediate state the entire volume of the superconductor breaks up into minute normal and superconducting regions. It is assumed that in the normal regions the magnetic field is $B = H_{cr}$ and that the relative volume η of the normal phase increases linearly with increasing external field:

$$\eta=(H-H_1)/DH_{cr}. \tag{2}$$

The formation of the intermediate state was predicted[6-8] and experimentally observed on the surface of the superconductor with the aid of bismuth probes[9,10] and by the powder decoration method.[11-14]

The muon method makes it possible to measure with high accuracy both the magnitude and the distribution of the magnetic fields in the normal regions of the intermediate state, not on the surface but in the interior region. In the present study we used the muon method to measure the magnetic fields in the intermediate state of lead.

The investigated lead sample was a flat ellipsoid of revolution 60 mm in diameter and 15 mm thick, with the major axis parallel to the external field H. The experiment was performed at a constant temperature $T = 4.3 \pm 0.1$ K. The external magnetic field strength was varied in the range $H = 200-700$ Oe. The critical magnetic field at $T = 4.3 \pm 0.1$ K was $H_{cr} = H_{cr}(0)[1-(T/T_{cr})^2] = 521 \pm 12$ Oe, where $H_{cr}(0) = 808$ Oe is the critical field for lead at $T = 0$, while $T_{cr} = 7.2$ K is the critical temperature. This ellipsoid has a demagnetizing factor $D = 0.15$, and hence the field is $H_1 = H_{cr}(1-D) = 442 \pm 10$ Oe.

We measured only the μ^+ signal corresponding to the precession of the μ^+ meson in the normal regions of the metal. There was practically no relaxation μ^+ signal in the Meissner phase, owing to the small values of the local magnetic fields in this metal. The relation (1) takes therefore in this case the form

$$N(t)=N_0e^{-t/\tau_0}[1-a_\perp e^{-\Lambda t}\cos\omega t]. \tag{3}$$

The exponential form of $P_\perp(t)$ is assumed in this expression. The values of $a_\perp$ and ω for different values of H, obtained from (3), yield the experimental $\eta(H)$ and $B_\mu(H)$ dependences. The experimental values of η are taken to be $\eta_{exp} = a_\perp/a_{max}$, where a_{max} is the asymmetry coefficient in the normal phase of the investigated sample. The field B_μ was determined from the relation $\omega = eB_\mu/mc$, where m is the μ^+-meson mass. The plots of $\eta(H)$ and $B_\mu(H)$ obtained in this manner are shown in Fig. 1.

It is seen from Fig. 1 that $B_\mu = H$ at $H > H_{cr}$, as it should be for a metal in the normal state. In the intermediate state, at $H_1 < H < H_{cr}$ the field $B_\mu = H_{cr}$ and is independent of H. The experimental $\eta_{exp}(H)$ dependence is close to the theoretical (2). The values $B_\mu = H_{cr}$ as well as some deviation of the experimental $\eta_{exp}(H)$ dependence from the theoretical at $H \approx H_1$ is possibly due to small deviations of the sample from a strictly ellipsoidal form.

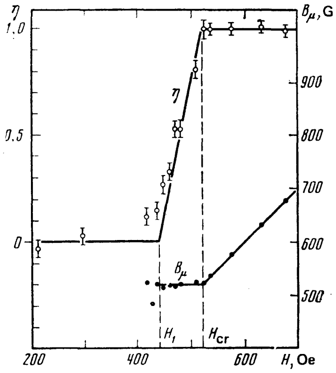

FIG. 1. Experimental values of $\eta(H)$ and $B_\mu(H)$ in lead at $T = 4.3$ K. The solid lines are the corresponding theoretical plots plots for the sample tested.

The data obtained have also made it possible to estimate the degree of homogeneity $\delta B_\mu/B_\mu$ of the magnetic field in the normal regions of the intermediate state. The value of $\delta B_\mu/B_\mu$ is determined by the damping rate Λ of the precession μ^+ signal. The value $\Lambda \lesssim 0.2\ \mu\text{sec}^{-1}$ measured in this experiment at $H_1 < H < H_{cr}$ corresponds to $\delta B_\mu/B_\mu \lesssim 1\%$.

4. INVESTIGATION OF THE MIXED STATE IN NIOBIUM AND IN V_3Ga

Niobium and V_3Ga are type-II superconductors. The external magnetic field penetrates into these superconductors in the form of spatially ordered filaments. In real samples of type-II superconducting metals, however, an important role is played by the pinning of the filaments by various inhomogeneities of the metal or on its surface. Such metals are sometimes called type-III superconductors. Pinning leads to hysteresis in the superconductors, i.e., to a phenomenon wherein the state of the superconductor depends not only on the external parameters but also on the previous changes of these parameters. As will be shown presently, hysteresis and pinning play a very important role in the investigated niobium and V_3Ga samples.

We used polycrystalline samples of niobium and V_3Ga with less than 0.1% impurity. Standard measurements yielded for V_3Ga a critical temperature $T_{cr} = 14.6$ K and the $H_{cr2}(T)$ dependence at $T > 11$ K. It was found that $H_{cr2}(11\text{ K}) = 140$ kOe at $T = 11$ K. The Ginzburg-Landau parameter[15] turned out to be $\varkappa = 35 \pm 5$. The niobium was an ellpsoid of revolution of 80 mm diameter and 10 mm thickness, with the major axis in the direction of the external magnetic field H. The V_3Ga sample was a disk of 80 mm diameter and 16 mm thick, and the external field H was parallel to the plane of the base of the disk. In all cases the field H was perpendicular to the direction of the spin of the μ^+ meson. The superconducting properties of these samples were investigated in three regimes with different temperatures (T) and external transverse magnetic fields (H).

I. The sample was cooled in a zero external field ($H=0$) to a certain temperature $T<T_{cr}$, after which the magnetic field was increased at a constant temperature T.

II. The sample was cooled in a zero external magnetic field to a temperature $T'<T_{cr}$, the magnetic field was raised to a certain value H' at the constant temperature $T'<T_{cr}$, after which the temperature was raised at a constant value $H=H'$.

III. The field H was decreased at a constant temperature $T<T_{cr}$ from a value $H''>H_{cr}(T)$, where $H_{cr}(T)$ is the critical magnetic field corresponding to the temperature T.

These three regimes are shown schematically in Fig. 2. It is very important in investigations of type-II superconductors to set exactly the regime of variation of the external parameters, since the strong hysteresis causes pinning.

The experimental $N_{exp}(t)$ dependences of niobium and V_3Ga were described by expression (1), which in this case took the form

$$N(t)=N_0e^{-t/\tau_0}[1-a_0e^{-\sigma_0^2t^2}-a_\perp e^{-\sigma_\perp^2t^2}\cos\omega t]. \quad (4)$$

A Gaussian time dependence was assumed for the relaxation and precession μ^+ signals $P_0(t)$ and $P_\perp(t)$ from comparison with the experiment. The $P_0(t)$ dependence for niobium and V_3Ga is considered in detail in Sec. 5.

The values of the parameters a and σ in V_3Ga and in niobium, as functions of the temperature and of the external magnetic field strength, are shown in Figs. 3–6. Before we proceed to describe the experimental results shown in these figures, we note first one common regularity typical of the relaxation μ^+ signals in both investigated superconductors, namely, that the damping rate σ_0 of the relaxation μ^+ signal is independent of the state of the super conductor and remains constant for all changes of H and T. The constancy of σ_0 is illustrated by Fig. 7, which shows a plot of $\sigma_0(H)$ for the superconducting state of V_3Ga at $T=11.5$ K. It follows from Fig. 3 and 7 that $\sigma_0=0.711$ remains unchanged when a_0 is changed by almost three times. Similarly, the value $\sigma_0=0.471$ for niobium remains constant at all measured values of H and T. This feature of σ_0 or, equivalently,

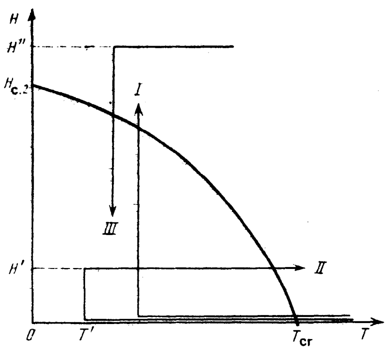

FIG. 2. Schematic representations of regimes I, II, and III of the variation of H and T, used in the present investigation of the superconductors V_3Ga and niobium. The continuous line separates the normal and superconducting states of the metal.

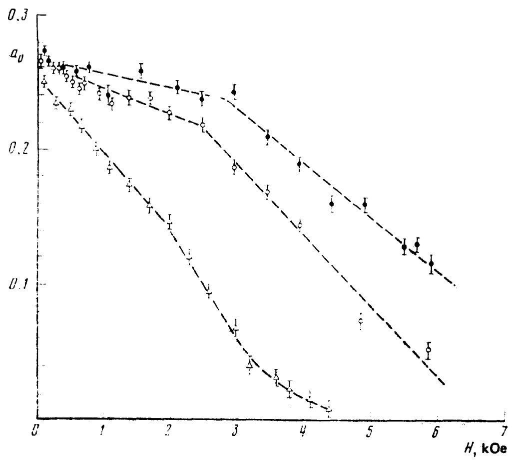

FIG. 3. Amplitude a_0 of the relaxation μ^+ signal in V_3Ga vs. the magnetic field H at $T=11.5$ (•), 12.5 (○) and 13.5 K (△). The data pertain to regime I. The dashed lines are drawn for the sake of clarity.

of the function $P_0(t)$, constitutes experimental proof that the relaxation μ^+ signal indicates the same state at all values of H and T. It is natural to assume that this state is the Meissner phase of the type-II superconductor, and that the amplitude a_0 of the relaxation μ^+ signal is proportional to the volume occupied by this phase at the given values of H and T.

We examine now the experimental results shown in Figs. 3–6. Figure 3 shows plots of $a_0(H)$ in V_3Ga for regime I. As indicated above, the values of a_0 are proportional to the ratio $\alpha=V_M/V$ of the volume of the Meissner phase V_M to the total volume of the sample V. At $H=0$ the Meissner phase occupies the entire volume of the superconductor, i.e., $\alpha=1$. This follows from the equality $a_0(H=0)=a_\perp(T>T_{cr})$, where $a_\perp(T>T_{cr})=0.265\pm0.002$ is the amplitude of the μ^+-meson spin precession in the given V_3Ga sample in the normal state state, i.e., at a temperature $T>T_{cr}$, With increasing field H, the volume of the Meissner phase in the superconducting state of V_3Ga

$$\alpha(H)=a_0(H)/a_0(H=0) \quad (5)$$

decreases, and at a certain value of the field H the Meissner phase vanishes ($\alpha\to0$). It is seen from Fig. 3 that the decrease of the volume of the Meissner phase is faster the higher the temperature. The obtained $a_0(H)$ dependences can be represented, as shown in Fig. 3, in the form of two straight lines with different slopes. We cannot offer any interpretation of this behavior.

Figure 3 shows only the amplitudes a_0 of the relaxation μ^+ signal. The experimentally measured amplitudes $a_\perp$ of the precession μ^+ signal at the values of H and T indicated in Fig. 3 were small, and to measure them reliably it would be necessary to increase substantially the statistical accuracy. A zero or small precession μ^+ signal with decreasing amplitude a_0 shows that the Meissner phase that is expelled with increasing H is replaced by a state with quite inhomogeneous external magnetic fields that lead to a rapid damping of

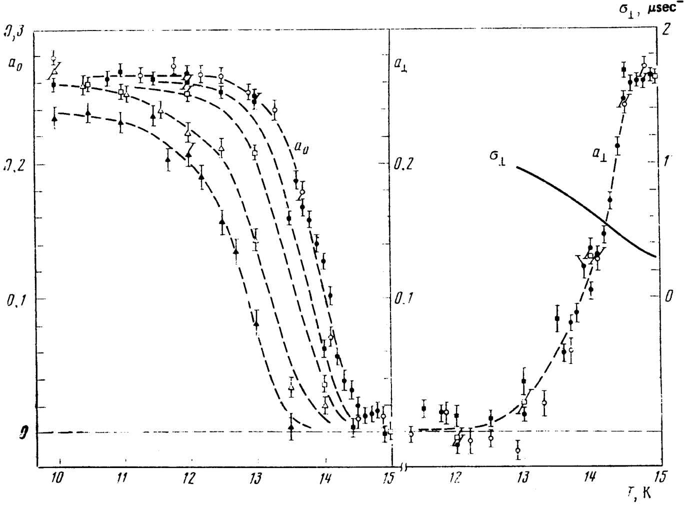

FIG. 4. The parameter a_0 of the relaxation μ^+ signal parameter $a_\perp$ and $\sigma_\perp$ of the precession μ^+ signal vs. the temperature T and external magnetic field strengths $H' = 120$ (●), 250 (○), 500 (■), 900 (□), 3500 (△), and 4500 (▲) Oe. The data pertain to regime II at $T' = 10$ K (see Fig. 2). No precession signal was registered at $H' = 3500$ and 4500 Oe. The experimental plot of $\sigma_\perp(H)$ is the solid curve in the figure. The smooth dashed curves are drawn for clarity.

the precession μ^+ signal. Such a state can be the Shubnikov phase, which penetrates into the superconductor with increasing H because the pinning is overcome. It follows from Fig. 3 that the volume occupied by the Shubnikov phase that penetrates into the superconductor as a given temperature increases with increasing field H. Complete expulsion of the Meissner phase at the investigated temperatures $T = 13.5-11.5$ K takes place in fields H much weaker than the corresponding critical values $H_{cr\,2}(T) = 50-200$ kOe.

Figure 4 shows the temperature dependences of the relaxation and precession μ^+ signals in V_3Ga for regime II at various fields H' and at $T' = 10$ K (see Fig. 3). The values of a_0 and $a_\perp$ shown in Fig. 4 characterize the change of the properties of the superconducting state of V_3Ga on going to the normal state at $T \approx 14.6$ K. It must be emphasized that for all the fields $H' \leqslant 4500$ Oe used in these measurements the temperature of the transition to the normal state was practically the same, since the critical field $H_{cr2} \approx 280$ kOe of V_3Ga is very strong. It is seen from Fig. 4 that the volume of the Meissner phase, which is proportional to the amplitude a_0, decreases with rising temperature. This decrease becomes particularly fast near the temperature T_{cr}. The increase of the field H' also leads to a decrease of a_0.

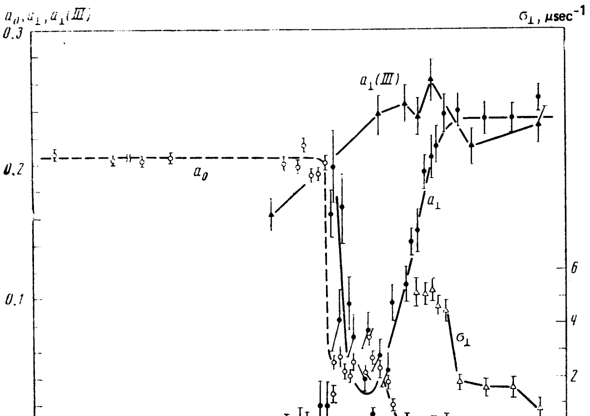

FIG. 5. The parameter a_0 of the relaxation μ^+ signal and the parameters $a_\perp$ and $\sigma_\perp$ of the precession μ^+ signal in niobium vs. the field H at $T = 4.3$ K, obtained in regime I; $a_\perp$ (III) is the amplitude of the precession signal in regime III in a field $H'' = 4800$ Oe and at $T = 4.3$ K (see Fig. 2). The continuous lines and the lines joining the experimental points are shown for clarity.

The amplitude $a_\perp$ of the precession signal at $T \leqslant 13$ K is close to zero and increases sharply near T_{cr}. It is difficult to offer an unambiguous interpretation of this increase, since the precession of the μ^+ meson near the point of transition into the normal state can be observed both when normal-phase sections are produced and in the mixed state, when the magnetic fields of the individual filaments begin to overlap significantly. The damping rate $\sigma_\perp$ of the precession signal increases with

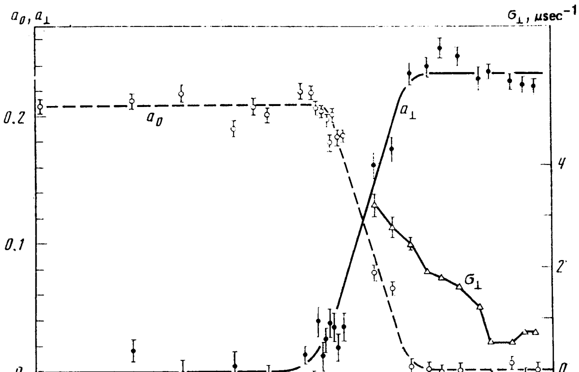

FIG. 6. The parameters of the relaxation (a_0) and precession ($a_\perp$ and $\sigma_\perp$) μ^+ signal vs. the field $H = 7.6$ K, obtained in regime I. The smooth curves are drawn for clarity.

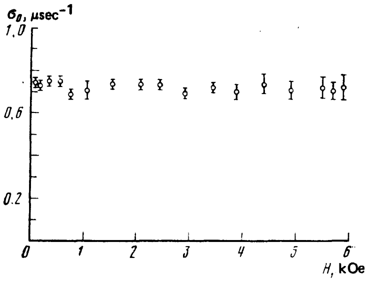

FIG. 7. Damping rate σ_0 of the relaxation μ^+ signal in V_3Ga at $T=11.5$ K for different values of the exeternal magnetic field H.

decreasing temperature, and this corresponds to an increase of the inhomogeneity of the magnetic field B_μ in the metal.

Figure 5 shows the parameters of the precession and relaxation μ^+ signals in niobium as functions of the field H at a constant temperature $T=4.3$ K for regime I. It shows also the function $a_\perp(H)$, measured in less detail, for the regime III at $T=4.3$ K. Figure 5 does not show a plot of $\sigma_\perp(H)$ for regime III. The value of $\sigma_\perp(\mathrm{III})$ increases monotonically with decreasing field H and reaches a value $\sigma_\perp(\mathrm{III})=4.2\pm0.3$ μsec^{-1} at $H=2800$ Oe.

We consider first the regime I and compare the obtained experimental results for niobium and V_3Ga. It is seen from Fig. 5 that in niobium, just as in V_3Ga, a large relaxation μ^+ signal is observed. The plots of $a_0(H)$, however, differ greatly for niobium and V_3Ga. The amplitude a_0 in niobium remains constant when the field is increased to $H=3200$ Oe, and is only slightly lower than the possible maximum value $a_0^{max}=a_\perp(T>T_{cr})$ $=0.232\pm0.005$. The decrease of $a_\perp(T>T_{cr})$ in niobium compared with V_3Ga is due to the relatively large background in the experiments with niobium. At $H>3200$ Oe there is a very strong decrease of a_0, accompanied by the appearance of a precession μ^+ signal. The $a_0(H)$ dependence observed in niobium means that in this metal the coexistence of the two phases, Meissner and Shubnikov, is unstable, in contrast to V_3Ga, where the two phases coexist in a wide range of fields H.

The interpretation of the precession μ^+ signal in niobium near the point of transition to the normal state encounters the same problem as in V_2Ge, namely the difficulty of distinguishing the formation of a mixed state with overlapping filaments from the formation of sections of a normal phase. The nonmonotonicity of the amplitude $a_\perp(H)$ of the μ^+-meson precession in niobium indicates that both processes are important. The $\sigma_\perp(H)$ dependence for niobium shows a systematic increase of the damping rate of the precession signal with decreasing magnetic field strength.

We consider finally the $a_\perp(H)$ dependence shown in Fig. 5, for regime III i.e., for a field H that decreases from a value $H''>H_{cr}$. In these measurements a value $H''=4800$ Oe was assumed, corresponding at $T=4.3$ K, as seen from Fig. 5, to the normal state of the metal. It is seen from Fig. 5 that this $a_\perp(H)$ dependence differs greatly from that obtained in regime I. The irreversibility of the rise and fall of the field H at equal temperature shows that the investigated niobium sample is subject to hysteresis and consequently that the pinning in it is strong. It is interesting to note that there is no relaxation μ^+ signal at all field values $H>2800$ Oe investigated in regime III.

Figure 6 shows the parameters of the μ^+ signals in niobium for regime I at $T=7.6$ K, plotted against the field H. It follows from this figure that, just as at $T=4.3$ K, the amplitude a_0 remains constant in a wide range of H, but its decrease near the point of transition to the normal phase is less abrupt and is accompanied by an increase of the amplitude $a_\perp$. Figure 6 shows also the change of the damping rate $\sigma_\perp$ of the precession μ^+ signal with changing field H.

5. DAMPING OF RELAXATION μ^+ SIGNAL IN NIOBIUM AND IN V_3Ga

As indicated in Sec. 4, the damping rates σ_0 of the relaxation μ^+ signals in niobium and V_3Ga do not depend on H or T. Figure 7 illustrates this with one cycle of V_3Ga measurements as an example. The constancy of σ_0 allows us to sum the time dependences $N(t)=N_0e^{-t/\tau_0}[1-a_0P_0(t)]$ of the relaxation μ^+ signals for different values of H and T and obtain an experimental expression for $P_0(t)$ with high statistic confidence. The precession μ^+ signal can be eliminated practically completely by performing the measurements in a strong alternating magnetic field and averaging them over a sufficiently long time interval. In our case we summed the $N(t)$ dependences at $H>1500$ Oe, and the width of the time interval was taken to be $\Delta t=0.2$ μsec. Figures 8 and 9 show the resultant $P_0(t)$ dependences for niobium and V_3Ga. It is seen from these figures that the $P_0(t)$ dependences in niobium and V_3Ga are of nearly Gaussian form $P_0(t)=e^{-\sigma_0^2t^2}$ with $\sigma_0(\mathrm{Nb})=0.471\pm0.002$ μsec^{-1} and $\sigma_0(V_3Ga)=0.711\pm0.007$ μsec^{-1}.

The $P_0(t)$ dependence, which describes the relaxation of the μ^+-meson spin in the metal, is of interest not only in the study of superconductivity but also for the investigation of the dilatation of the crystal lattice by a singly charged impurity particle,[16] magnetic dipole interac-

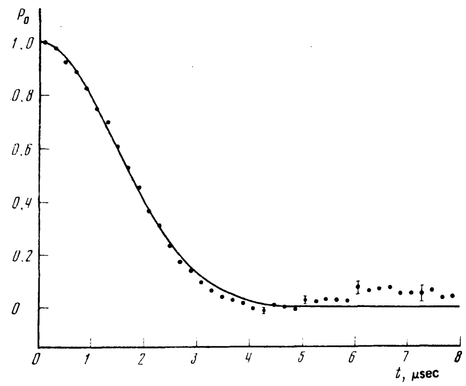

FIG. 8. Plot of the polarization $P_0(t)$ of the μ^+ mesons in niobium, obtained by summing 30 distributions $N(t)$ for relaxation μ^+ signals at different values of H and T. The errors are statistical, and for the values of $P_0(t)$ at $t<3$ μsec they do not exceed the size of the points. The smooth curve is the Gaussian function $P_0(t)=e^{-\sigma_0^2t^2}$ at $\sigma_0=0.471\pm0.002$ μsec^{-1}.

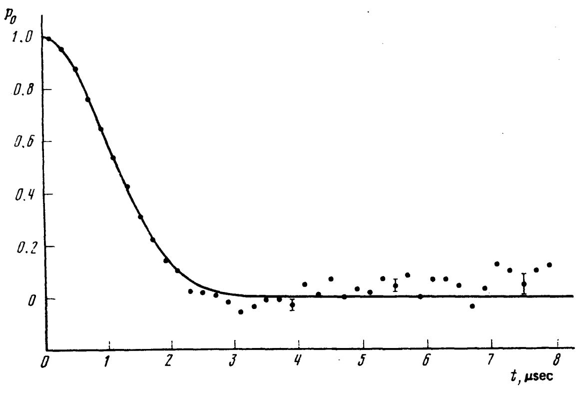

FIG. 9. Plot of $P_0(t)$ in V_3Ga, obtained by summing 20 $N(t)$ distributions for the relaxation μ^+ singals at different values of H and T. The smooth curve is the Gaussian function $P_0(t) = e^{-\sigma_0^2 t^2}$ at $\sigma_0 = 0.711 \pm 0.007\ \mu\text{sec}^{-1}$.

tions,[17] and the diffusion[17,18] of the μ^+ meson. The experimental $P_0(t)$ of niobium and V_3Ga, shown in Figs. 8 and 9, were obtained with the metal in the superconducting state and in a strong transverse magnetic field. Measurement of $P_0(t)$ under such conditions offers an important methodological advantage in that the background of the cryostat, which comprises in this case part of the precession μ^+ signal, can be completely separated.

The experimental $P_0(t)$ plots obtained for niobium and V_3Ga can be compared with the predictions of the theory[19] that describes the relaxation of the particle spin in time-constant local magnetic fields. According to this theory $P_0(t)$ is Gaussian only at small t. With increasing t the polarization P_0 first decreases almost to zero at $t \approx 2/\sigma_0$, and at $t \approx 3.5/\sigma_0$ it reaches practically its asymptotic limit $P_0(t \to \infty) = \frac{1}{3}$. The experimental time dependences of the polarization, shown in Figs. 8 and 9, do not agree with this form of $P_0(t)$. This contradiction means that the local nuclear magnetic fields in niobium and V_3Ga can not be regarded as constant during the relaxation of the μ^+-meson spin. Some increase of the polarization P_0, observed in niobium and V_3Ga at $t > 4$ μsec (see Figs. 8 and 9) can be qualitatively explained[19] by assuming that the correlation time τ that characterizes the rate of change of the local magnetic fields at the μ^+ meson in this metals is approximately $\tau \approx 2.7/\sigma_0$, i.e., $\tau(\text{Nb}) \sim 6\ \mu$sec and $\tau(V_3Ga) \sim 4\ \mu$sec. It is interesting that the time dependence of the μ^+-meson spin relaxation in MnSi is in agreement[17] with the model of the constant local magnetic fields.

The experimental results of our study show that the muon technique permits effective investigation of the superconducting state. Using lead as the example, we have shown that the technique is effective in the study of the intermediate state, in which the magnitude and degree of homogeneity of the magnetic field were measured in the normal regions inside the metal. The muon technique was used to measure the volume of the Meissner phase in type-II superconductors (niobium, V_3Ga) as a function of the temperature and of the external magnetic field intensity, as well as the penetration of the external magnetic fields into a superconductor near the point of transition into the normal state. It is important to perform similar measurements on a sufficiently large number of superconductors and to compare the results of the muon analysis with data obtained by other methods.

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