Study of the magnetic structure of the superconducting state of Nb_3Al by a muon method

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A muon method has been used to measure the critical temperature $T_c^\mu = 17.4 \pm 0.05$ K and the distribution of the internal magnetic fields in the mixed state of Nb_3Al in external magnetic fields $H_0 = 62$ Oe and $H_0 = 285$ Oe over the temperature interval $T = 9$–17 K.

The properties of superconductors can be studied effectively by a muon method.[1–4] The muon method is particularly convenient for studying the properties of type II superconductors, since it allows measurement of the distribution of the internal magnetic fields in a mixed state.

We have now used the muon method to study the magnetic structure of the mixed state of the alloy Nb_3Al in experiments carried out at the synchrocyclotron of the Leningrad Institute of Nuclear Physics at Gatchina. The polycrystalline Nb_3Al sample was produced by electric-arc melting in an argon atmosphere. Chemical analysis of the alloy revealed the composition to be nearly stoichiometric: 75.4 at.% niobium and 24.6 at.% aluminum.

The superconducting properties of the alloy are studied by measuring the specific heat[5] over the temperature range $T = 4.5$–30 K in an external magnetic field $H_0 = 0$–8 T. The average critical temperatures found by this method are $T_c = 17.3$ K at $H_0 = 0$ and $T_c = 14.4$ K at $H_0 = 8$ T. The total width of the superconducting phase transition is $\delta T_c = 0.6$ K. From the difference between the specific heats in the normal and superconducting states we find the value of the parameter κ of the Ginzburg-Landau theory; over the temperature range $T = 14.4$–17.3 K it turns out to be $\kappa = 42$. The temperature dependence $c(T)$ found for the specific heat of Nb_3Al at $H_0 = 0$ agrees well with the data reported by other investigators.[6,7] It follows from the measured dependence $c(T)$ that this alloy is homogeneous in terms of superconducting properties, and, within $\sim 20\%$, it contains no other superconducting or normal phases.

The Nb_3Al test sample is a disk 80 cm in diameter and 10 mm thick. The external magnetic field H_0 is directed parallel to the plane of the disk and perpendicular to the direction of the beam of longitudinally polarized muons. The external magnetic fields in these experiments are $H_0 = 62$ Oe and $H_0 = 285$ Oe. The transition from the normal state to the superconducting state occurs at a constant value of the field H_0, which is also held constant as the temperature is reduced further. The sample temperature is measured within $\Delta T \simeq 0.05$ K by germanium thermometers.

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In the experiments we measure the time dependence

$$N(t) = N_0 e^{-t/\tau_0}[\,1 + aP(t)\cos\omega t\,] + A \tag{1}$$

of the number of positrons from the decay $\mu^+ \to e^+$ which are emitted along the direction of the initial polarization of the muons. Here τ_0 is the muon lifetime, a is the measured asymmetry of the angular distribution of decay positrons, $\omega = \gamma\bar{B}$ is the precession frequency of the muon spin, $\bar{B}$ is the average magnetic field B at the muon, γ is the gyromagnetic ratio for the muon, and A is the background. The function $P(t)$ describes the relaxation of the muon spin due to the nonuniformity of the field B. To find a common description of the time dependence (1) over the entire temperature range studied, $T = 9$–23 K, we assume that $P(t)$ is Gaussian:

$$P(t) = e^{-\Lambda^2 t^2}\,. \tag{2}$$

A Gaussian $P(t)$ agrees with experiment. Expression (1) does not include the background of muons which are stopped in the wall of the cryostat and which precess at the frequency corresponding to the external magnetic field. This background amounts to 15% of the total number of $\mu^+ \to e^+$ decay events detected, and it is subtracted from the experimental results $N_{\rm expt}(t)$ during the analysis of the data.

It follows from expressions (1) and (2) that the quantities measured directly in this experiment are the average field $\bar{B}$, the relaxation rate (Λ) of the muon spin, and the asymmetry coefficient a. Figures 1 and 2 show the temperature dependence of $\bar{B}(T)$ and $\Lambda(T)$.

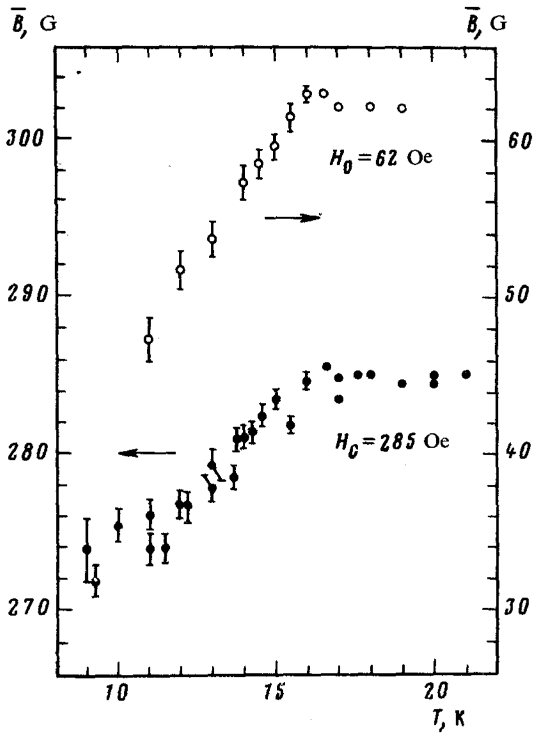

FIG. 1. Temperature dependence $\bar{B}(T)$ of the average magnetic field at the muon in Nb_3Al in external magnetic fields $H_0 = 62$ Oe and $H_0 = 285$ Oe.

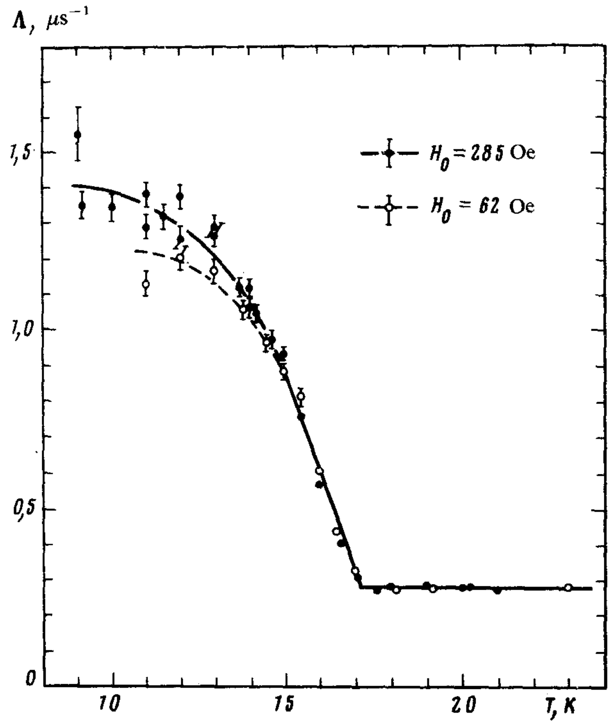

FIG. 2. Temperature dependence $\Lambda(T)$ of the relaxation rate of the muon spin in Nb_3Al in fields $H_0 = 62$ Oe and $H_0 = 285$ Oe. The solid lines are drawn to aid the eye.

It can be seen from Fig. 1 that at $T < T_c$ the field $\bar{B}$ decreases monotonically with decreasing temperatures. This behavior of $\bar{B}$ corresponds to a partial displacement of the magnetic flux from the superconductor at low temperatures. The decrease in $\bar{B}$ as the Nb_3Al is cooled from $T > T_c$ to $T = 10$ K is approximately the same for $H_0 = 62$ Oe and $H_0 = 285$ Oe: $\simeq 13$ G. We cannot offer a theoretical interpretation of this behavior. The asymmetry coefficient $a = 0.273 \pm 0.003$ remains constant over the entire temperature range studied, $T = 9$–23 K; i.e., it does not change at $T < T_c$. The fact that the coefficient a remains constant indicates that there are no unobserved processes involving a relaxation of the muon spin.

Figure 2 shows the experimental results on $\Lambda(T)$. The horizontal part of the $\Lambda(T)$ curve at $T > T_c$ in Fig. 2 corresponds to the value $\Lambda_d = 0.275 \pm 0.002\ \mu s^{-1}$, which determines the rate of the relaxation of the muon spin due to dipole interactions of the magnetic moments of the muon and of the surrounding niobium and aluminum nuclei. The good agreement with the experimental Gaussian dependence in (2) at $T > T_c$ indicates that there is no diffusion of muons over the measured temperature interval $T < 23$ K.

It can be seen from Fig. 2 that at $T < T_c$ the quantity Λ increases with decreasing temperature. The increase in Λ at $T < T_c$ results from a nonuniformity of the field B in the filaments of the Nb_3Al mixed state. At $T \lesssim 14$ K, the rate of increase of Λ falls off with a further decrease in the temperature. An experimental determination of the dipole relaxation rate Λ_d makes it possible to eliminate the effects of dipole interactions in Nb_3Al at $T < T_c$ and to find a function $P_n(t)$ which describes the muon depolarization caused exclusively by the nonuniformity of the magnetic field B_n in the filaments of the mixed state. For a Gaussian $P(t)$ as in (2), the function $P_n(t)$ is also Gaussian:

$$P_n(t) = e^{-(\Lambda^2 - \Lambda_d^2)t^2}.$$

The quantity $\sigma^2 = (\Lambda^2 - \Delta_d^2)$ is proportional to the variance $(\delta B_n)^2$ of the distribution

$$W(B_n) = Ce^{-(\bar{B} - B_n)^2/2(\delta B_n)^2} \tag{3}$$

of the magnetic field B_n in the filaments:

$$(\delta \bar{B}_n)^2 = 2\left(\frac{\sigma}{\gamma}\right)^2 .$$

Figure 3 shows the temperature dependence $\delta B_n(T)$. We see that the degree of nonuniformity of the magnetic field in the filaments of the Nb_3Al mixed state increases with decreasing temperature, reaching $\delta B_n = 23$ G at $T = 10$ K in a field $H_0 = 285$ Oe and only a slightly lower value, $\delta B_n = 20$ G, in a field $H_0 = 62$ Oe. Similar values of δB_n have been found[8] by an NMR method in V_3Ga and V_3Si.

We see from Fig. 3 that the temperature dependence $\delta B_n(T)$ can be approximated well in the interval $T = 15.5$–17.0 K by a straight line, which determines the critical temperature of Nb_3Al in the limit $\delta B_n \to 0$: $T_c^\mu = 17.41 \pm 0.05$ K. The indicated error in T_c^μ is the accuracy of the calibration of the germanium thermometers used to determine the sample temperature. The statistical error of the determination of T_c^μ by

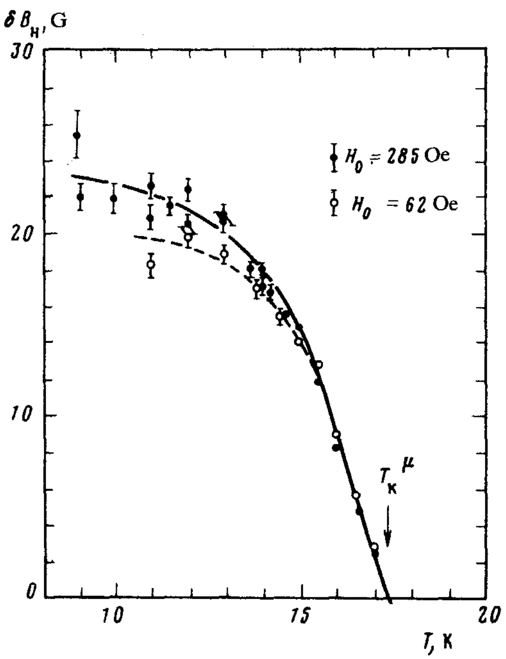

FIG. 3. The temperature dependence $\delta B_n(T)$ of the degree of nonuniformity of the internal magnetic fields in the mixed state of Nb_3Al. Here T_c^μ is the critical temperature. The solid curves are drawn to aid the eye.

the method described above is $(\Delta T_c^{\mu})_{stat} = 0.02$ K. This value of T_c^{μ}, the critical temperature found by the muon method, agrees with the temperature $T_c = 17.3 \pm 0.3$ K given above, which is found by measurements of the specific heat.

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[1]V. G. Grebinnik, I. I. Gurevich, V. A. Zhurkov, *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **29**, 82 (1979) [JETP Lett. **29**, 75 (1979)].
[2]M. Gladisch, D. Herlag, H. Metz, *et al.*, Hyperfine Interact. **6**, 109 (1979).
[3]V. G. Grebinnik, I. I. Gurevich, V. A. Zhukov, *et al.*, Zh. Eksp. Teor. Fiz. **79**, 518 (1980) [Sov. Phys. JETP **52**, 261 (1980)].
[4]F. N. Gygax, A. Hintermann, H. R. Ott, *et al.*, Hyperfine Interact. **8**, 623 (1981).
[5]M. N. Khlopkin, N. A. Chernoplekov, and P. A. Cheremnykh, Preprint IAÉ-3549/10, I. V. Kurchatov Institute of Atomic Energy, Moscow, 1982.
[6]R. H. Willens, T. H. Geballe, and A. C. Gossard, Solid State Comun. **7**, 837 (1969).
[7]A. Junod, J. L. Staudenmann, J. Muller, *et al.*, J. Low Temp. Phys. **5**, 25 (1971).
[8]P. Pincus, A. C. Gossard, and V. Jaccarino, Phys. Lett. **23**, 21 (1964).

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