Measurement by the μ^+-meson method of the internal magnetic field in superconducting lead

V. G. Grebinnik, I. I. Gurevich, V. A. Zhukov, L. A. Levina, A. B. Lazarev, V. N. Maĭorov, A. P. Manych, B. A. Nikol'skiĭ, V. I. Selivanov, and V. A. Suetin
I. V. Kurchatov Institute of Atomic Energy

(Submitted 2 December 1978)

Pis'ma Zh. Eksp. Teor. Fiz. **29**, No. 1, 82–85 (5 January 1979)

The magnetic field was measured by μ^+-mesons in a superconducting lead ellipsoid at $T = 4.3$K. It is shown that in the intermediate superconducting state the internal magnetic fields in the normal region of the sample are independent of the external magnetic field and equal the critical field $H_c(T)$.

PACS numbers: 74.30.Ci, 74.70.Gj

The observation of precession of the spin of the μ^+-meson in superconductors represents a new method of investigating the superconducting state of metals. This method can determine internal magnetic fields in superconductors of the first and second kinds and also certain parameters that characterize the superconducting state.[1-3] In this work the magnetic fields are studied in a superconductor of the first kind—lead—as a function of the external magnetic field. The work was performed on the Joint Institute for Nuclear Research synchrocyclotron.

An external magnetic field H partially penetrates a superconductor of the first kind in the so-called intermediate state when $H_1 \leqslant H \leqslant H_c$, where $H_1 = H_c(1 - D)$, H_c is the critical magnetic field, and D is the coefficient of demagnetization of the sample. In the intermediate state the entire volume of the superconductor divides into small normal and superconducting regions. Presumably in the normal regions the magnetic

 0021-3640/79/010075-04$00.60

field $B = H_c$, and in the superconducting ones $B = 0$. The relative volume η of the normal regions increases linearly with increasing external field:

$$\eta = \frac{H - H_1}{DH_c} \,. \qquad (1)$$

The formation of such an intermediate state was theoretically postulated in older work[4,5] and was discovered experimentally on the surface of a superconductor with the aid of miniature bismuth probes[6,7] and the method of powder decoration.[8,9]

With the help of μ^+-mesons it is possible to measure with high accuracy magnetic fields in normal regions of the intermediate state inside metals. In this work magnetic fields in the intermediate state of lead were measured by the μ^+-method.

The specimen of lead in question is a flat ellipsoid with a diameter of curvature of 60-mm and thickness of 15-mm, with a major axis which was in the direction parallel to the external field. The experiment was carried our at a temperature $T = (4.3 \pm 0.1)$ K. A normalized error δT represents the accuracy of specimen temperature measurement. The intensity of the external magnetic field varies through a range of $H = 200$–700 Oe. Associated with the temperature $T = (4.3 \pm 0.1)$ K was a critical field H_c nearly equal to $H_c(0)\ [1 - (T/T_c)^2] = (521 \pm 12)$ Oe, where $H_c(0) = 808$ Oe is the critical field of lead for $T = 0$, and $T_c = 7.2$ K is the critical temperature. The experimental ellipsoid gave a demagnetization factor $D = 0.15$ and, therefore, field $H_1 = H_c(1 - D) = 442 \pm 10$ Oe.

The spin precession of the μ^+-mesons stopped in lead is described by the formula

$$N(t) = N_0 e^{-t/\tau}\,[1 - a e^{-\Lambda t} \cos \omega t\,] \,. \qquad (2)$$

Here $\tau = 2.2 \times 10^{-6}$ sec is the lifetime of the μ^+-meson; a is the experimental coefficient of the asymmetric angular distribution of the positron decay $\mu^+ \to e^+$; Λ is the rate of relaxation of the μ^+-meson spins; $\omega = (e/mc)B_\mu$ is the Larmor frequency of μ^+-meson spin precession in field B_μ. Parameters N_0, a, Λ, and ω were determined by the method of maximum probability when comparing Eq. (2) and the experimental functions $N_{\exp}(t)$. Derived in this way the parameters a and ω for various values of H permit determination of the experimental functions $\eta(H)$ and $B_\mu(H)$. The relative size η of the normal phase is determined from the ratio $\eta = a/a_{\max}$, where $a_{\max}$ is the value of coefficient a for $H > H_c$, i.e., with the substance in the normal state. The magnetic field B_μ is determined by the spin precession frequency of the μ^+-meson $\omega = (e/mc)\,B_\mu$, where m is the mass of the μ^+-meson.

The experimental functions $\eta(H)$ and $B_\mu(H)$ for lead are shown in the Fig. 1. It can be seen that for $H > H_c$, i.e., with samples in the normal state, the field B_μ on the μ^+-mesons equals the external field H. In the intermediate state $H_1 \leqslant H \leqslant H_c$; the field of the normal regions $B_\mu = H_c$ and is independent of H. It is significant to note that field B_μ in the normal regions of the intermediate state is practically uniform. Inhomogeneity of field B_μ is characterized by Λ (see Ref. 1), which was $\leqslant 0.2\ \mu\text{sec}^{-1}$ in the experiments. The resultant degree of inhomogeneity of the B_μ component is $\delta B_\mu / B_\mu \lesssim 1\%$.

The experimental function $\eta(H)$ in the intermediate state is nearly linear and is

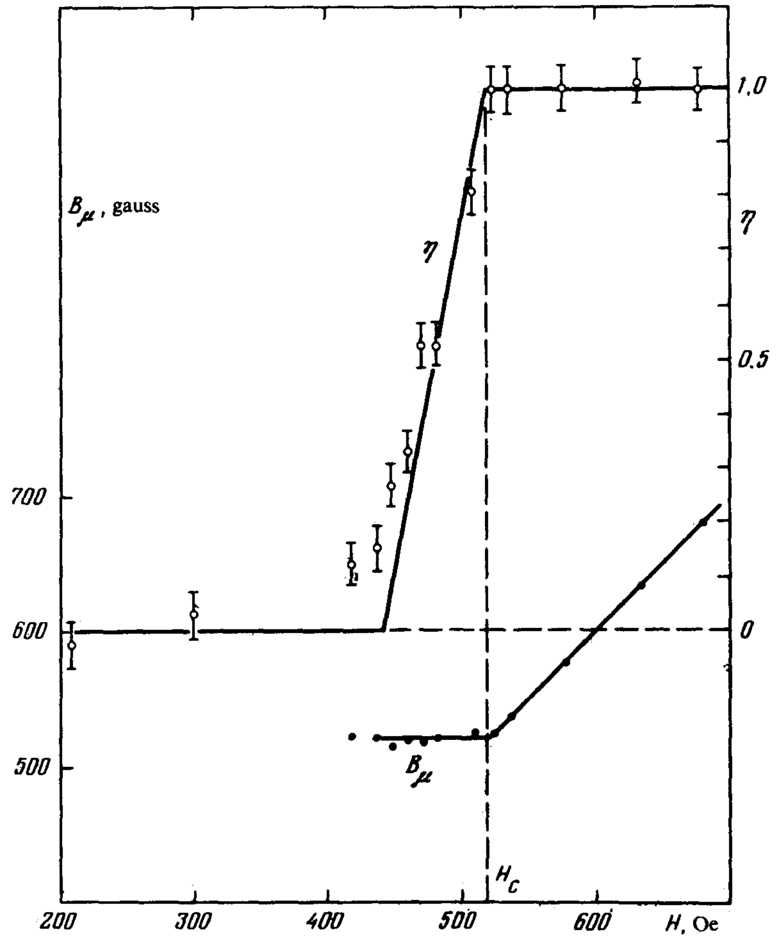

FIG. 1. Experimental functions $\eta(H)$ and $B_\mu(H)$ in lead for $T = 4.3$ K. Continuous lines represent the fit of theoretical functions to data on samples for $H_c = 520$ Oe:

satisfactorily described by the theoretical expression (1) for $H_c = 520$ Oe. Some variation of the experimental values of η from the linear function (1) for fields $H \approx H_1$, is explained by possible small deviations from a strictly ellipsoidal form. For $H < H_c$, $\eta = 0$. This is necessarily true, because for such fields the normal phase in superconductors of the first type is absent.

The authors are grateful to V.P. Dzhelepov for extending the use for this work of the sychrocyclotron at JINR, and A.V. Pirogov, A.N. Ponomarev, and V.S. Roganov for assistance with the work.

[1]D.E. Murnic, Physica Scripta **11**, 140 (1975).
[2]V.G. Grebinnik, I.I. Gurevich, V.A. Zhukov, A.B. Lazarev, L.A. Levina, V.N. Maĭorov, A.P. Manych, E.V. Mel'nikov, B.A. Nikol'skiĭ, V.S. Roganov, V.I. Selivanov, and V.A. Suetin, Pis'ma Zh. Eksp. Teor. Fiz. **28**, 397 (1978) [JETP Lett. 28, 367 (1978)].

[3]M. Gladisch, D. Herlach, H. Mets, H. Orth, G. Zn. Putlitz, A. Seeger, H. Teichler, W. Wahl, and M. Wigand, Report on the First International Scientific Conference on μSR Methods, Rorschah, Switzerland, September, 1978.
[4]R. Peierls, Proc. Roy. Soc. **A155**, 613 (1936).
[5]F. London, Physica **3**, 450 (1936); L.D. Landau, Zh. Eksp. Teor. Fiz. **7**, 371 (1937).
[6]A.G. Meshkovskiĭ and A.I. Shal'nikov, Zh. Eksp. Teor. Fiz. **17**, 851 (1947).
[7]B.G. Silbernagel, M. Weger, and I.H. Wermick, Phys. Rev. Lett. **17**, 384 (1966).
[8]T.E. Faber, Proc. Roy. Soc. **A248**, 460 (1958); A.I. Shal'nikov, and K.A. Tumanov, Collected Papers Commemorating the 70th Year of Academician A.F. Ioffe, USSR Academy of Science, 303 (1950); B.M. Balashova and Yu. V. Sharvin, Zh. Eksp. Teor. Fiz. **31**, 40 (1956).
[9]R.W. Shaw and D.E. Mapother, Phys. Rev. **118**, 1474 (1960).