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EXPERIMENTAL INVESTIGATION OF A SUPERCONDUCTING Nb—Zr ALLOY AT 9250 Mc[1]

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Results of an investigation of a superconducting Nb—Zr alloy at 9250 Mc are presented. An anomalously large shift is observed in the frequency of the sample-containing cavity in an external magnetic field; hysteresis and gradual assumption of its maximal value by the frequency shift after several remagnetization cycles are also observed. These phenomena are apparently due to a change in the surface structure of the superconductor.

An experimental study of the behavior of superconductors in high-frequency magnetic fields makes it possible to determine the penetration depth in a superconductor from the change in resonant frequency of a cavity with the sample during a transition from the superconducting to the normal state [1-3]. The study of superconductors with large critical parameters (T_c and H_c), with the aim of clarifying the surface structure of superconductors, has definite interest.

This work was devoted to measurement of the change in the resonant frequency of a superconducting Nb—Zr sample (60% and 40% by weight) as a function of the external magnetic field.

The Nb—Zr alloy was made by melting without a crucible in an electromagnetic field. Preliminary experiments with the initial alloy and with a plate rolled from this alloy have shown that a constant magnetic field does not penetrate into the sample to a noticeable degree, right up to fields of 30,000 Oe. The testing procedure based on the change of inductance of a coil and sample is analogous to that described by Shoenberg [4].

This same sample, in the form of a plate having dimensions 22 × 9 × 0.75 mm, was measured in high-frequency experiments. The cavity was a length of waveguide with a cross section 10 × 23 mm, silver plated inside. The H_{102} mode was used; tuning was with contactless piston on which the sample was mounted.

The Q of the cavity and sample was about 5000 at room temperature. The cavity and sample were placed between poles of an electromagnet so that the field direction was parallel to the plane of the plate and perpendicular to the magnetic vector of the microwave field. The measurements were carried out at 9250 Mc and 4.2° K.

The measuring circuits consisted of a klystron connected through decoupling and matching elements to the cavity. The circuit contained directional couplers, of which one made it possible to display an oscillogram of the resonance curve, and the other was connected to a 44-I wavemeter. The klystron was modulated at a frequency of 1000 cps.

The results, presented in Fig. 1, show the change in the frequency of the cavity and sample as a function of the magnetic field when the sample was cooled to 4.2° K in zero field. (The precision of the measurement of the shift in resonant frequency is 0.2 Mc.) The value and direction of the external magnetic field are shown on the abscissa.

In Fig. 1, curve 1 gives the change in frequency during the initial increase of field from 0 to 4000 Oe. The second and subsequent variations of the field in this same direction from 0 to 4000 Oe give an appreciably smaller frequency change (curve 2).

If the direction of the magnetic field is reversed and its intensity increased from 0 to 4000 Oe, then the frequency of the cavity and sam-

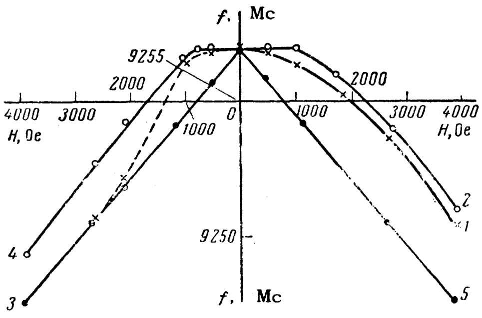

FIG. 1. Dependence of the frequency shift of the cavity with sample on the external magnetic field when the sample is cooled to 4.2° K in zero field.

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ple decreases according to curve 3 of Fig. 1. The dashed curve gives the shift in frequency for a decreasing field. Repeated variation of the field in this same direction leads to an appreciably smaller frequency shift (curve 4).

If one returns to the initial field direction, then the frequency shift will again be significantly greater than in the very first test run (curve 5).

It should be indicated that with an unchanged orientation of the sample relative to the magnetic field, the results of the experiments were repeated with great precision both in repeated cycles of measurement and from experiment to experiment. If the cavity together with the sample are turned so that the direction of the external magnetic field makes a certain angle with the plane of the sample, then at any angle (up to 5°) the character of the frequency shift as a function of magnetic field will be the same as in the curves of Figs. 1 and 2, i.e., hysteresis phenomena are observed, and a successive approach to a final value of the frequency shift. However, the magnitude of the shift, in a given field and under substantially the same conditions, depends on the angle of rotation. The form of this dependence was not established.

Figure 2 shows the results of experiments where the sample was cooled to 4.2°K in the presence of an external magnetic field of 4000 Oe.

Curve 1 of Fig. 2 shows practically no frequency shift (precision ± 0.2 Mc) when the field is decreased to zero. A repeated increase of field in this same direction (curves 2—5 coincide; the numbering of the curves in Figs. 1 and 2 signifies the order in which the magnetization of the sample was carried out) did not give an observable frequency change in a magnetic field. A magnetic field in the other direction changes the resonant frequency according to curve 6 but a return to the initial field direction (curve 7) gives a frequency variation already differing from curves 2–5.

Summarizing the results, one should notice, first, the very large frequency shift of the cavity with sample in an external magnetic field, which, of course, cannot be attributed only to a change in the penetration depth; second, the hysteresis phenomena connected with the change in field direction; and third, the successive approach to the ultimate value of the frequency shift (curve 5 of Fig. 1).

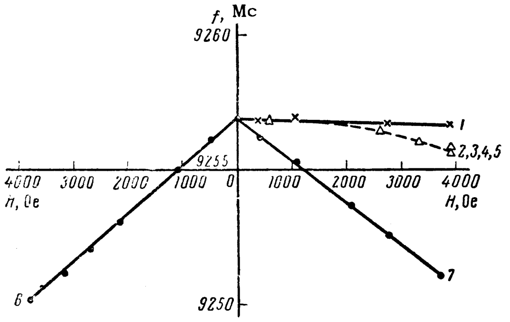

FIG. 2. Dependence of the frequency shift of the cavity with sample on the external magnetic field when the sample is cooled to 4.2° K in a field of 4000 Oe.

Control experiments with plates of the original materials showed that the frequency shift, for example in the case of Nb, did not exceed 0.4 Mc.

It was also established that all the indicated phenomena involving the dependence of the frequency of the cavity with sample on the external field disappear as soon as the temperature of the sample exceeds the critical temperature, i.e., when the sample goes into the normal state. These experiments definitely show that the above-mentioned phenomena cannot be ascribed to the presence of any magnetic impurities.

For a qualitative explanation of the observed phenomena it is natural to assume the presence of normal regions or regions with low critical field in a metal which does not have "ideal" superconductivity [5]. Such regions can increase in size along the surface with increasing external magnetic field. The observed hysteresis phenomena may cause the "frozen-in fluxes" in multiply-connected regions, observed during the variation of the field.

However, the order of magnitude of the frequency change (about 10 Mc) indicates that in zero field the overwhelming part of the surface of the metal under investigation is in the superconducting state. The notions regarding the presence of normal regions may be insufficient to explain why the resonant frequency in an external 4000 Oe field when the sample is cooled in the field differs from that when the sample is cooled in zero field and the field is then increased to 4000 Oe. The reasons for the gradual approach to the ultimate frequency shift after several cycles of magnetization are also unclear.

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[1] M. S. Khaĭkin, DAN SSSR **86**, 517 (1952); JETP **34**, 1389 (1958), Soviet Phys. JETP **7**, 961 (1958).

[2] A. B. Pippard, Proc. Roy. Soc. **A191**, 399 (1947); Proc. Roy. Soc. **A203**, 210 (1950).

[3] I. Simon, Phys. Rev. **77**, 384 (1950).

[4] D. Shoenberg, Proc. Cambr. Phil. Soc. **33**, 559 (1937).

[5] K. Mendelssohn, Proc. Roy. Soc. **A152**, 34 (1935).

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