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LOCAL MAGNETIC FIELDS ON THE SURFACES OF Nb-Zr *SUPERCONDUCTORS IN THE MIXED STATE*

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The results are presented of the measurements of local magnetic fields on the surfaces of Nb-Zr (60—40 wt.%) superconductors subjected to an external magnetic field of ≈ 3000 Oe. The experiments showed that the value of the local field depended considerably on the magnetization conditions in the superconductor. The local field is evidently the field of the currents induced in the superconductor by a varying external magnetic field.

IN 1962—63, it was discovered[1,2] that the absorption of microwave energy in a Nb-Zr superconductor exhibits, in the presence of an external magnetic field, a number of features which are characteristic only of the superconducting state. It was pointed out that these features were evidently associated with the magnetic properties of the superconductor surface.

In the present paper we report the results of an investigation of the local magnetic field on the surface of a Nb-Zr superconductor in the mixed state, i.e., in an external magnetic field whose value was between H_{c1} and H_{c2}.[3] To measure the local field, we used the position of the electron paramagnetic resonance (EPR) line of diphenyl picryl hydrazyl (DPPH), relative to the external magnetic field magnetizing the superconductor.[4] As is known, the EPR signal is observed in a magnetic field, whose value is constant for a given paramagnet, at a definite microwave frequency. This field is known as the resonance field. Usually, the resonance value of the field is equal to the applied external field. However, if a grain of DPPH is placed on the surface of a superconductor, the applied external field needed to produce the EPR signal differs from the resonance field by the value of the local field at the given point on the superconductor surface.[4] By measuring the applied external field and subtracting from it the resonance field (having determined it, in particular, above the temperature of the transition of Nb-Zr to the superconducting state), we can determine $H_{loc} = H_{ext} - H_{res}$.

δ/d	Local field, Oe	
	experiment	calculation
0.017	169.0±0.5	43.0
0.104	174.5±0.5	240.0
0.156	189.8±0.5	322.0
0.180	270.0±0.5	390.0

To observe the EPR signal, we placed the field detector—a grain of DPPH—and the superconductor sample in a microwave (≈ 9200 Mc) resonator. Therefore, it was possible to investigate in the same experiment both the local field on the superconductor's surface and the high-frequency properties of the superconductor itself in a magnetic field.

In the present investigation, the local fields were measured on Nb-Zr (60—40 wt.%) samples which did not exhibit intrinsic microwave energy absorption in a magnetic field up to 4000 Oe. The measurements were carried out at the frequency of ≈ 9200 Mc at temperatures of 4.2°K and $T > T_c$ (i.e., above the critical value). The Nb-Zr samples were in the form of disks 7.3 mm in diameter and 0.12—1.36 mm thick (the ratio of the thickness δ to the diameter d is given in the first column of the table). The disk formed the central part of the bottom of a rectangular resonator. During the experiments, the sample could be rotated about an axis passing through its center and perpendicular to the bottom of the resonator.

One or several DPPH grains, having a volume of 4×10^{-3}—5×10^{-2} mm^3, were used as the field detectors. They were attached to the surface of the disk. The external magnetic field was directed parallel to the plane of the disk and measured with a proton resonance meter type IMI-2.

The experiments showed that the values of the local field and the form of the EPR line, which gave qualitative information on the degree of uniformity of the local field, depended strongly on the conditions of magnetization of the superconductor.

We measured the local fields for all the samples when they were cooled to 4.2°K in the absence of an external field and then the magnetic field was increased gradually until the EPR signal appeared. The values of the local field are listed in the second column of the table. The EPR signal half-width was within the limits 10—14 Oe, and the area bounded by the signal indicated that the field on the sample surface was sufficiently uniform to observe an EPR signal from the greater part of the detector volume (90—95%).

It was interesting to compare the observed values of the local field with H_{loc} calculated for ideal diamagnetic ellipsoids of revolution with the same ratio of the major and minor semiaxes (the third column of the table). As expected, there was no agreement and the greatest difference (169.0 Oe instead of 43 Oe) was observed for the thinnest sample.

It was found that the local field appearing on the surface extended considerably into the space above the surface. The EPR signal was measured with a detector placed on a thin mica plate at various heights above the surface of a sample 0.12 mm thick. At a height of 1.59 mm, the local field was still 40 Oe and the EPR signal half-width was 5.5 Oe.

Next, we investigated the dependence of the local field on the external magnetic field in which the sample was cooled. Then, at 4.2°K, the external field was varied until an EPR signal appeared. The results are shown in Fig. 1. The abscissa gives the value of the external magnetic field in which the Nb-Zr sample was cooled. The ordinate gives H_{loc}, i.e., the difference between the applied external field and the resonance field.

Three points are worth noting. First, when a sample was cooled in a field $H_{ext} = H_{res}$ the EPR line was neither displaced with respect to the external field nor did its half-width increase, i.e., the local field was in this case very nearly equal to zero. This could be explained by assuming that the magnetic field penetrated completely the superconductor, although its value was far from H_{c2} (70 kOe). A similar effect of field penetration into a sample cooled in a field was observed by LeBlanc[5], who measured the magnetic moment of a coil made of Nb-Zr (75—25 wt.%) wire.

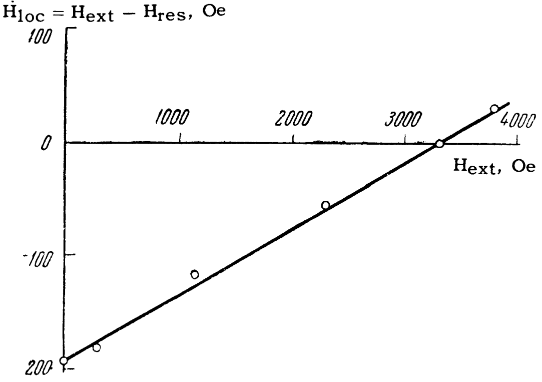

FIG. 1. Dependence of the local field on the surface of Nb–Zr on the external magnetic field in which the sample was cooled to 4.2°K.

Secondly, when a sample was cooled in an external field higher or lower than the resonance value, the local field had different signs. Obviously, the change in the sign was associated with the fact that after cooling the sample to 4.2°K the external field in the former case was reduced to produce an EPR signal, while in the remaining cases this field was increased.

Thirdly, there was no marked deviation of the dependence given in Fig. 1 from linearity both in the cases of cooling in fields up to H_{c1} and in the cases of cooling in fields > H_{c1}.

Thus, the experiments showed that the local field was evidently the field of the currents induced in the superconductor by a varying external magnetic field.

Later experiments established that the dependence of the local field on the change in the external field was not single-valued, but was governed by previous magnetization cycles.

After several sweeps of the external magnetic field from zero to the appearance of an EPR signal, the value of the local field changed by 5—20 Oe in various samples.

When the magnetization was reversed, the local field changed by 100 Oe or more. At the same time, the EPR line was frequently split into two, within the scan limits (35—50 Oe). If several detectors were placed on a sample, the values of H_{loc} for each of them changed by different amounts after the magnetization reversal, although during the initial external field sweep the local fields indicated by different detectors were identical.

The local field varied when a sample was rotated in a magnetic field and this variation was not single-valued. After the first appearance of an EPR signal a sample of Nb-Zr was rotated about an axis perpendicular to its plane and the external magnetic field was adjusted so that the EPR signal was always observed. Figure 2 shows the data obtained in one such experiment. After considerable rotation of the sample in the external field (this part of the curve is denoted by I) there was no marked change in the local field. The half-width of the signal also remained approximately constant.

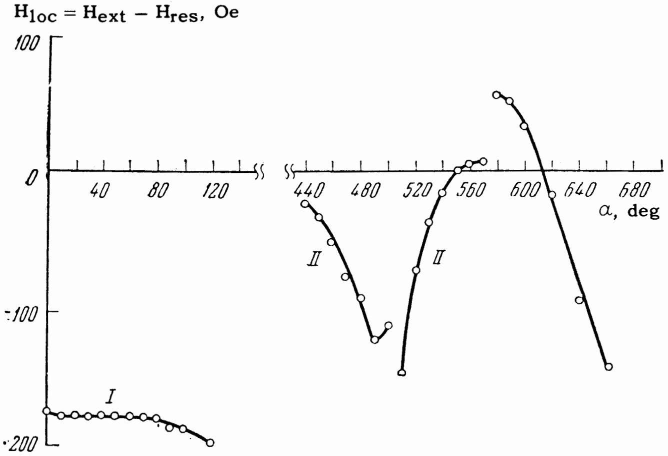

FIG. 2. Dependence of the local field on the angle of rotation of the sample along the azimuth in the external magnetic field corresponding to the appearance of an EPR signal.

Then, the signal rapidly broadened and disappeared on rotation through an angle of 10°. No EPR signal was observed at larger angles although the external magnetic field for each of those angles was swept from 2800 to 3800 Oe. The EPR signal reappeared (part II of the curve) on rotation through an angle α larger than 360°. The dependence of the local field on the angle of rotation was sinusoidal with an amplitude amounting to a considerable fraction of H_{loc}. Sharp discontinuities in the local field dependence on the angle rotation were observed. When the value of the local field passed through zero ($H_{res} = H_{ext}$) the half-width of the EPR signal was several times greater than the half-width in the absence of a superconductor (10—12 Oe instead of 3 Oe). Further rotation caused the EPR signal to disappear again.

Thus, beginning from a certain moment, a considerable fraction of the local field seems to be rigidly attached to the sample; we may assume that this is due to the presence of centers in the lattice which maintain induced currents of definite orientation.[6] Such centers may be various structure defects, which appear when the samples are mechanically deformed during preparation.

Thus, the properties of the local field on the surface of an Nb-Zr superconductor reflect the properties of currents within the superconductor, which appear due to variation in the external magnetic field. When the orientation of these currents changes relative to the external magnetic field, the currents become redistributed and concentrate at various defects in the superconductor structure. The properties of real defective (i.e., multifilament) superconductors of type II may thus differ considerably from the theoretically predicted properties of type II superconductors.

The relationship between the local surface fields and the high-frequency properties of a superconductor requires further studies. However, if we compare the absence of induced currents under the conditions of complete penetration by the field, i.e., when an Nb-Zr sample is cooled in a magnetic field, with the absence of high-frequency anomalies under the same conditions,[1,2] we may assume a direct relationship between these effects.

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