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Evidence for Superconducting Effects on the Measured Resistivity Well above T_c for a Type-I Bulk Metal

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A superconducting contribution $\delta\sigma(T)$ to the electrical conductivity $\sigma(T)$ has been observed at temperatures up to about twice the transition temperature $T_c \simeq 1.17$ K for bulk aluminum. The form of $\delta\sigma(T)$ is found to be $\alpha[T_c/(T-T_c)]^n$, with α independent of $\sigma(T)$, in agreement with the theory of superconducting fluctuations. However, significant differences from the theory are found, with α more than two orders of magnitude too large and $n \simeq \frac{3}{4}$ rather than $\frac{1}{2}$.

Superconducting effects in the form of enhanced diamagnetism have been observed[1] at temperatures up to about twice the transition temperature T_c for type-I bulk metals. We report here the first experimental observation of enhanced electrical conductivity for a type-I bulk metal. We find traces of the effect up to about $2T_c$. As was concluded for the enhanced diamagnetism, the enhanced conductivity is attributed to fluctuation superconductivity.

Enhanced conductivity well above T_c has been previously observed[2] for other classes of materials, such as thin films and very dirty bulk samples. However, in contrast to almost all these previous observations, our results show an effect which is more than two orders of magnitude larger than the prediction of Aslamazov and Larkin,[3] Maki,[4] and Thompson.[5] Moreover, we find a temperature dependence of $[T_c/(T-T_c)]^{3/4}$, intermediate between the predicted exponent of $\frac{1}{2}$ for bulk metals and of 1 for thin films. These discrepancies appear to be more severe than others that have been reported, such as that for diamagnetism by Fassnacht and Dillinger,[6] which was explained by them in terms of isotopic purity.

Measurements were carried out using a flux-gate null detector to measure the sample resistance against a standard reference. The double current source (master and slave) is especially designed for long-term stability of about 2 ppm with currents of about 900 mA. The sensitivity achieved, one to a few ppm, is limited by both the detector and the measuring current used.

Ten sets of measurements were carried out on three different samples,[7] one of which was annealed and remeasured (see Table I). The samples were in the shape of a 5-cm-diam bifilar wound ring. Each sample is denoted by S-RRR, where RRR is the value of the residual resistance ratio for that sample. The results for sample S-62 are shown in Fig. 1. The open and solid circles give the measured values for the resistivity $\rho_{expt}(T)$ with and without, respectively, a longitudinal magnetic field of 10 G. Above 2 K, no effect was detectable. However, below 2 K, a detectable decrease in $\rho_{expt}(T)$ is clearly seen as the magnetic field is removed. The data were taken at each temperature alternately with and without the magnetic field. The sample current was 200 mA. The magnetic field was generated by a dc current through a Nb-Ti toroid wound onto the coiled sample.

After the above measurements were completed, sample S-62 was annealed in a vacuum for 2 h at 240°C, which lowered its resistance to an RRR of 98. This sample, now denoted S-98, was measured twice, once with a current of 200 mA and then with a current of 900 mA. The superconducting effect above T_c is quenched by the transverse magnetic field associated with the higher current density (about 4 G at the sample surface). This is shown in Fig. 2, where we have plotted $[\rho_{expt}(T) - \rho_0]/T^2$, where ρ_0 is the residual resistivity.

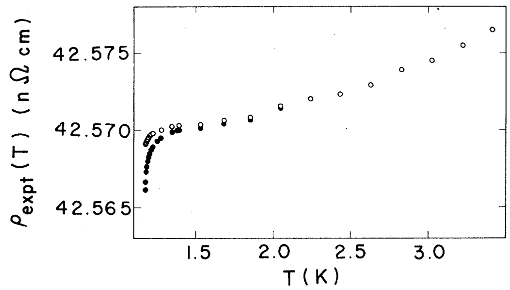

FIG. 1. The measured resistivity $\rho_{expt}(T)$ is plotted vs temperature for an Al sample having a RRR of 62. The open circles show the values obtained for $\rho_{expt}(T)$ in the presence of an applied longitudinal magnetic field of 10 G. Measured values at temperatures below about 2 K where a difference in $\rho_{expt}(T)$ was detectable when the applied magnetic field was switched off, are denoted by closed circles.

The open and solid circles give the data taken at the higher (900 mA) and lower (200 mA) sample currents, respectively. The open circles, for which the superconductivity above T_c has been quenched, show the characteristic sharp drop of $\rho(T)$ at T_c. By contrast, the closed circles show a distinct superconducting effect extending about 0.4 K above T_c.

The normal-state behavior of $\rho(T) - \rho_0$ is expected to be T^2 in this temperature range due to electron-electron scattering.[8,9] The open circles show very clearly the expected T^2 behavior with a coefficient of 0.52 $p\Omega$ cm/deg^2. This value is in agreement with other measurements.[9-11]

A third sample (S-380) was also measured, with a sample current of both 900 and 100 mA, both with and without a magnetic field of 10 G. The effect for this sample was much smaller, a result which we attribute to the larger value of RRR. Finally, a fourth sample (S-65) was measured, again both with and without a magnetic field. The results are very comparable to those found for S-62. We attribute the similarity of these two results to the closely comparable values of

TABLE I. Description of the samples measured.

Sample	Shape	Length (m)	Diameter (mm)	Purity (%)	RRR	Mean free path (10^{-4} cm)
S-62	Wire	2.55	1.0	99.98	62	2.7
S-65	Wire	1.33	1.0	99.98	65	2.8
S-98	(S-62 after annealing)				98	4.2
S-380	Wire	6.54	0.63	99.99	380	16.5

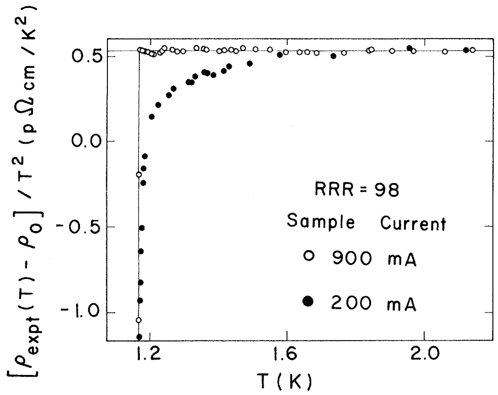

FIG. 2. The difference between the measured value $\rho_{\text{expt}}(T)$ and ρ_0 is divided by T^2 and plotted vs temperature. A high sample current of 900 mA is seen to completely destroy the superconducting fluctuation effect above the transition region. A reduced sample current of 200 mA shows superconducting effects extended several tenths of a degree above T_c.

RRR for these two samples.

All of the four samples measured showed evidence of a small but noticeable decrease in the resistivity at temperatures well above the narrow superconducting transition region. In each case, this small decrease could be described by the formula

$$\delta\rho(T) \equiv \rho_n(T) - \rho_{\text{expt}}(T) = \rho_0 + AT^2 - \rho_{\text{expt}}(T) \equiv \alpha[T_c/(T-T_c)]^n \rho_0^2, \tag{1}$$

where $\delta\rho(T)$ denotes the change in $\rho(T)$ due to the small superconducting effects above T_c and $\rho_n(T)$ is the value that $\rho(T)$ would have in the absence of $\delta\rho(T)$. The quantity AT^2 is the usual electron-electron contribution[8] to $\rho(T)$ and T_c is taken to be the measured temperature for which $\rho(T) = \frac{1}{2}\rho_n(T)$.

It appears extremely unlikely that the observed effect could be attributed to sample inhomogeneity. The observation of superconducting effects several tenths of a degree above T_c is far beyond changes in T_c normally associated with bulk inhomogeneity, such as due to cold work.[12] Moreover, the correlation observed between the magnitude of the superconducting effect and the RRR of the sample is incompatible with the lack of correlation which would be expected if sample inhomogeneity were a significant source of the observed effect. Finally, spot-welded Al electrodes of the same stock of Al as the sample were used to avoid inhomogeneities at the sample-electrode interface.[13]

In spite of the above discussion, it should be noted that surface layers, or small isolated regions of impurities in the bulk, if present, could cause the effect reported here. While in the ideal case, surface effects should not be present in type-I superconductors, this has not been demonstrated to be true in fluctuation experiments. The way to check experimentally the influence of surface treatment is (i) by repeating the measurements after various surface treatments such as etching or anodization and (2) by repeating the measurements on Al from different sources. Such experiments are currently in progress.

Another possible source of superconducting effects above T_c is the smearing of T_c caused by the intermediate state associated with the critical current.[14] This effect can also be ruled out for the following two reasons. First, the smearing of T_c is typically an order of magnitude smaller than the effect we observe. Second, the observed effect is in the *opposite* direction to the current-smearing effect which causes the smearing of T_c to increase with increasing current.

It should be pointed out that we do observe all of the usual superconducting effects in the temperature region within 0.05 K of T_c. This includes the lowering of T_c upon the application of an external field and/or a larger electrical sample current, as well as the smearing (temperature broadening) of the transition width when the sample current is increased. Thus the standard transition region is clearly distinct from the fluctuation region.

We associate the presently observed effect with superconducting fluctuations. This would imply[3-5] that when the electron mean free path l is longer than the coherence length ξ_0, one should obtain the same superconducting contribution $\delta\sigma(T)$ to the total conductivity $\sigma(T)$ for all samples. For each of our samples, the mean free path is larger than $\xi_0 = 2.4\times10^{-4}$ cm. Therefore, a basic test of the hypothesis of superconducting fluctuations is to see whether $\delta\sigma(T)$ is the same for all samples. The sample-independent quantity $\delta\sigma(T)$ is readily related to the measured quantity $\delta\rho(T)$ by

$$\delta\rho(T) = \delta\sigma(T)\rho_0^2. \tag{2}$$

To test the sample independence of $\delta\sigma(T)$, we plot $\delta\rho(T)$ as a function of $T - T_c$ on a log-log scale, as shown in Fig. 3. For each sample, the data are seen to fit to a straight line. This confirms the temperature dependence given in (1). To compare the magnitude of the effect for different samples, we use sample S-62 as a reference.

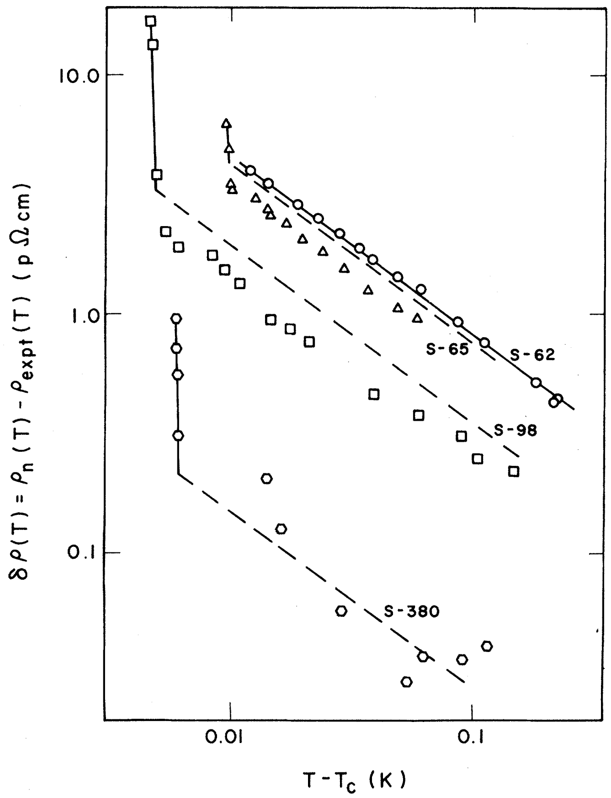

FIG. 3. The difference $\delta\rho(T)$ between the extrapolated normal value of $\rho_n(T)$ minus the measured value $\rho_{expt}(T)$ is plotted vs the temperature difference above T_c on a log-log scale. The sample with the least experimental scatter (S-62) closely follows a straight line with a slope of -0.73. The three dashed lines are the expected values for the other samples assuming the same temperature exponent and assuming that $\delta\sigma(T)$ is a constant independent of $\sigma(T)$. Note, however, that the sample current for S-380 is lower than for the others. The steep vertical rise in $\delta\rho(T)$ marks the onset of the superconducting transition proper, which is distinct from the fluctuation regime.

The expected value $\delta\rho(T)$ for the other three samples can then be determined from (2) assuming that $\delta\sigma(T)$ is sample independent. The results are given by the three dashed lines in Fig. 3. It is seen that for each of the three samples S-380, S-98, and S-65, the expected values (dashed lines) lie reasonably close to the observed values (symbols). This agreement is supportive to the suggestion that the observed effect is indeed a result of superconducting fluctuations.

As previously stated, the magnitude of the observed effect is much larger than that predicted by theory.[3-5] For Al, the theory yields

$$\delta\rho(T) = [0.17(\Omega\ \text{cm}^{-1})][T_c/(T-T_c)]^{1/2}\rho_0^{\,2}. \qquad (3)$$

Our measurements yield the sample dependence predicted by (3), but the coefficient equals 70 (instead of 0.17) and the exponent is about $\frac{3}{4}$ (instead of $\frac{1}{2}$). The reason for these differences between the theory and experiment is not yet understood. A possible source of discrepancy may be associated with the fact that for our samples, the mean free path is of the same order of magnitude as the coherence length. For such a case, (3) may require modification.

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