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T_c ENHANCEMENT?

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We present experimental evidence which indicates that recent experiments claiming observation of microwave radiation stimulated T_c enhancement in superconducting bridges may be incorrect. Our results indicate that energy gap and T_c enhancement theories and experiments should be seriously reevaluated.

One of the most striking results to recently appear in the field of superconductivity is the theoretical prediction and experimental observation of superconductivity at temperatures above the equilibrium transition temperature T_c. These enhancements of T_c have been reported in aluminum bridges subjected to microwave radiation at frequencies of order, but less than, the energy gap $\Delta(T)$. We show that the interpretation of these recent experiments as showing T_c enhancements may be incorrect. We demonstrate using sensitive measurements of critical currents I_c down to < 0.01 µA that finite supercurrents exist above the "T_c" that would be obtained from the conventional extrapolation of the I_c or $I_c^{2/3}$ versus temperature curves. We find that superconductivity exists over a range of temperatures above "T_c" of roughly the same amount over which T_c enhancement has been reported. An alternative explanation for the experiments reported to date may be enhancement of very low I_c's (the Dayem-Wyatt Effect)[1-2] rather than T_c enhancement.

In the last several years there has been extensive experimental interest in the enhancement of superconducting properties by phonon[3] and microwave irradiation[4-6] as well as by tunnel injection of quasiparticles.[7] Theoretical work[8-10] predicting an enhancement of the energy gap Δ has been in good agreement with these experiments. However, recent simultaneous energy gap and critical current I_c measurements on long bridges[11], I_c measurements on short bridges[12] as well as tunneling measurements in lead films[13] are inconsistent with the idea of gap enhancement by microwave irradiation. It should be pointed out that alternative theories[1-2;14-17] are available which satisfactorily explain the enhancement of I_c's without the necessity of invoking the concept of gap enhancement under microwave irradiation.

To resolve these inconsistencies, it is of major importance to understand whether an external perturbation, such as a microwave field, is able to stabilize a superconducting phase above the equilibrium thermodynamic transition temperature T_c. Experiments reporting T_c enhancements in superconducting Al bridges subjected to microwave perturbation have derived values for the unperturbed thermodynamic transition temperature T_c from extrapolations of $I_c^{2/3}$ or I_c versus temperature plots.[6,18,19] The essential point of this Letter is that "T_c's" determined from such extrapolations can differ significantly from true measured T_c's.

In order to prove T_c enhancement, it is crucial to have precise measurement of the equilibrium critical temperature. This is made difficult in bridges by thermal noise rounding of the current-voltage characteristics.[20] Unfortunately, determinations of "T_c's" in the enhancement experiments reported to date have been inferred either from the I-V characteristics[4], from resistance versus temperature[6,19] measurements or else from extrapolations of I_c measurements which were made at very high currents (> 100 µA).[18] We have undertaken a series of measurements on narrow Al bridges of the type used by others in microwave induced gap and T_c enhancement studies. In order to measure very low I_c's, and hence to experimentally determine the true T_c, we have measured differential resistance vs I as a function of temperature for a number of bridges. These measurements were done in a well shielded probe which is known to give a noise temperature for the bridges equal to the bath temperature.[20] In this way, we were able to routinely measure I_c's as small as 0.01 µA; two to three orders of magnitude smaller than reported in the work of References 4, 6, and 18. The temperature at which all structure in the dV/dI vs I curve vanishes is the true T_c of the bridge and, in this way, can be directly determined to within 0.1 mK without the necessity of extrapolating data to $I_c = 0$. This point is crucial, as we do not have to assume any functional dependence of the critical current on temperature in order to obtain T_c.

The bridges consist of 700 - 1500 Å films

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evaporated onto sapphire substrates at a rate of 10 - 150 Å/sec in a background pressure of 1×10^{-5} - 1×10^{-6} torr. By altering the pressure and evaporation rate we produced films with T_c's varying from only slightly above that of bulk Al up to ∿ 1.5°K. The actual geometry for the short bridges consisted of a row of six "straw stalk" like microbridges defined by conventional photoresist and etching techniques. Typical widths were 1-4 μm with a length of 10 μm. This allowed us to obtain systematic data for up to six different stalk widths on each Al film by running the entire "straw" row in our probe. In all of these measurements the temperature of the helium bath was electronically controlled to better than 0.1 mK using a Ge resistor and relative temperatures were measured to this same accuracy using a different calibrated Ge resistor. Absolute temperatures are accurate to 5 mK. A mu-metal shield reduced the ambient magnetic field to less than 10^{-6}T and all measurements were conducted in a screened room. The samples were contained in an electrically shielded probe[20] and standard phase-sensitive detection techniques used to determine dV/dI. Data was taken at each temperature for both directions of current bias.

$I_c > 20$ μA are quite accurately determined even from I-V characteristics (since noise rounding effects are relatively small). These data are then fitted to a straight line and the $I_c = 0$ extrapolated intercept is defined as "T_c". However, as can be seen from this Figure, deviations from the $I_c^{2/3}$ behavior begin to occur just in the region near T_c where measurements of the type used by previous workers[4,6,18] can no longer detect them due to thermal noise rounding of the I-V characteristics. These deviations are almost always in the direction that causes the true measured T_c to lie at a higher temperature than the extrapolated "T_c". This Figure shows true T_c's as high as 34 mK above the extrapolated "T_c's". This range is roughly the same over which T_c enhancement has been reported.[4,6,18] In this temperature range where other types of measurements would not detect an I_c, a perturbation which would cause the Dayem-Wyatt effect to give rise to an enhancement of I_c from e.g., 1 μA to 20 μA, could be misinterpreted as T_c enhancement. For completeness, we also show in Fig. 1 a case where T_c lies very slightly below the extrapolated "T_c". We found this to occur mainly in very clean films with T_c's close to that of bulk Al. Measurements made on long (1 mm) narrow (< 1 μm) bridges show similar deviations

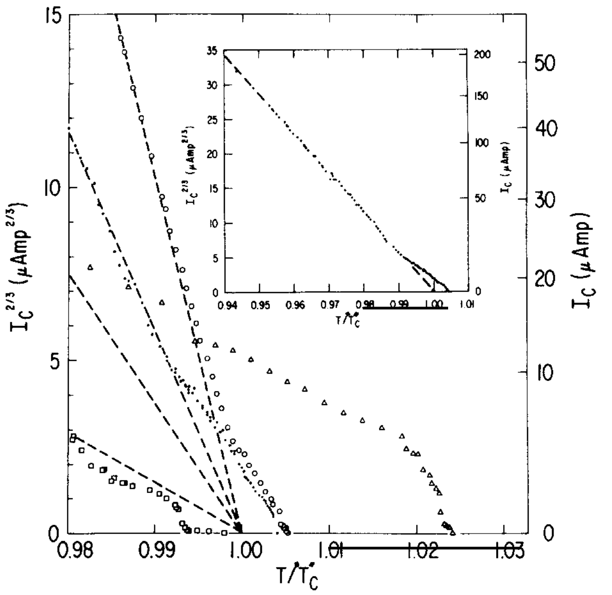

Figure 1. $I_c^{2/3}$ vs T/"T_c" for several short bridges near the transition temperature. The inset shows how "T_c" is defined by the extrapolation to I = 0 of data for $I_c \geq 20$ μA. "T_c's" for the bridges are: squares 1.242 K; closed circles 1.227 K; open circles 1.224 K; triangles 1.408 K.

Figure 1 shows I_c data for several bridges near T_c. The dashed curves demonstrate the conventional procedure for determining "T_c" from a plot of $I_c^{2/3}$ vs temperature. Data for

from mean field theory.

In order to check the universality of these deviations we have also performed measurements on Sn and Nb_3Sn weak links.

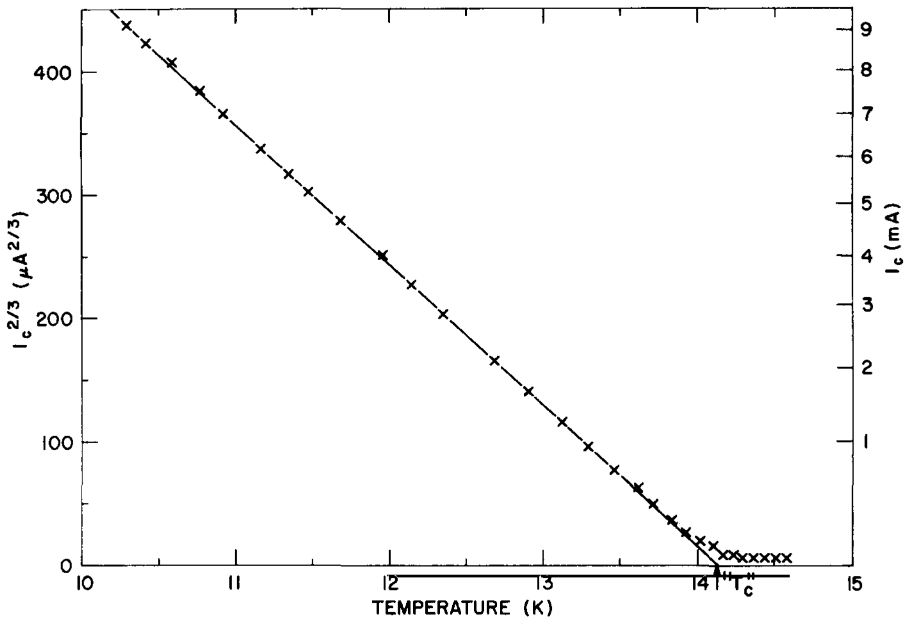

Figure 2. $I_c^{2/3}$ vs Temperature for a 0.3 μm x 10 μm Nb_3Sn weak link. The true T_c lies 600 mK above the extrapolated "T_c".

Figure 2 shows the deviation measured in a Nb_3Sn weak link above 13 K. Notice that the temperature range of the deviation is much larger in this material; roughly scaled up by the T_c. Deviations also scaled by the T_c have been observed in Sn bridges as well, showing that this phenomenon is not restricted to any one particular material.

Deviation from mean field behavior is a very general phenomenon, occuring very near the critical temperature in a wide variety of systems.(21-26) It has been shown that the mean field prediction for the superconducting energy gap breaks down in Al films near T_c due to inhomogeneities.[21] Fluctuations produce large deviations from mean field behavior in a variety of zero,[22] one[23] and two[24] dimensional and granular[25] superconductors. In fact, magnetic systems show similar deviations from mean field behavior close to T_c.[26]

In the case of superconducting bridges, we have shown that these deviations usually cause the true T_c to lie at a significantly higher temperature than the extrapolated "T_c". At the same time experiments on bridges show that quantum phase coherence is maintained even in the non-mean field region.[27] It is therefore possible to misinterpret the well known phenomenon of critical current enhancement (Dayem-Wyatt effect[1-2]) as the more striking phenomenon of enhancement of the superconducting critical temperature T_c. No results claiming to observe T_c enhancement reported to date have made a sensitive enough determination of T_c.(19) As we have shown, without such a determination, it is not possible to substantiate claims of T_c enhancement. Because of this, future work in this area must include direct measurements of the equilibrium T_c.

In summary, we have shown experimentally that no conclusive evidence has been published to date that shows the existence of T_c enhancement.

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