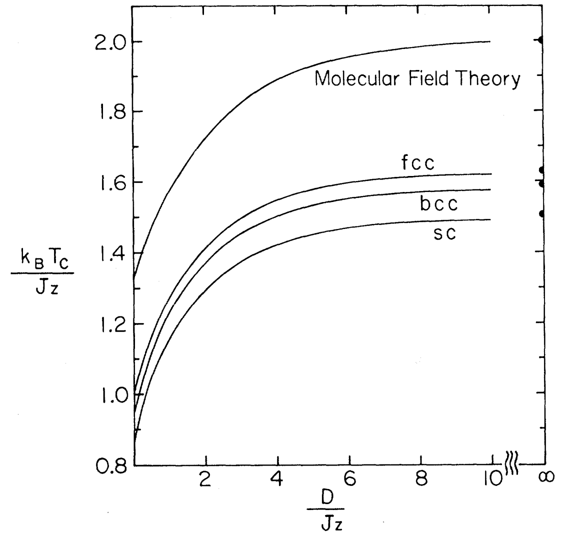

FIG. 1. Plot of critical temperature vs single-ion anisotropy strength for the spin-1 Heisenberg ferromagnet with easy-axis single-ion anisotropy, in sc, bcc, and fcc lattices. The curve showing the values in the molecular-field approximation is included for comparison.

can be computed analytically or numerically without difficulty. With all these flexibilities the method is up to now the only suitable one for the analysis of rare earths and actinides.

Work on higher-order terms of the spin-1 systems reported above and on a singlet-triplet model which can be extended to discuss Pr_3Tl and TbSb is in progress.

One of us (Y.-L.W.) enjoyed the warm hospitality extended to him by colleagues of the National Tsing Hua University during a summer's visit. We would like to thank Dr. H. H. Chen, Dr. R. A. Kromhout, Dr. Y. Shan, and Dr. D. H. Yang for their interest in the problem and for their helpful discussions. Special thanks are due to K. Rauchwarger for his assistance in setting up a computer program, and to R. A. Kromhout for a critical reading of the manuscript.

*Supported in part by the National Science Foundation under Grant No. DMR73-2318 A01.

†Supported by the National Science Council of the Republic of China.

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Observation of Interactions between Two Superconducting Phase-Slip Centers*

D. W. Jillie,† J. E. Lukens, and Y. H. Kao

State University of New York at Stony Brook, Stony Brook, New York 11794

(Received 14 February 1977)

A superconducting microbridge has been used as a probe to detect quasiparticle diffusion currents and "heating", produced by a phase-slip center (PSC) in a second microbridge. The critical current of the detector is modulated by the voltage V_{PSC} across the PSC. This modulation provides a measure of quasiparticle current I_Q thru the PSC and gives $I_Q = V_{PSC}/R_D$ for low voltages, R_D being the high-current differential resistance of the PSC.

The dynamics of the voltage-sustaining state in thin-film superconducting microbridge weak links is poorly understood in contrast to Josephson tunnel junctions, and, hence, is the subject of much current investigation. These microbridges are inherently nonequilibrium devices, with their voltage-producing state being the result of a periodic collapse of the order parameter and its subsequent recovery to a state with a change of 2π in the phase difference across the bridge. This process is referred to as a phase slip and the microbridge as a phase-slip center (PSC). During these oscillations both the pair and normal-electron, or quasiparticle, densities and currents are out of equilibrium. Many of the properties of the bridge such as its current-voltage (I-V) curve are determined by the relaxation rates for this disequilibrium. It has recently been shown by Skocpol, Beasley, and Tinkham (SBT)[1] that the resistance of such a PSC is largely determined by the inelastic scattering time over which the quasiparticle current decays. In addition there have been attempts to compare the detailed shape of the I-V curve with calculations taking into account the pair relaxation rate.[2] Efforts to use the I-V characteristics to deduce information about bridge dynamics are always complicated by the problem of distinguishing the pair and quasiparticle components of the bridge current. It is thus desirable to have an external probe[3] of the state of the microbridges to separate the various processes. This Letter describes the use of a thin-film indium microbridge as a detector of the nonequilibrium conditions including quasiparticle currents created by a PSC in another generator bridge.

The two microbridges are coupled by fabricating them in close proximity ($\simeq 2\ \mu$m) to each other, with a superconducting pad of the same material as the bridges separating them. They are made from a 1000-Å indium film using electron-beam lithography and are always $\leq 1\ \mu$m square. The sample geometry is illustrated schematically in Fig. 1, along with the measurement circuit. This circuit consists basically of two four-terminal circuits, with individual current supplies for the two bridges as well as individual voltage circuits. Measurements are made with the sample in a fully shielded Dewar. Low-pass filters are installed at helium temperature on the current and voltage leads and effectively protect the bridges from external noise and shocks. The temperature is monitored with a germanium resistance thermometer and is electronically regulated to within a few microkelvins.

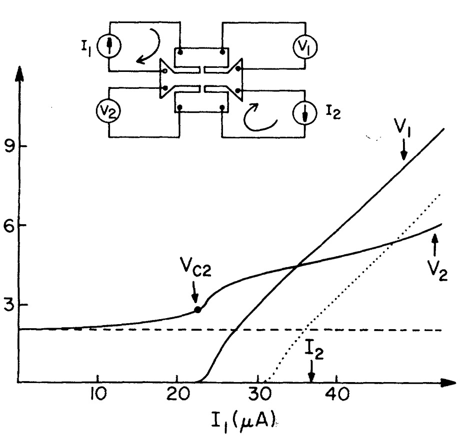

FIG. 1. The change in the voltages across two interacting microbridges as the current through bridge 1 is varied with a constant current in bridge 2. The dashed and dotted lines show the voltages for bridges 2 and 1, respectively, if no interaction was present (see text). The inset shows the sample geometry and measuring circuits.

The general effect of the interaction between two bridges on their current-voltage characteristics is shown by the data in Fig. 1. These data were taken with the bridges biased as shown with the current flowing in opposite directions through the two bridges and out opposite sides of the interconnecting pad. The current through bridge 2 is fixed and the current through bridge 1 is slowly swept while V_1 and V_2 are monitored. The dotted and dashed lines show the bridge voltages if there were no interaction (i.e., the I-V curve for bridge 1 would be that obtained with $I_2 = 0$ and V_2 would be independent of I_1). In general the interaction appears to increase the voltage of each bridge above what it normally would be. Also, at the point where the V_1 and V_2 curves cross, the voltage across the bridges tend to lock to a common value. This voltage-locking interaction is discussed in detail elsewhere.[4] When the measurements are repeated with the current through bridge 2 reversed so that it flows in series through the two bridges, the results are strikingly different from the opposing current situation. There is virtually no increase in V_1 above its noninteracting value, and V_2, after an initial small rise (for $V_1 = 0$), drops below its noninteracting voltage as V_1 increases. Although there is a strong interaction where the two curves cross, there is no voltage locking as is observed in the opposing-current bias case.

A quantitative understanding of this interaction is most easily obtained from measurements of the change in the apparent critical current of one bridge (that is, the external bias current through the bridge for which a PSC appears in the bridge) as a function of the current and voltage in the other bridge. The change in the critical current of bridge 1, ΔI_{c1}, has been monitored for different values of the fixed current through bridge 2, I_2, in the cases of both opposing and series current bias. In addition, the voltage across bridge 2 at $I_1 = I_{c1}$ has been measured and is denoted as V_{c2} (refer to Fig. 1). Since the voltage leads are superconductors many diffusion lengths long, the various voltages measure the difference in the pair electrochemical potential across a bridge. The results of these experiments are shown in

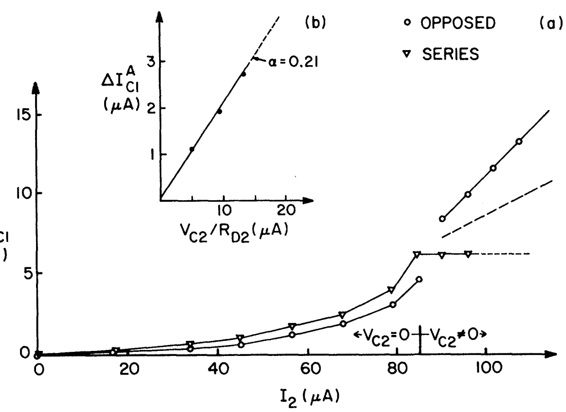

FIG. 2. (a) The change in the apparent critical current of bridge 1 for a range of fixed currents thru bridge 2. Data include both polarities of I_2 relative to I_1 (series and opposing). The voltage across bridge 2 when $I_1 = I_{c1}$ is denoted as V_{c2} and is zero for $I_2 < 85$ μA. The dashed line (long dash marks) is the symmetric or average component of ΔI_{c1} for the two polarities of I_{c2}. (b) The antisymmetric component, $\Delta I_{c1}{}^A$, of ΔI_{c1} as a function of V_{c2} divided by R_{D2}. The constant R_D which equals 0.32 Ω is the differential resistance of bridge 2 for $I \gg I_c$. V_2/R_{D2} is the assumed quasiparticle component of I_2. These data are for a lower temperature than that in Fig. 1.

Fig. 2. For $V_{c2}=0$ there is a current-dependent depression in I_{c1} evident in both curves. This is in reasonable agreement with that expected due to the current-induced order parameter depression in the region between the bridges[5]—the small difference in ΔI_{c1} for the two current polarities being attributed to the difference in current distributions. When V_{c2} becomes nonzero, however, the opposed and series curves split apart very radically. Since a depression of I_{c1} independent of the polarity of I_2 would be expected due to heating in bridge 2 for $V_2 > 0$, it is useful to sort this out by separating ΔI_{c1} into parts which are symmetric, $\Delta I_{c1}{}^S$, and antisymmetric, $\Delta I_{c1}{}^A$, in I_2: i.e., $\Delta I_{c1}{}^S = [\Delta I_{c1}\text{ (series)} + \Delta I_{c1}\text{ (opposing)}]/2$ and $\Delta I_{c1}{}^A = [\Delta I_{c1}\text{ (series)} - \Delta I_{c1}\text{ (opposing)}]/2$. The origin of these two components of ΔI_{c1} is discussed in the remainder of this Letter.

We first consider the effect of the quasiparticle diffusion current (as opposed to simply an excess quasiparticle density) which flows in the neighborhood of a PSC. The dc component of the quasiparticle current flowing through the weak link having a PSC is assumed to be approximately given by $I_Q = V/R_D$, where V is the difference in the pair electrochemical potential measured across the PSC and R_D is the measured differential resistance of the PSC for $I \gg I_c$. The magnitude of R_D is determined by the distance the quasiparticles diffuse before returning to equilibrium. SBT, in their experiments with long tin bridges, were able to determine this length in tin and found it to be the temperature-independent inelastic scattering length—about 10 μm for a 1000-Å film. This quasiparticle diffusion length Λ in long indium bridges has been measured in our laboratory and is about 5 μm for $T < 0.999T_c$.[5] This is much greater than the coherence length, ξ, over which the order parameter is depressed. As SBT noted, this tends to inhibit the formation of a new PSC within Λ of an existing one since the total current must remain constant along the bridge and part of the current within Λ of the PSC is carried by quasiparticles. The supercurrent is thus reduced below its critical value within Λ even though the total current may be greater than I_c. This effect should also occur in closely coupled microbridges, and thus it is expected that one microbridge can be used as a probe of the quasiparticle current generated by a PSC in a neighboring microbridge located within a distance Λ. When current flows in series through the two bridges, the supercurrent should be reduced in the sensing bridge by the amount of the quasiparticle current, and hence the total necessary to reach the critical supercurrent will increase by the same amount. When the current through the sensing bridge only is reversed (opposing current bias) the quasiparticle diffusion current remains in the same direction and increases the supercurrent in the sensing bridge. This should be reflected by a decrease in the apparent critical current of the sensing bridge. This interaction between the bridges is antisymmetric, in contrast to heating effects which should be symmetric. If we assume that there are no other important antisymmetric interactions, the fraction, α, of quasiparticle current generated in the PSC in bridge 2 that flows through the detector bridge 1 may be obtained from $\Delta I_{c1}{}^A$ which would then just be the quasiparticle current I_{Q1} that flows through bridge 1. The values of $\Delta I_{c1}{}^A$ shown in Fig. 2(b) are calculated as the differences between points of constant V_{c2} on the series and opposing curves in Fig. 2 since these points, rather than those of constant I_2, should have quasiparticle currents of equal magnitude. The upper limit on V_{c2} is determined by the appearance of a PSC in the pad, which has a critical current only slightly larger than that of the bridge, for series data. This problem is not encountered for opposing current measurements since in this case the quasiparticle currents injected by the bridge PSC's carry a significant part of the current in the pad permitting pad currents considerably in excess of the pad critical current to flow without the formation of a pad PSC. The quasiparticle current I_{Q2} generated by bridge 2 is assumed to be given by V_2/R_{D2}. Thus $\alpha \equiv I_{Q1}/I_{Q2}$ is given by the slope of the graph of $\Delta I_{c1}{}^A$ vs V_{c2} in Fig. 2(b). This yields a value $\alpha = 0.21$ independent of V_2. This value of α obtained from the critical-current data may be compared with the value expected from the resistance of the various paths open to quasiparticle diffusion.

The quasiparticle current injected into the region between the two bridges has three paths that it can take: either side of the interconnecting pad or the detector bridge. If these paths are taken to be three parallel resistors, the proportion of current flowing through the detector bridge would be $\alpha = R_p/(2R_b + R_p)$, where R_b is the bridge resistance and R_p is the resistance of each half of the interconnecting pad. These resistances could be estimated from the geometry. However, since the resistance will be effected by quasiparticle relaxation before reaching the wide parts of the film, a more direct and accurate method of finding R is to measure the resistance of PSC's in the various branches. Using these directly measured values for R_b and R_p gives $\alpha = 0.24$. Considering the rather crude nature of the models involved, this is certainly satisfactory agreement. These measurements have been repeated for a number of samples with different separations, giving a wide variation in the amount, α, of the coupling, which nearly vanishes for separations greater than 3 to 4 μm. The results for these other separations are consistent with those discussed above.

As seen from the dashed line in Fig. 2(a), the symmetric effect of I_2 and V_2 is to decrease I_{c1}. This would be expected as a result of order parameter depression in the pad between the bridges either from lattice heating or from an excess of quasiparticles generated in the pad by V_2. We cannot distinguish between these effects in our samples since, among other things, the effects are closely connected by the large phonon-trapping factors present in the indium film.[6] $\Delta I_{c1}{}^S$ is, however, within a factor of 2 of that calculated due to measured lattice heating. The lattice temperature rise has been determined from similar samples immersed directly in liquid helium by observing the onset of boiling in the helium and is about 2 mK/nW. The symmetric change in ΔI_{c1} shown in Fig. 2(a) was accounted for by a temperature rise of 1.3 mK/nW. Given the uncertainties in these measurements we conclude that $\Delta I_{c1}{}^S$ is consistent with heating although the existence of other mechanisms is not ruled out.

We have shown that it is possible to use one microbridge as a detector of nonequilibrium conditions created by a PSC in a second bridge. Measurements so far lend strong support to the idea that PSC's many coherence lengths apart interact through quasiparticle currents which modulate the total supercurrent through the PSC. Since the primary purpose of these experiments has been the detection of quasiparticle currents, the bridges have been made close together with narrow connecting pads. This, coupled with the need to avoid PSC's in the pads, has limited the measurements to low voltages and made it especially difficult to study quantitatively the effects of excess quasiparticle density and conductivity at high voltages. It appears that it will, in fact, be possible to refine the techniques described above to permit measurements to be made to much higher voltages, providing important information on the dynamics of the superconductor.

*Work supported by the National Science Foundation and the Office of Naval Research.

†Present address: Sperry Research Corp., 100 North Road, Sudbury, Mass. 01776.

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