el predicts a decrease in effective hyperfine structure in the paramagnetic state. Using Eq. (3) on $KMnF_3$, for example, we predict $A'(\text{para}) = A + 6a$ compared with $A'(\text{isolated}) = A$ and $A'(\text{antiferro}) = A - 6a$. There is some indication that such an effect occurs in $\alpha$-MnS[13] and in MnSe[14] though it does not appear to be present in MnO.[15] Further experimental data on this point are very desirable.

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# MICROWAVE-ENHANCED CRITICAL SUPERCURRENTS IN CONSTRICTED TIN FILMS

A. F. G. Wyatt, V. M. Dmitriev,* W. S. Moore, and F. W. Sheard
Physics Department, Nottingham University, Nottingham, England
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We have found that the value of the maximum supercurrent, at zero voltage, that can flow through a constriction in a tin film depends on both the temperature and the incident microwave power at the constriction, and that under certain conditions the critical current is larger than its value without microwaves at the same temperature.

The effect of microwaves on a constricted thin film superconductor was first investigated by Anderson and Dayem.[1] They found that at certain microwave powers and at certain nonzero voltages the current through the constriction could be increased without any change in voltage. The voltages ($V$) at which this could occur were found to be simply related to the frequencies ($\nu$) of the microwaves by $2eV = nh\nu$, where $n$ is an integer. This behavior is very similar to that of a Josephson junction[2] which was measured by Shapiro.[3] However, Anderson and Dayem found instability at low voltages and so did not find the zero-voltage effect which we have observed.

In our experiment the tin, which was approximately 2000 Å thick, was evaporated through a mask on to a glass substrate, giving the same geometry to that used by Anderson and Dayem. The widths of the constrictions were between 3 and 4 $\mu$. Many samples were made under identical conditions and they all behaved similarly. The sample was placed in a wave guide which had a stationary wave inside it. The position of the sample was such that the transport current in it was parallel to, and coincident with, the maximum electric field of the microwaves. The film extended beyond the walls of the wave guide so that current and voltage leads could be attached to it. The sample was screened from magnetic fields with an iron cylinder.

Because the wave guide and the specimen were immersed in liquid helium the temperature of the film was always the same as the bath, and during measurements the pressure was kept constant to within an equivalent temperature of $\pm 10^{-4}\,^\circ$K, although the absolute accuracies of the temperatures are $\pm 10^{-3}$ °K.

The microwave power from a klystron oscillating at $9.6 \times 10^9$ cps was coupled through an isolator and a calibrated attenuator to the wave guide. The critical current was measured by plotting the current through the sample as a function of voltage on an $XY$ recorder which with a preamplifier gave 4 $\mu$V per inch on the voltage axis.

The resistance of the samples at 4.2°K was ~0.3 Ω and this did not change as the temperature was lowered until a temperature within ~15 mdeg of observing a supercurrent was reached. Here the sample was very unstable but then became stable at a slightly lower temperature with a resistance of ~0.1 Ω and without any sign of a supercurrent. A critical supercurrent of ~1$\mu$A appeared approximately 5 mdeg lower. This effect occurred in all the specimens but as yet has not been explained.

Below $T_c$, the zero-voltage supercurrent was measured as a function of microwave power.[4] The results for three temperatures are shown in Fig. 1. At $T = 3.842$°K the critical current is increased by a factor of 3.3 and at $T = 3.830$°K by a factor of 1.7. At $T = 3.79$°K there is no appreciable increase. As the power is increased beyond the maximum, the supercurrent decreases smoothly to zero, where it remains when the power is further increased.

In Fig. 2 we show the critical current with zero power, and the power that reduces the critical current to zero, as functions of temperature; over the small temperature range shown, both dependences are linear. The results for two samples are shown. The interesting point is that the extrapolated threshold power curve does not intersect the temperature axis at the same point as the critical-current curve. This suggests that over a small range of temperatures it might be possible to create a supercurrent by applying microwaves. Because of small instabilities this will be difficult to verify directly.

The current steps at finite voltages do not appear until the temperature is well below the transition temperature. It is interesting to note that Shapiro, Janus, and Holly[5] found the zero-voltage supercurrent ($n = 0$ step) for a Josephson junction to first increase with microwave power whereas theory predicts an initial decrease. This is similar to the behavior of the constriction very near to $T_c$ but at lower temperatures, when the other steps are

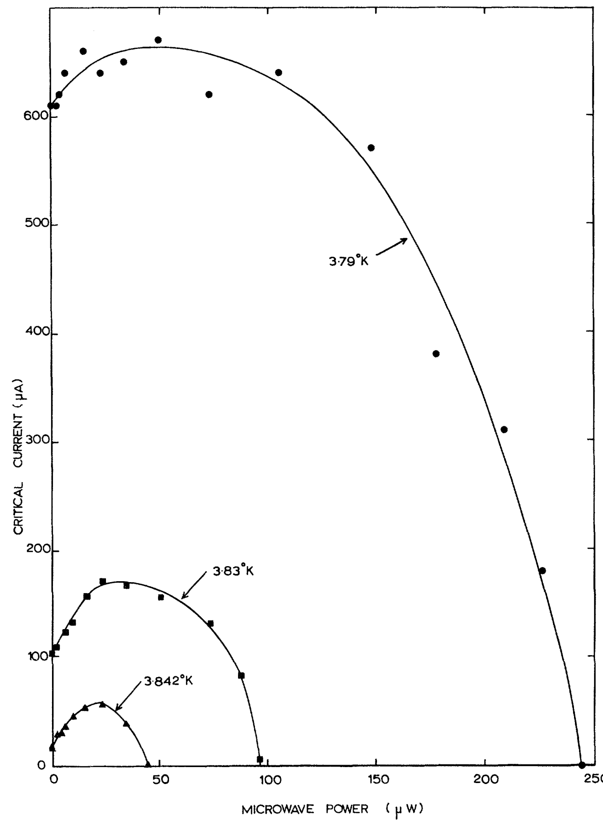


FIG. 1. Critical current through the constriction as a function of microwave power at different temperatures. The "transition" temperature of the film is 3.845°K.

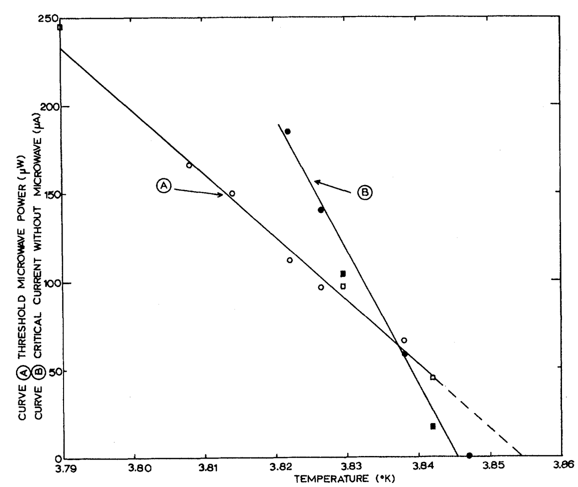


FIG. 2. Curve A shows the theshold microwave power as a function of temperature, and Curve B shows the critical current without microwaves as a function of temperature. Square characters are for the same sample as in Fig. 1. Circular characters are for an identical sample.

clearly defined, the zeroth step decreases monotonically with increasing microwave power.

Anderson and Dayem[1] explained that a normal current and supercurrent could flow down a potential difference ($V$) if the correct rate of change of the relative phase of Ginzberg-Landau wave function was maintained between the two superconducting regions on each side of the constriction. They postulated that vortices crossed the constriction transversely at a rate $r = 2eV/h$ to give this phase change. However, the same phase change can be produced by a vortex pair with the two components having opposite circulation, moving longitudinally through the constriction. Since the experiment is performed in zero applied dc magnetic field, pairs of vortices retain the two-fold symmetry of the experimental arrangement. If a pair were created, we would expect it to move in this way because initially the Lorentz force[6] tends to change the separation of the two vortices which in turn changes the interaction of one line on the other and this accelerates the pair antiparallel to the transport current.[7]

Vortex-pair production in the constriction removes energy from the superfluid and so, in the absence of microwaves, gives a criterion for the critical supercurrent that can flow at finite voltages. This situation is analogous to the ideas of Zimmermann,[8] who considered the flow of superfluid helium through a small hole under a pressure head.

If the loss mechanism is solely creation of vortex pairs,[9] we can take Zimmermann's equations with the pressure head replaced by $2eV$ and the energy of the vortex pair given by de Gennes.[10] For a constriction of rectangular cross section of width $2b$, the equilibrium superelectron flow velocity is $V_c = (\hbar/4m_e b)\ln(\lambda/\xi)$, and the critical current density is $J_c = n_s e V_c$. Close to $T_c$, $n_s$ varies linearly with $\Delta T = T_c - T$ and except very near to $T_c$, $\ln\lambda/\xi \sim 3$ which gives $J_c/\Delta T \sim 6\times10^6$ A cm$^{-2}$ deg$^{-1}$. From Fig. 2 we see that the experimental value is $J_c/\Delta T \sim 10^6$ A cm$^{-2}$ deg$^{-1}$. Although the agreement is only within an order of magnitude, we feel it provides some support for the hypothesis for the creation of vortex pairs within the constriction. Moreover, the energy of very short vortex lines in the tin film will not be the same as that of the same length of an infinite line which was calculated by de Gennes.

The effect of microwaves is more difficult to understand. At 80 mdeg below $T_c$ the microwaves have two effects. First, they generally depress the value of the supercurrent at all voltages, presumably in a similar way to a dc magnetic field. Secondly, they cause current steps to occur at periodic intervals in the dc voltage. Even when the microwave power is sufficient to remove apparently completely the dc supercurrent at zero voltage, steps are superposed on the linear $I$-$V$ characteristic.

Anderson and Dayem[1] considered that the microwaves induced an ac current in the constriction which modulated the Lorentz force on the vortex lines. The vortices will be strongly accelerated every period of the microwave field when this force is maximum. They also assume that at all voltages vortices cross at a rate $2eV/h$ which at certain voltages is equal to the driving force frequency or harmonics of it. However, it is not clear why this synchronization should lead to current steps. Also when the $I$-$V$ characteristic is strictly linear there is no dc supercurrent flowing through the constriction and hence no vortices would be created.

What is observed is that microwaves at frequency $\nu$ are able to generate a dc supercurrent at nonzero voltages $V = nh\nu/2e$. Once this current has been generated vortex pairs can be produced at the appropriate rate or once we have vortex pairs we can have a supercurrent. The two are inseparable and represent a state which is stabilized by the microwaves. It is possible that the microwaves periodically lower the energy required to create a vortex pair and so production at the microwave frequency or a harmonic of it would be energetically most favorable.

Another possibility is that at finite voltages there exists an ac supercurrent of frequency $2eV/h$. This would be frequency modulated by the microwave voltage, and when $\nu = 2eV/h$ the first sideband on the low-frequency side would have zero frequency and appear as a dc supercurrent.[5] As in the case of Josephson tunneling, we would expect the size of each step to be an almost periodic function of the microwave power. However, any variation of microwave voltage across the constriction would tend to smear out this periodicity but it is difficult to estimate whether it would be completely removed. Effects periodic with microwave power have, however, been observed in other constricted thin film experiments.[11] Further experiments are needed to clarify the situation.[12]

These considerations for relatively low temperatures clearly do not apply to those nearer to $T_c$ as here the effect of the microwaves is initially to increase the critical current. As yet we have no explanation for this effect.

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*On leave from Physical Technical Institute for Low Temperatures, Kharkov, USSR.

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# LASER PHOTON COUNTING DISTRIBUTIONS NEAR THRESHOLD

Archibald W. Smith and J. A. Armstrong*
IBM Watson Research Center, Yorktown Heights, New York
(Received 12 May 1966)

We have observed the photoelectron counting distribution produced by light from a single-mode cw gas laser operating at output powers as low as twice the threshold output. In this region we are able to detect deviations from the predictions of linearized oscillator theory. Moreover we are able to fit all our observed counting distributions to one theoretical distribution containing a single parameter which varies with laser excitation. Measurements of single-mode laser counting distributions below threshold have been reported previously.[1,2] Preliminary measurements on lasers near but above threshold have also been reported.[3-5]

The laser consisted of a dc He-Ne discharge tube with Brewster-angle windows in a 15-cm cavity; the laser wavelength was 6328 Å. The axial mode separation is 1000 Mc/sec, which is larger than the full Doppler width of the Ne fluorescence line. An aperture was placed in the cavity to reduce the $Q$ of off-axis modes and to reduce the background light from the discharge. A piezoelectric driver on one of the mirror mounts was used to tune an axial mode to the center of the fluorescence line. Under these conditions only a single mode was important for the excitations used in these experiments. The laser output was stabilized against slow drifts by means of feedback control of the discharge current; the feedback time constant was 0.03 sec.

The counting distributions were obtained using an $S$-20 photomultiplier, a 100-Mc/sec discriminator, a gated 100-Mc/sec scaler, and a multichannel analyzer. The number of counts $n$ registered during a single 0.5-$\mu$sec counting period was used as an address, and a one was added to the memory register of the $n$th channel. The process was cycled at a 16-kc/sec rate until about $10^5$ samples were obtained. This normally required less than 10 sec. The accumulated distribution was read onto punched cards for data processing. A variable attenuator in front of the photomultiplier was used to maintain an average counting rate of 2.5 per counting period independent of laser excitation. Under these conditions, dead-time and other systematic effects were found to be constant and relatively unimportant.