Modulated microwave absorption spectra from Josephson junctions on a scratched niobium wire

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Modulated microwave absorption (MMA) spectra from Josephson junction formations on a scratched Nb wire have been studied at 9.3 GHz and 4 K. The peak-to-peak separation, δH of the Josephson lines was found to vary linearly with $P^{1/2}$, where P is the applied microwave power, in contrast to a recent interpretation of junction formation in pressed lead pieces by Rubins, Drumheller, and Trybula. The interpretation of the MMA data on Nb are given in terms of the theory of Vichery, Beuneu, and Lejay for superconducting loops containing weak links. [S0163-1829(97)05118-7]

Modulated microwave absorption (MMA) spectra, consisting of many sets of narrow, regularly spaced lines, were reported originally by Blazey *et al.*[1,2] in a single crystal of the high-temperature superconductor Y-Ba-Cu-O, and attributed to Josephson junctions occurring at (110) twin planes. Similar spectra have been reported from this material and other noncrystalline conventional superconductors, such as $PbMo_6S_8$, Nb, In, and Pb.[2–7] Some features common to the experimental work are the following:[1,2,4–6,8] (i) a constant separation ΔH between neighboring lines; (ii) the existence of a microwave power threshold P_0, below which no spectrum is observed; (iii) the approximate independence of the intensity of the MMA signal on the microwave power P for $P>P_0$; (iv) an increase in the peak-to-peak splitting δH of each line with increasing microwave power; (v) an increase in δH with temperature for a given P; (vi) the occurrence of additional sets of lines as either the microwave power or temperature is increased. Other features associated with single-crystal Y-Ba-Cu-O spectra have been listed by Vichery, Beuneu, and Lejay[5] (hereafter denoted VBL). Blazey *et al.*[1] demonstrated the geometrical origin of the line separations by observing a doubling of ΔH when the crystal cleaved into two halves.

The Josephson junction spectra to be described in this work were obtained from a 3-mm length of 0.003″ diameter Nb wire, scratched with a razor blade. The MMA signals were produced by a Varian E 109 series EPR spectrometer operating at 9.3 GHz, with temperatures regulated by an Oxford Instruments ''flowthrough'' cryostat and temperature controller. The sample was placed at one end of a cylindrical cavity operating in a TE 102 mode in a position of maximum magnetic and minimum electric field. The sample could be rotated about a vertical axis, while the external magnetic field was fixed in a direction perpendicular to the microwave magnetic field at the sample. Many sets of signals were observed at all orientations of the sample with respect to the steady magnetic field. The sharpest occurred when the 100 kHz modulation was adjusted to the lowest available value of 5 mOe peak-to-peak amplitude.

Several quite distinct theories have been proposed to explain these spectra. Xia and Stroud[9] used a superconducting glass model in which a changing magnetic field causes ''phase slips'' in loops of weakly linked superconducting grains. The ensuing voltages created between neighboring grains produce energy losses through the normal resistances of the Josephson junctions. Blazey, Portis, and Holtzberg,[4] in their later work, associated the spectra with microwave-induced nucleation and annihilation of fluxons within single Josephson junctions. VBL (Ref. 5) used Silver and Zimmerman's theory[10] of superconducting loops containing one or more Josephson junctions to show that above a threshold microwave field, the fluxon state can oscillate at the microwave frequency as the sweep field is changed, leading to an energy exchange with the microwave field. Rubins, Drumheller, and Trybula[8] (denoted RDT) used a quantum interference model based on the earlier work of Drumheller, Trybula, and Stankowski[5] in which microwave absorption occurs when the field-dependent critical current of a parallel junction system is exceeded.

The existence of a periodic spectrum follows naturally from all of the above models. Three of them give a line separation

$$\Delta H=\Phi_0/S, \tag{1}$$

where ϕ_0 is the flux quantum and S is the projected area of a superconducting loop perpendicular to the steady magnetic field. Only in the theory of Blazey *et al.*[4] does the relevant area correspond to a single Josephson junction. VBL have shown from their sample dimensions, that the surface giving ΔH could not be that of a single junction. All the models, except that of Xia and Stroud[9] require a microwave power threshold, which has been confirmed experimentally.[1,2,5,6] Thus, in interpreting the data, we shall confine ourselves to the models of VBL (Ref. 5) and RDT.[8]

VBL's superconducting loop model assumes that transitions between fluxoid states can occur only when the loop current reaches a critical magnitude i_c. Each transition corresponds to the entry (or exit) of one flux quantum into (or

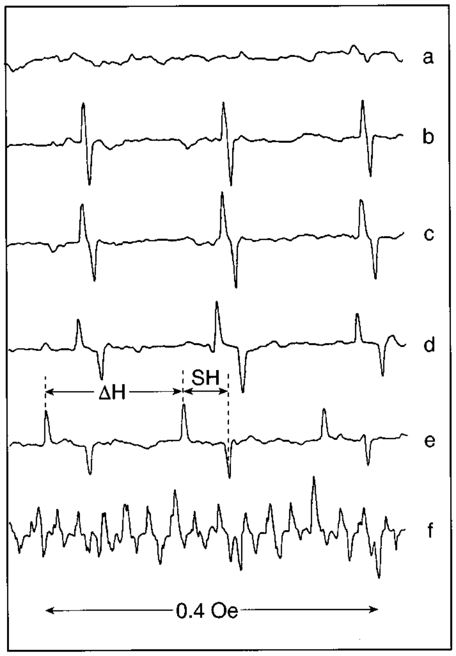

FIG. 1. Josephson junction spectra near 100 Oe from a scratched Nb wire are shown at 9.3 GHz and 3.9 K for microwave power values of 0.20 mW (curve a), 0.25 mW (curve b), 0.30 mW (curve c), 0.40 mW (curve d), 0.60 mW (curve e), and 0.80 mW (curve f). The separations δH and ΔH are illustrated in curve e. The 100 kHz modulation field in each case has a peak-to-peak value of 5 mOe.

out of) the loop. This flux change produces an instantaneous emf peak, which alone is too small for detection. However, above a threshold of the microwave field, the system oscillates between two fluxoid states at the microwave frequency, leading to a detectable signal. The signal occurs periodically

TABLE I. Variation of the peak separation δH with microwave power P for a MMA line from a scratched Nb wire at 3.8 K and 9.3 GHz.

P (mW)	δH [a] (mOe)	$\delta\alpha$ [b] (rad)
0.20	2	0.03
0.25	9	0.12
0.30	19	0.28
0.35	27	0.39
0.40	37	0.55
0 45	45	0.65
0.50	54	0.78
0.60	69	1.00
0.70	83	1.21
0.80	94	1.38
0.90	106	1 55
1.00	117	1.70

[a]Since the 100 kHz modulation field had a peak-to-peak value of 5 mOe, this number was subtracted from the actual readings of δH to correct for modulation broadening. The error in δH was estimated to be about ± 2 mOe.

[b]$\delta\alpha = \pi \delta H / \Delta H$, where $\Delta H = (215 \pm 5)$ mOe.

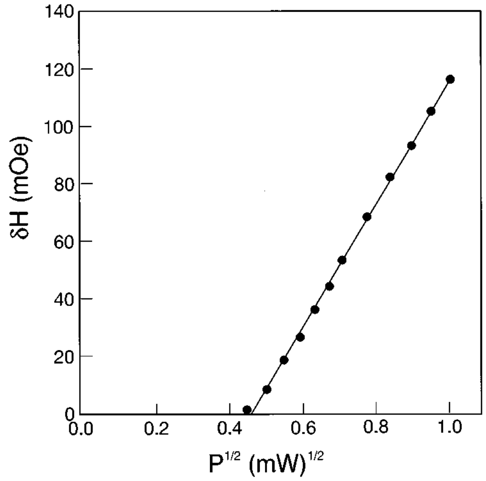

FIG. 2. A plot of δH vs $P^{1/2}$ is shown for the data of Table I. The straight line represents a least-squares fit of the data to Eq. (4) with $a = 215$ mOe/(mW)$^{1/2}$ and $b = -98$ mOe.

over a field range δH, which corresponds to the peak-to-peak splitting of each line. VBL's expression for δH is

$$\delta H = 2H_1 - \Omega / S, \tag{2}$$

where H_1 is the amplitude of the microwave field. The parameter Ω is given by

$$\Omega = 2 L i_c + (\tfrac{1}{2} N - 1)\Phi_0, \tag{3}$$

where L is the inductance of the loop, assumed to consist of N-like junctions, and i_c is the critical current. Equation (2) leads to a relationship of the form

$$\delta H = a P^{1/2} + b, \tag{4}$$

where a and b are constants, and $P(\propto H_1^2)$ is the applied microwave power.

According to VBL, the microwave power P' absorbed by the loop may be written as

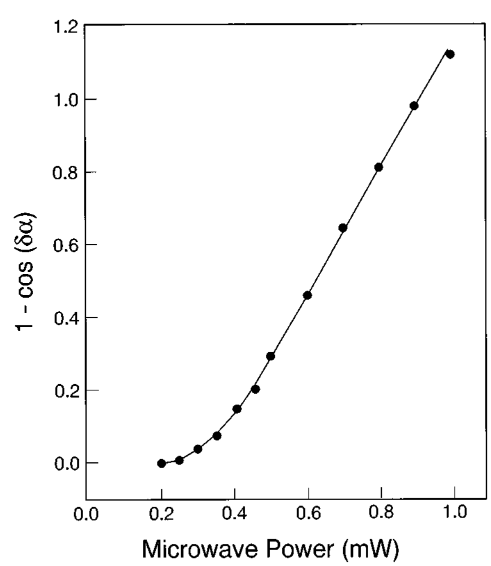

FIG. 3. A plot of $(1 - \cos\delta\alpha)$ vs P, where $\delta\alpha = \pi \delta H / \Delta H$. H is shown for the data of Table I.

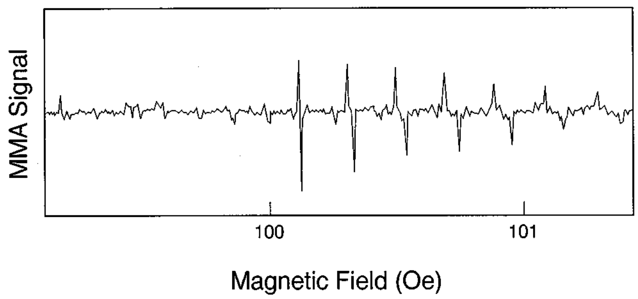

FIG. 4. A Josephson junction spectrum in which δH increases in field from line to line is shown for 9.3 GHz and 3.8 K with a 100 kHz peak-to-peak modulation field of 5 mOe and a microwave power of 0.45 mW.

$$P' = \kappa\Omega, \tag{5}$$

where $\kappa = \omega\Phi_0/2\pi L$ and ω is the microwave frequency. The EPR spectrometer detects dP/dH, where H is the slowly varying sweep field. Since the MMA absorptions are step functions, the magnitude of dP'/dH should be proportional to P'. Thus, according to Eqs. (3) and (5), the peak-to-peak magnitude of the MMA signal should increase as i_c increases.

RDT use a simple quantum interferometer model containing two parallel Josephson junctions with unequal critical currents. The net effect is a total critical current $i_c(H)$, which varies periodically with the applied magnetic field H. Absorption occurs when the effective current produced by the microwave source, which is assumed to be proportional to the square root of the microwave power, is greater than i_c. According to this model,

$$P = P_0 + k(1 - \cos\delta\alpha), \tag{6}$$

where P is the microwave power, P_0 is the threshold power, k is a constant, and $\delta\alpha = \pi\delta H/\Delta H$. For $\delta\alpha \ll 1$ (i.e., $\delta H \ll \Delta H$), this expression reduces to a linear relationship between $(\delta H)^2$ and P, i.e.,

$$(\delta H)^2 = cP + d, \tag{7}$$

where c and d are constants.

It may be seen from Eqs. (4) and (7), that the measured relationship between δH and P gives a clear method of distinguishing between the two theories. Equation (4) has been found to fit measurements in both powder and single-crystal samples of Y-Ba-Cu-O,[1,3,5] while Eq. (6) fitted the data for pressed lead pieces analyzed by RDT.

In our experiments, peak-to-peak widths δH and line separations ΔH were measured as functions of the microwave power P. Figure 1 shows a typical set of spectra obtained for a field range of about 0.5 Oe centered near 100 Oe. Curves a–f show how the spectrum changed as the microwave power was varied from 0.2 to 0.8 mW. No signal was observed in curve a, indicating a threshold power $P_0 \simeq 0.20$ mW. Curve b shows that a sharp signal was observed for $P = 0.25$ mW. The 7-mOe peak-to-peak width of this signal was probably an artifact associated with the comparably sized modulation field.[8] Curves c–e show a monotonic increase of the peak-to-peak splitting δH with increasing microwave power, while curve f shows the appearance of new sets of Josephson junction spectra with increasing microwave power, as first observed by Blazey et al.[2]

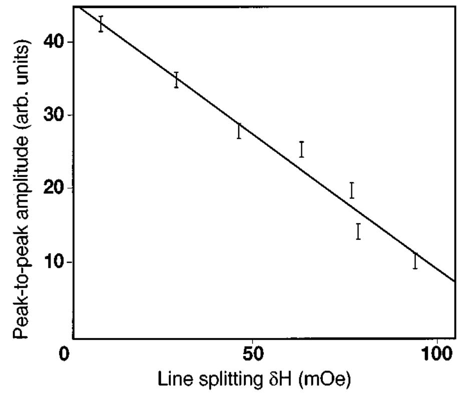

FIG. 5. The peak-to-peak heights vs the peak-to-peak separations (δH) are shown for the data of Fig. 4. The straight line represents a linear least-squares fit of the data points.

Data for one member of a set of lines, similar to that shown in Fig. 1, are given in Table I. Plots of δH versus $P^{1/2}$ and $(1-\cos\delta\alpha)$ versus P for these data presented are in Figs. 2 and 3, respectively. These show decisively that Eq. (4) is satisfied over the complete range, while appreciable deviations from Eq. (5) occur for the data at low microwave powers, indicating the failure of the RDT theory in this case. Thus, we confine our interpretation to the VBL theory.

As pointed out by VBL, the effective area of a Josephson junction s may be obtained from the magnetic field $H_{\min}$ at which the first intensity minimum in the envelope of the multiline spectrum occurs, through the relationship

$$s = \Phi_0/H_{\min}. \tag{8}$$

As might be expected, a wide variety of values for s were obtained in the present work. At one extreme was a set of lines which were observed from near zero field to above 4.5 kOe. An apparent intensity minimum near 1.8 kOe would, according to Eq. (8), correspond to a value for s of approximately 0.01 $(\mu\mathrm{m})^2$. At the other extreme were spectra of the sort shown in Fig. 4, in which there is an appreciable difference in splitting δH for two neighboring Josephson lines. Here, $H_{\min}$ would be replaced in Eq. (8) by the field range of the spectrum (≈ 1.2 Oe), leading to a value of s of roughly 10 $(\mu\mathrm{m})^2$.

Spectra like those shown in Fig. 4 may be explained by the VBL theory in terms of a critical current i_c which decreases appreciably with increasing field over a field range of less than 1 Oe. Equations (2) and (3) show that for a fixed microwave power, decreasing i_c would decrease Ω and therefore increase δH provided that $\Omega < 2H_1S$. For constant microwave power, the relationship between δH and i_c is of the form

$$\delta H = m - n i_c, \tag{9}$$

where m and n are positive constants. If $\Omega > 2H_1S$, no spectrum is observed, as is the case in Fig. 4 for fields below 100.1 Oe.

The peak heights depend on the absorbed power P', which, from VBL's theory, may be written as

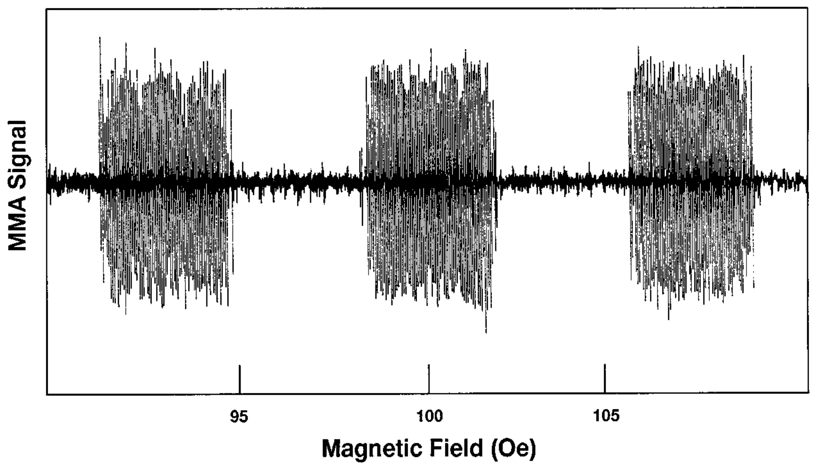

FIG. 6. A portion of a Josephson junction spectrum with a line separation of about 50 mOe is shown over a range of about 20 Oe at 4.0 K and 9.3 GHz with a 100 kHz modulation field of 5 mOe and a microwave power of 0.45 mW.

$$P' = p i_c + q, \tag{10}$$

where p is a positive constant. Thus, Eqs. (9) and (10) may be combined to give

$$P' = C - K\delta H, \tag{11}$$

where $K = p/n = \omega\Phi_0 S/2\pi L$ is a positive constant and the subscripts i and j refer to the ith and jth lines, respectively. If the peak-to-peak height of the signal is assumed to be proportional to P', then a test of Eq. (11) may be made on the MMA data of Fig. 4. The resulting graph, displayed in Fig. 5, shows that the data are essentially consistent with Eq. (11) and VBL's theory.

In Fig. 6, we show a set of Josephson lines of separation $\Delta H = 50$ mOe over a field range of about 20 Oe. On this scale, the envelope of the spectrum stands out. In Fig. 6, this appears as a series of uniformly spaced square-wave functions with both width and separation of about 3.4 Oe. In interpreting this result, it is important to realize that the envelope of the Josephson junction spectrum does not give the dependence of i_c on field directly. While, according to Eq. (10), the absorbed power varies linearly with i_c, the sharp edges to the envelope are probably related to the passing of the parameter $\Omega(i_c)$, given by Eq. (3), through the value $2H_1S$ [see Eq. (2)].

While spectra of the type shown in Figs. 4 and 6 indicate that further experimental work is needed to unravel the complexities of the Josephson junction spectra, the present study has shown that the dependence of δH on the microwave power fits the VBL theory for junctions in series rather than the RDT theory for parallel junctions. On the other hand, the data for the pressed lead pieces fitted RDT's quantum interferometer model. This result agrees with the field dependence of the critical current obtained by Barone *et al.*[11] from junctions between a niobium film and Y-Ba-Cu-O pellet, which was characteristic of a quantum interferometer.

In conclusion, we note that the δH versus P dependence is a subtle way of distinguishing between series and parallel Josephson junctions. We plan to fabricate samples in which both types of behavior are present at the same time.

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