of spin dynamics, by the appearance of a spread in angles and magnitudes of the slow components of the local fields. Thus, experimental facts do not actually hint toward a usual kind of magnetic phase transition at T_G although the existence of a fairly well-defined, unique temperature at which all (or almost all) spins are correlated seems to be emerging from a host of different experiments, including EPR,[11] with the possible exception of neutron scattering with finite wave-vector transfer.[5]

A possible picture which comes to mind and accounts for the behavior of A is due to Smith[12] and it is that of small clusters forming above T_G and growing so as to become linked together at T_G. The proportion of clustered spins varies with temperature as shown in Fig. 1. The dynamical behavior of clustered spins is represented by an average fluctuation time τ_e in Fig. 3. However, the absence of transitional features on τ_e—that the dynamical properties of a given spin in a finite cluster slightly above T_G are little different from its behavior on the infinite cluster slightly below T_G—does not hint at the existence of a cooperative phenomenon at T_G.

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High-Frequency Behavior of "Ideal" Superconducting Point Contacts

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We have studied niobium point contacts which are very consistent and reproducible from junction to junction, in both their dc and high-frequency behavior. We find a strong correlation between the sharpness of the gap structure and the ac Josephson effect, and we present the first quantitative measurements of the far-infrared frequency dependence of the Josephson effect above the energy gap. The measured I-V curves are also compared with available theoretical models.

Of all the types of superconducting weak links that exhibit the ac Josephson effect, niobium cat-whisker point contacts[1] have the best high-frequency performance, and have shown direct evidence of the ac Josephson effect up to about 6 times the energy-gap voltage.[2] Their very small area minimizes the shunt capacitance,[1] while their three-dimensional geometry and high resistance minimize the effects of heating,[3] making them the best type of weak link for a study of the behavior of the ac Josephson effect at high frequencies. Unfortunately, the dc I-V curves and high-frequency behavior can vary considerably from junction to junction. We have conducted a systematic study of cat-whisker point contacts and have correlated the high-frequency behavior and the characteristics on the dc I-V curves of the various types of junctions commonly obtained. We find that those junctions with the best high-frequency performance have both a shape of dc I-V curve[4] and a high-frequency behavior[5] that are consistent and reproducible from contact to

contact, suggesting that they are approaching the "ideal" low-capacitance, clean point contact. Furthermore, this consistency and reproducibility has allowed us to study the unique characteristics of this sort of junction, and to make the first quantitiative measurements of the strength of the ac Josephson effect at far-infrared (FIR) frequencies well above the energy gap. We report these results in this Letter, and compare both the frequency dependence of the Josephson effect and the shape of the ideal dc I-V curve with available theories.

We study the high-frequency behavior by monitoring the Josephson steps induced on the dc I-V curves by an optically pumped FIR laser. The existence of a step at a voltage, V, is direct evidence of the ac Josephson effect at the frequency $\omega = 2eV/\hbar$. The maximum current width of the fundamental step is a measure of the strength of the ac Josephson effect at this frequency. We use FIR frequencies extending from about half to nearly twice the gap. The technical details of these measurements will be presented elsewhere.[6]

The I-V curve of a typical high-quality point contact is shown in Fig. 1. Such junctions readily show ac Josephson steps when irradiated with any FIR laser frequency up to 2.52 THz (119 μm). Their dc I-V curves show the following characteristic features: (i) an I_cR product very near the theoretical value of ~2.2 mV (within 20%); (ii) a very steep, and sometimes slightly hysteretic voltage onset to $V_j \sim 0.5 I_c R$; (iii) pronounced structure at the energy-gap voltage (~2.8 mV); and (iv) a linear region just above the gap which extrapolates back at zero voltage to an "excess current", $I_{ex} \sim 0.8 I_c$. The differential resistance just above the gap is taken as a measure of the resistance, R, of the junction; it is found to be equal to the resistance when enough laser power is coupled into the contact to drive it Ohmic. These four features are *very* reproducible from junction to junction for the point contacts that show good response to the FIR laser radiation.[4]

We find a very strong correlation between the existence of the high-frequency ac Josephson effect and the sharpness of the structure at the energy gap. We characterize this sharpness by the parameter S, defined as the ratio of the differential resistance just above the gap (R) to that just below the gap (r). (See Fig. 1.) All our high-quality point contacts have values of S greater than ~2.0, and readily show a Josephson step above 5 mV. In Fig. 2. we plot N_{max}, the highest observed harmonic of the 1.25-mV step induced by 496-μm radiation, against S for those junctions for which sufficient laser power was available to establish a definite maximum. The approximately linear dependence of N_{max} on S makes the sharpness parameter very useful for identifying individual point contacts which will work well at high frequencies. The strong correlation observed tends to support, but does not prove, a casual link between the Josephson effect and the gap-related structure.[7]

The consistency and reproducibility of our point contacts, as well as their excellent high-frequency response, have allowed us to make a quantitative study of the voltage dependence of the strength

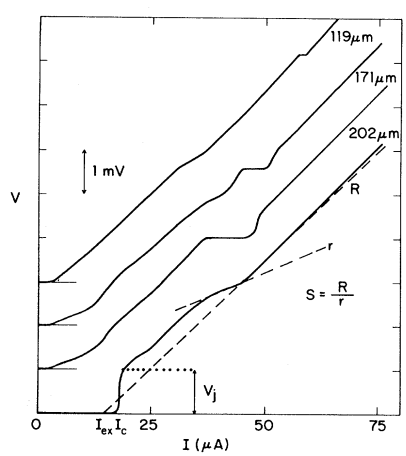

FIG. 1. dc I-V curves of a typical high-quality junction. The lowest curve is with no incident radiation, and shows the characteristic features of these I-V curves. The remaining curves show the Josephson steps induced by radiation at three different FIR wavelengths.

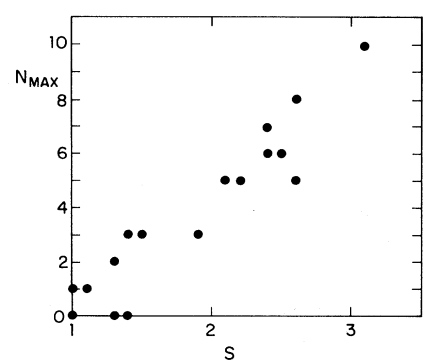

FIG. 2. N_{max}, the highest harmonic of the 1.25-mV step induced by 496-μm radiation, plotted against the gap sharpness parameter, S, for those junctions for which there was enough laser power to determine a definite N_{max}.

of the ac Josephson effect. In Fig. 3, we plot (solid circles) the maximum observed current half-widths of the fundamental ($N=1$) Josephson step, I_1^{max}, normalized to the zero-power critical current, as a function of the step voltage normalized to the energy gap (taken as 2.8 mV). The laser lines used were at 496 μm (0.604 THz), 233 μm (1.28 THz), 202 μm (1.48 THz), 171 μm (1.76 THz), and 119 μm (2.52 THz). The measured step widths must be corrected by (10–15)% for the effects of heating and substantially more for the effects of noise rounding.[5] Fitting our data to the noise-rounded step shape predicted by Stephen[8] has allowed us to estimate the step half-widths in the absence of noise. Our best estimates for these values corrected for noise and heating are also plotted in Fig. 3 (crosses). The vertical error bars are a measure of the uncertainty in our fitting process, while the horizontal error bars indicate the uncertainty (~10%) in the exact voltage of the energy gap, reflecting the width of the structure on the dc I-V curve. Nevertheless, the data show a definite trend, peaking near the energy gap and rolling off beyond it.

Such a peak and rolloff are predicted by Werthamer's frequency-dependent self-coupling (FDSC) theory.[9] The simplest version of this theory is for the voltage-bias approximation, shown as the solid line in Fig. 3. In a real experiment, the gap-related singularities are expected to be rounded off,[10] and the theoretical curve should also be altered at low voltages (frequencies) because our point contacts are more nearly current-biased than voltage-biased. The dashed line in Fig. 3 shows the reduction expected at low voltages for a current bias within the frequency-independent, resistively-shunted-junction (RSJ) model.[11] At the lowest frequency shown (496 μm) we have used a time-domain formulation[12] of the FSDC theory, applied to a current-biased junction, to calculate $I_1^{max}/I_c \approx 0.35$, similar to the RSJ model prediction and in reasonable quantitative agreement with the data. At higher voltages, the results should be less sensitive to the type of bias, and the numerical discrepancies between the voltage-bias version of the FDSC theory and the observed data are not yet understood. Relaxation-time effects[13,14] may provide an additional rolloff mechanism, although the substantial decrease that we observe just above the energy gap does not seem to be explained by the RSJτ model,[13] except by using a relaxation time that is at least an order of magnitude longer than expected from time-dependent Ginzburg-Landau (TDGL) theory. Furthermore, the internal consistency of the RSJτ model has been questioned,[15] and more theoretical work is required before we can make a quantitative comparison with our data.

The reproducibility and consistency of our "ideal" point contacts provide hope for an eventual theoretical description of the dc I-V curves.

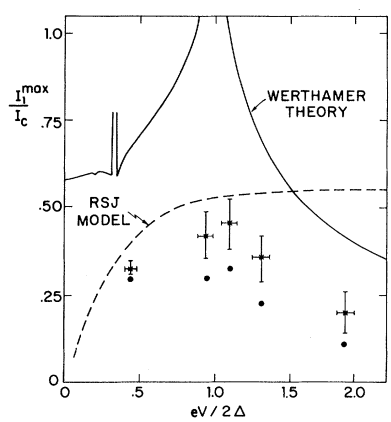

FIG. 3. The voltage dependence of the ac Josephson effect. The maximum width of the fundamental Josephson step normalized to the critical current is plotted against the step voltage normalized to the energy gap. The dots represent the measured data, while the crosses represent the values corrected for the reductions due to noise and heating.

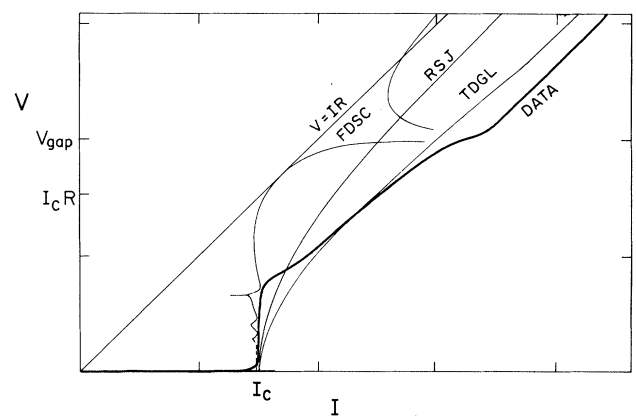

FIG. 4. Comparison of an "ideal" I-V curve with the results of the calculations based on three theoretical models. All three theoretical curves are scaled to have the same normal resistance as the data. The RSJ and TDGL curves are scaled to have the same critical current while the FDSC curve is scaled to have the same gap voltage as the data. The TDGL curve is calculated for a constriction one coherence length long and for an order-parameter relaxation time as given by microscopic theory for the dirty limit.

In Fig. 4, we compare an I-V curve of a typical high-quality junction with the available theoretical predictions of three different models, each scaled to fit the data. The smooth, structureless RSJ curve provides a qualitative description, but does not contain any of the distinctive features of the data. McDonald, Johnson, and Harris[16] have used the FDSC theory to calculate the I-V curve of a current-biased, zero-capitance tunnel junction. This prediction does show large currents below the gap (unlike the more familiar capacitance-dominated tunnel-junction I-V curve), but it is calculated for $T=0$ and for an ideal BCS density of states, leading to the sharply singular structure at the gap. A more realistic handling of the singularity and a treatment of the effect of current-induced disequilibrium in the electrodes is necessary before any more-quantitative comparison with the data can be made. The major feature not accounted for by the FSDC model is the obvious "excess current" above the gap. Calculations[14,17] which apply TDGL theory to short metallic constrictions have been shown to contain this feature with approximately the correct magnitude. The TDGL curve shown in Fig. 4 was calculated[17] for a constriction length equal to the coherence length, and for the value of the order-parameter relaxation time predicted by microscopic theory. Since the physical characteristics of the minute active region at the point contact are not known in detail, it is difficult to decide *a priori* the best way to model the junction theoretically. Some synthesis of the present models, each of which seems to explain some features of the observed I-V curves, may be required. A more detailed treatment is clearly desirable, and we hope that the reproducible and consistent behavior of junctions like ours will help stimulate the search for such a model.

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