COHERENT AC JOSEPHSON EFFECT IN A BULK GRANULAR SUPERCONDUCTING SYSTEM*

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ABSTRACT

A three-dimensional close-packed array of Josephson junctions was successfully produced in the form of a bulk granular superconductor. The granular system is a tightly compressed solid of oxide coated small tin particles in the thousand Å range. The three-dimensional array of Josephson junctions thus formed showed coherent Josephson oscillations when external rf radiation was imposed. rf induced constant voltage steps were observed on its I-V characteristics at voltages a few thousand times the Josephson voltage $h\nu/2e$. The external rf radiation also induced stable dc voltages on unbiased bulk samples, suggesting a practical mode of microwave detection. The analogy of this bulk superconducting system with a magnetic spin system will be discussed.

1. INTRODUCTION

The applicability of Josephson junctions for sensitive radiation detection over a wide frequency range is well known. The next step is to use them in an array so that the signal level may be raised to a convenient value and the impedance may be tailored to fit the circuit and thereby improve the coupling, which is a serious problem for single junctions. Also, when working coherently, the array of junctions can further improve the signal to noise ratio of the device since the signal goes as N , the number of junctions, while the noise voltage goes as $\sqrt{N}$.

We took the approach of forming such an array system inside a composite material; the bulk granular superconductor.¹ It has the advantage of requiring only simple fabrication and handling technique to attain a large density of Josephson junctions. Our granular system to be reported here was formed by pressing together very fine tin particles which had been coated with a thin layer of naturally grown oxide. The tin particles were produced by evaporating tin slowly in a helium atmosphere of a few torrs pressure and collecting them on a glass surface at room temperature. The sizes of these tin particles, as determined by electron microscopy, ranged from a few hundred Å to a thousand Å. The particles were then compressed in a hollow insulating cylinder into a 0.4 cm diameter disc with a similar dimension in thickness. The dc resistance ranged from a hundred kilo-ohms to a hundred ohms. The resistance indicates the amount of coupling among particles and values close to one kilo-ohm or below were usually chosen. Indium contacts were pressed on for electrical measurements. A similar system using aluminum particles had been examined.² Conduction through our granular system was found to be dominated by tunneling through the interparticle oxide barriers. This can be seen on Fig. 1 which shows the temperature dependence of the critical current for a hundred ohm sample which very closely follows that predicted for a Josephson tunnel junction.³ For weakly coupled samples with higher resistivity, the resistive transition usually has a "tail" region characteristic of a fluctuation dominated transition. These large

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Fig. 1. Comparison between the temperature dependence of the critical current of a granular sample and the theoretical prediction of Ambegaokar and Baratoff for Josephson tunneling current.

numbers ($\sim 10^4$) of small superconducting particles are weakly coupled to each other through tunneling, forming a 3-dimensional random array of Josephson weak links.

The samples were tested for the ac Josephson effect in the frequency range from ten to a hundred megahertz. Since it is a 3-dimensional random array, charge conservation alone can no longer force the arrays to work coherently as in the case of a 1-dimensional array. The rf current can choose its own path through the granular system to satisfy charge conservation. Interaction among junctions is mostly through electromagnetic fields, both external and from individual junctions. There had been speculations⁴ and some experimental evidence^{2,5} that an interacting Josephson junction array can form a superradiant state with a coherent ac Josephson effect. Here we are going to present experimental evidence of such a coherent state in our granular system.

II. COHERENT PHENOMENA

Radiation induced constant voltage steps of sizes comparable to the critical currents were observed on I-V characteristics of samples at voltages as high as a few thousand times the Josephson voltage $h\nu/2e$, where ν is the frequency of the external radiation. Figure 2 shows the V-I characteristics of a granular sample subjected to 24 MHz radiation. Current steps with a gentle slope were observed at as high as 150 μ V which is practically 3000 times $h\nu/2e$. There is no evidence of higher order steps. We believe that most of the junctions were probably biased at the first order step ($n=1$, $V_{DC}=h\nu/2e$) at which the internal oscillation frequency of the junctions is the same as that of the external radiation, and frequency pulling⁶ is most effective. This suggested that as many as 3000 Josephson junctions in series were each biased at step voltage $h\nu/2e$ despite the randomness of the array. The gentle slope of the voltage step probably reflects the noise and nonuniformity of the junctions in the array. The dc voltage at the step also increases with rf power, indicating that more

Fig. 2. V-I characteristics of a granular sample subjected to different levels of 24 MHz radiation.

Josephson junctions are being driven in unison with the applied radiation and are contributing to the current step. This may be the reason why no Bessel function behavior with rf voltage was observed on the step size.

A direct observation on the coherence of the internal Josephson oscillation was made by measuring the radiation coming out from the granular system. Figure 3 shows the rf voltage across a granular

Fig. 3. Curve A shows part of a current step on the V-I characteristic of a granular sample subjected to 33 MHz radiation. Curve B shows the rf voltage across the sample as the bias current was swept into the step.

sample as the bias current was swept into the step. We observed a weak (<1%) amplification of the rf by the granular sample when it was biased right at the low current end of the voltage step. This is exactly the bias point at which Stancampiano and Shapiro⁷ observed rf amplification by injection locking in a single Josephson junction. This was followed by a strong absorption mode when biased into the step. With a frequency resolution of 3 kHz we failed to notice any appreciable change in the line width of the radiation which is less than 3 kHz. Periodic magnetic field modulation of the rf voltage was also observed in both amplification and absorption modes, with a typical period of about 50 mΩ.

All of these results imply that the granular system behaved like a giant Josephson junction. This is to be expected from a partially coherent super-radiant state. In the superradiant state, the Josephson oscillations not only radiate with a uniform frequency but also with the same phase $\phi(t)$. If it has a series chain with n junctions, it will resemble a giant single junction with Josephson frequency $\omega = 2eV/\hbar$ where V is the total voltage across the chain. As the dc voltage bias is swept through the step voltage the coherent radiation can add either constructively or destructively with the external radiation, depending on the relative phase. For a single Josephson junction subjected to external rf radiation, it was shown^{8,9} that parametric amplification is possible when biased just at the low current edge of the first step. This explains the amplification observed. When the single junction is biased in the current step, the relative phase between the external rf and the internal oscillation is determined by the bias position. The dc component of the tunnel current when biased at the first ($n=1$) step with external radiation $V_{rf} \cos \omega t$ is given by

$$I_{DC} = -I_0 J_1 \left(\frac{2eV_{rf}}{\hbar\omega} \right) \sin \phi_0 \quad (1)$$

while the component at the rf frequency is given by

$$I_{\omega} = I_0 J_0 \left(\frac{2eV_{rf}}{\hbar\omega} \right) \sin(\omega t + \phi_0) + I_0 J_3 \left(\frac{2eV_{rf}}{\hbar\omega} \right) \sin(\omega t - \phi_0). \quad (2)$$

When the current bias sweeps through the $n=1$ step, $\sin \phi_0$ goes from +1 to -1, I_{ω} has a component in phase with V_{rf} , and the junction looks resistive and dissipates rf power. In our sample, the arrangement of the dc current paths is too complex to predict the distribution of the phase factor $\sin \phi_0$, but it probably gives a good qualitative explanation for the absorption mode.

The external rf radiation also induced dc voltages across unbiased granular sample similar to that across an unbiased single Josephson junction. For a single junction, all those discrete voltages $V_n = \hbar\omega/2e$ ($n=0,1,2,\dots$) can be induced across the irradiated junction. The magnitude V_{rf} of the rf determines the few values of V_n it can take. It was shown that¹⁰

$$V_n = -RI_0 \left| J_n \left(\frac{2eV_{rf}}{\hbar\omega} \right) \right| \sin \phi_n \quad (3)$$

where R is the resistance of the junction. Since $\sin \phi_n$ can take up any value from +1 to -1, V_n is not unique and can switch both in amplitude and polarity and this was observed experimentally.¹⁰

In contrast to a single junction, our bulk granular system gives a stable and reproducible dc voltage which was observed to reach a value as high as a thousand times $\hbar\omega/2e$. The huge number of junctions and the partial coherence probably contribute to the stability. The dc voltage so induced oscillated in polarity with rf power (Fig. 4) which may reflect the

Fig. 4. rf induced dc voltage as a function of rf power at different magnetic fields.

Bessel function behavior in equation 3. Magnetic field modulation of this rf power dependence was also observed. This phenomenon suggests a very promising mode of radiation detection. Besides its relatively simple operation, the rf response defined as signal voltage per unit rf power absorbed may have a frequency dependence that surpasses that for a single junction in the conventional mode at microwave frequencies. With this new mode of detection, the induced dc voltage is expected to be proportional to the frequency as the Josephson's voltage frequency relationship. Consider a junction which is subjected to a small V_{rf} so that by equation 3 only $V_{DC} \sim \hbar\omega/2e$ can be induced across it. Since the Josephson tunneling is non-dissipative, the only rf power required is to supply the dissipation $V_{DC}^2/R + V_{DC}^2/R \sim V_{DC}^2/R$. So the rf response $= V_{DC}/(V_{DC}^2/R) = R/V_{DC} = 2eR/\hbar\omega$. For a one ohm junction at 10 GHz, this is about 5×10^4 volts/watt, comparable to other modes of detection using Josephson effects and it drops off only with the first power of the frequency. Analysis on modification of I-V characteristics of single junctions by external rf radiation gives a response that drops off with the square of the frequency. This rf response makes the granular system an attractive candidate for sensitive detection in the microwave region.

III. THE SPIN ANALOGY

To a certain extent, this system is analogous to a system of weakly interacting 2-dimensional spins. The Josephson current $I = I_0 \sin \phi$ tunneling from one superconductor to another with a phase difference ϕ

is just the projection on the y-axis of a vector of modulus I_0 making an angle ϕ with the x-axis (Fig. 5).

Fig. 5. The vector representation of the Josephson current and the superradiant state.

With the application of an electric field, the vector precesses in the x-y plane with an angular frequency $\omega = 2eV/\hbar$ where V is the voltage across the junction. This is very similar to a magnetic moment precessing in a magnetic field. The superradiant state corresponds to both uniform precession rate and same phase angle $\phi(t)$. The occurrence of the current step in our experiment indicated that our dc biased granular system is close to such a state and a uniform precession angular velocity of the 2-dimensional spins can easily be induced by the external radiation through frequency pulling. The amplification phenomenon is a form of stimulated emission of radiation from these spins and it also shows a partial coherence among the phases ϕ . Both the absorption and emission modes at the step voltage bears a strong resemblance to the behavior of a spin system in a spin resonance experiment with the dc voltage replacing the dc magnetic field to tune the precession frequency to the external radiation. This simple spin description is particularly attractive for our bulk sample where cross fields may be applied and many spin related phenomena may find their analogy in this granular solid which displays Josephson effects.

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