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Investigation of Microwave-Induced dc Voltages across Unbiased Josephson Tunnel Junctions*

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We have studied the power dependence of the microwave-induced dc voltages across "unbiased" Pb—Pb oxide—Pb Josephson tunnel junctions and found a systematic dependence. We have also found that the Josephson effect in the form of induced quantum voltages was observable in a large dc magnetic field as high as 0.5 kG, about one-half of the H_{c2} of the superconducting Pb film.

I. INTRODUCTION

It is commonly known that when a Josephson junction is exposed to external microwave radiation of frequency ν and dc biased at a voltage $V_n = nh\nu/2e$, a zero-resistance dc current will flow resulting from the interaction between the microwave field and the ac Josephson current.[1] These dc currents appear in its current-voltage (I-V) characteristic as current steps[2] at constant voltages

V_n. This manifestation of the ac Josephson effect has been extensively studied and its application has been successfully made to determine with high accuracy such an important constant as e/h.[3] Another interesting manifestation of the ac Josephson effect, first observed by Langenberg *et al.*,[4] is that when a junction is exposed to microwave radiation alone and left *unbiased*, dc voltages (sometimes quantized) can be induced across the junction. According to Langenberg *et al.* the microwave-induced dc voltages depended on the microwave power and dc magnetic field in a complicated fashion. Perhaps owing to these complicated parameter dependences, this latter manifestation of the ac Josephson effect, although it appeared to offer a simple way to study directly the interaction between the Josephson junction and the external radiation, has not been further studied. In this paper, we report our investigation of this latter phenomenon by using samples of simpler geometry, and with a different technique to detect voltage. Our results reveal that the transition of the induced voltages has a systematic dependence on the power of the external microwave radiation. The observed power dependence indicates that a Josephson tunnel junction can be used to detect external radiation with a very simple arrangement (a voltmeter alone).

II. THEORY

According to the phenomenological theory,[5] when a Josephson junction is dc biased at a voltage V and is simultaneously driven by microwave radiation of voltage v and frequency ν, the superconducting tunneling current I can be given by

$$I = I_J \sum_{n=-\infty}^{\infty} \left| J_n\left(\frac{2ev}{h\nu}\right) \right| \times \sin\left[2\pi\left(\frac{2eV}{h} - n\nu\right)t + \phi_0 - n\theta\right] \quad , \quad (1)$$

where I_J is the Josephson current amplitude, J_n is the nth-order Bessel function, and ϕ_0 and θ are the phases of the Josephson junction and the microwave voltage, respectively. Equation (1) shows that, at the voltage V, there are, in general, numerous ac components of supercurrent of frequencies $(2eV/h - n\nu)$, where n is an integer. At particular voltages $V_n = nh\nu/2e$, the supercurrent will have, in addition to many ac components of frequency ν and its harmonics, a dc component

$$I_{dc} = I_J \left| J_n(2ev/h\nu) \right| \sin(\phi_0 - n\theta) \quad , \quad (2)$$

where, for a fixed v, I_{dc} is determined by the relative phase $\phi_n = \phi_0 - n\theta$, and vice versa. Although Eq. (2) is obtained under the condition that a dc voltage of V_n is first *applied* across the junction, experimentally it is often convenient to control the current I_{dc} to force the junction to develop the voltage. The experimental results show that Eqs. (1) and (2) are still correct in describing the situation in which the current and the voltage reverse roles. To be more precise, in most experimental arrangements where a junction I-V characteristic is swept, the biased current I_{dc} is actually controlled by an external emf E according to

$$\frac{E - V_n}{R} = I_{dc} = I_J \left| J_n\left(\frac{2ev}{h\nu}\right) \right| \sin\phi_n \quad , \quad (3)$$

where R is the total resistance in the external circuit. V_n and I_{dc} as well as ϕ_n are all dependent variables determined by E and v. Because of the fact that there are two independent variables in one equation, each of the three dependent variables has a wide range of solution as a function of E and v.

We assume here that Eq. (3) still holds for $E = 0$. (To save the confusion hereafter we use the term "unbiased" for $E = 0$ instead of $V = 0$.) For this case, the parameters E and I_{dc} can be dropped from Eq. (3) since I_{dc} is now related to V_n by $I_{dc} = -V_n/R$. Equation (3) becomes that of only one controlling parameter v, i.e.,

$$-\frac{V_n}{R} = I_J \left| J_n\left(\frac{2ev}{\hbar\nu}\right) \right| \sin\phi_n \quad . \quad (4)$$

Unlike the case where E is nonzero and adjustable, the unbiased junction can remain in a V_n for a very limited range of v since $\sin\phi_n \le 1$. For example, V_n is stable only if $|J_n(2ev/h\nu)| \ge |V_n/RI_J|$. Therefore, only for a large enough R and for a certain range of v can V_n be a stable voltage across the junction. After the junction has assumed a particular V_n, and if v is varied such that $|J_n(2ev/h\nu)|$ approaches $|V_n/RI_J|$, the junction will make a transition to a new voltage which again satisfies Eq. (4). The new V_n will probably be the one which has $J_n(2ev/h\nu)$ near maximum as it can be locked to the microwave with a small relative phase ϕ_n. In practice, a voltmeter has a large R and therefore quantum voltages can be easily induced. The termination of V_n and the transition will take place at v corresponding to $J_n(2ev/h\nu) \simeq 0$. The stable V_n's as a function of $X = 2ev/h\nu$ according to the above arguments are given in Fig. 1. In the direction of increasing X, the horizontal bars in the figure each start at J_n = maximum and end at $J_n = 0$. The right end of each bar represents the point where the junction will be decoupled from the microwave. Hence, the main difference between the experimental conditions of a biased junction and an unbiased one is that in the former, because of the multiple relationships among V, I, and v, the junction can be biased at any V_n over a wide continuous range of v, but in the latter, because of the fact

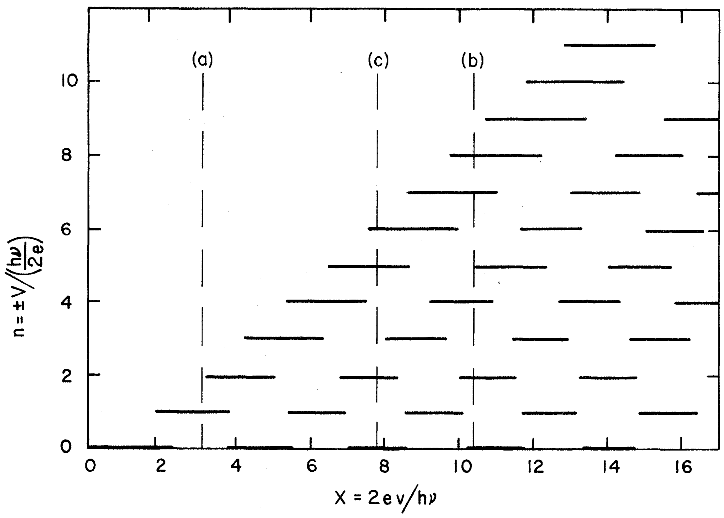

FIG. 1. Allowed quantum voltage states (both polarities) as a function of effective microwave voltage. The explanations for the horizontal bars and the dashed lines are given in the text.

that there is only one independent controlling parameter v in Eq. (4), the response of V_n to v is systematically restricted in a limited range.

III. SAMPLE AND EQUIPMENT

A. Sample

In order to minimize the effect of junction capacitance which we have neglected in the theoretical discussions in Sec. II, we have chosen to use samples of small junction area. The samples we used were tip-overlap thin-film Pb–Pb oxide–Pb tunnel junctions.[6] The Pb films of thickness roughly 1500 Å each were evaporated in vacuum of 10^{-6} torr at a rate of 20 Å/sec. The tunnel barrier was obtained by oxidizing the first Pb film in pure oxygen for several hours. A typical junction area was about 10^{-6} cm^2 and the junction resistance was of the order of ohms. These junctions were sensitive to the microwave radiation and had uniform response over the frequency range we studied. They were also free from the possible complications arising from an interaction between the Fiske mode[7] and the microwave radiation.

B. Equipment

The sample was placed in and near one end of an X-band rectangular waveguide which had an adjustable termination. During the course of the power-dependence study, the termination was first adjusted to optimize the coupling between the microwave and the junction, and then fixed. The microwave frequencies between 9–11 GHz were generated by a klystron which was operated either in the constant-frequency and constant-power mode or in the sweep mode with varying power over a bandwidth of about 65 MHz. To measure the induced voltages as well as their transitions as a function of microwave power, the junction was connected through two leads to a high-impedance (20 MΩ) differential amplifier followed by an oscilloscope. The differential amplifier, with a rise time of 10^{-4} sec to 99.9% of a step voltage, was capable of detecting a step voltage of a few microvolts and 100-μsec duration. For the I-V characteristics measurement, the conventional four-lead method was employed. Both low- and high-impedance current sources were used.

IV. EXPERIMENTAL RESULTS

Unlike the microwave-induced current steps which are observable and have been shown to exhibit generally similar behavior in all types of Josephson junctions (tunnel junctions, weak links, point contacts, and S-N-S junctions), the microwave-induced voltage steps which we will describe in the following depend significantly on the quality and the type of Josephson junction. For this reason, we describe our experimental results separately for a good tunnel junction and a bad junction.

A. Good Tunnel Junction

A good Josephson tunnel junction is the one which has an ideal Giaver quasiparticle-tunneling I-V characteristic and a zero-voltage dc current which can be *completely* suppressed by an external dc magnetic field of a few gauss. The effect of the source resistance in the measuring circuit on the I-V curve of this type of junction has been described in Ref. 6. Our good junctions had essentially the same properties as those described in Ref. 6. One of the good junctions which we have studied most extensively had a junction resistance of 1 Ω and a zero-voltage dc current of 1.1 mA at 1.4 K. The behavior of this junction will be described in detail for $H = 0$ and $H \neq 0$ separately in the following.

1. $H = 0$

In the absence of any external dc magnetic field and when the junction was not dc biased, only quantum voltages V_n have been observed across the junction. Without exception they were all time dependent. Stability of these quantum voltages were studied by displaying them as a function of time on an oscilloscope.

Two typical examples of V_n induced at *fixed* microwave-power levels are shown in Fig. 2. The upper trace shows that the junction is switching back and forth between $n = 1$ and -1 quantum voltage states (where $h\nu/2e \simeq 20\ \mu$V for 10 GHz), which are the only two allowed states at the microwave voltage indicated by the dashed line (a) in Fig. 1. The duration of each state seems to be arbitrary. The lower trace represents the state at microwave voltage v near the dashed line (b). In this trace, the oscillations are predominantly between $n = 8$ and 0 with occasional transitions to other allowed states (e.g., $n = 2$ and 5). The oscillations among the different states depend sensitively on the microwave power. However, it is experimentally possible to make the junction to oscillate only between any pair of two symmetrical voltages, say V_8 and V_{-8}.

As the microwave power increases, the *amplitude* of V_n (i.e., the largest V_n at a particular v) increases continuously without showing any sign of saturation at least up to V_{35} (≈ 0.7 mV). Within the experimental uncertainty, the effective v estimated from V_n by using Fig. 1 was in agreement with the relation $v^2 \propto P$, where P is the microwave power. The coupling constant $C = v^2/P$ decreases gradually at higher V. This indicates that the coupling of the junction to the microwave radiation may be voltage dependent at higher voltages.

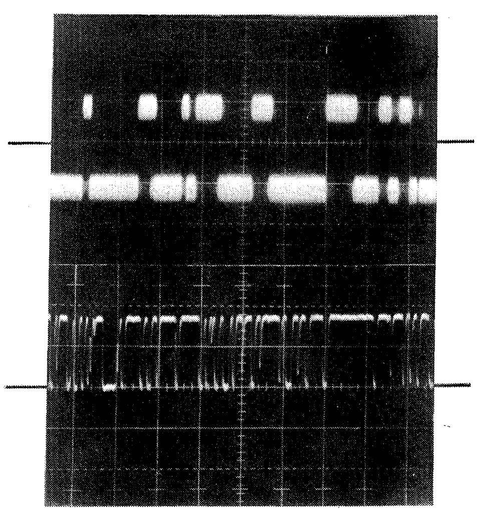

FIG. 2. Induced dc voltages across a Pb—Pb oxide—Pb junction at $T = 1.4$ K and $H = 0$. Here $\nu = 10$ GHz. Upper trace: vertical, 20 μV/div; horizontal, 0.2 sec/div; microwave power, -20 dBm, $n = 1$ and -1. Lower trace: vertical, 0.1 mV/div; horizontal, 0.5 msec/div; microwave power, -9 dBm, $n = 8$ and 0.

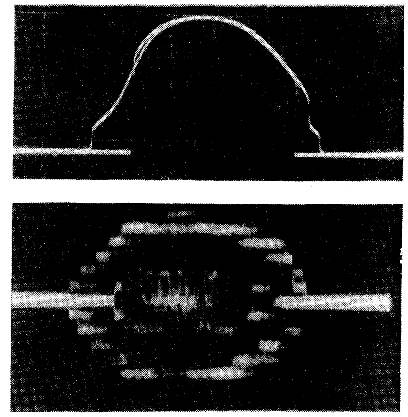

FIG. 3. Upper trace: power spectrum of the klystron output. $P_{\rm rms} = 1.2 \times 10^{-4}$ W. Horizontal sweep rate is 80 Hz, the central frequency 10 GHz, and the signal width 65 MHz. Lower trace: induced quantum voltage vs frequency and time (synchronized to the horizontal of the upper trace). Vertical, 50 μV/div (center is shifted slightly to the left).

The transition of one V_n to another as a function of varying microwave power can be demonstrated by another method as shown in Fig. 3. In this case, the klystron is operated in the sweep mode. The power vs frequency of this mode is shown in the upper trace in which the central frequency of the spectrum is 10 GHz and the horizontal width 65 MHz. This mode allowed power to change continuously from zero (at the left) to maximum (at the center) as a function of time and frequency. However, the frequency variation of 65 MHz out of 10 GHz only affects the quantum voltage by 0.65%. Therefore, the horizontal axis can be considered as a time base alone. The lower trace is the induced voltage across the junction synchronized to the microwave-power mode shown in the upper trace. Three features clearly emerge: First, the outer "envelope" of the induced V_n's agrees well with the power variation of the incident microwave. Second, the induced V_n's show statistically a symmetrical property in polarities (the lower trace is a superposition of eight complete cycles). Third, the induced V_n's *inside* the envelope also agree with the allowed states shown in Fig. 1 up to the microwave voltage indicated by the dashed line (c). For example, as the microwave power increased, the envelope of the induced voltages successively rises from zero to V_1, V_2, and then to V_3. Directly below V_3 and V_4, there is also V_1. Toward the center of the spectrum, where V_4 and V_5 are induced, there also appear V_2 and V_0 (but no other V_n).

The phenomena just described remain similar for the microwave power ranging over 20 dB. In Fig. 4, the induced voltage vs time was obtained in the same way as that in Fig. 3, except that the microwave power for this case is larger. As can be seen, the envelope of the induced voltages still closely resemble the power mode of the incident radiation.

The effect of R in the external circuit has also been studied. For a junction of $I_J = 1$ mA, if R is less than 1 kΩ, no voltages can be induced. This lower limit of R is smaller than what one would expect from the condition $|J_n| \geq |V_n/RI_J|$. It is not clear what actually has caused the reduction of the allowed range of R. One possibility is that I_J has been reduced by the microwaves or trapped flux, or both. However, the fact that there is a lower limit on R for which a V_n can be induced supports our analyses in Sec. II.

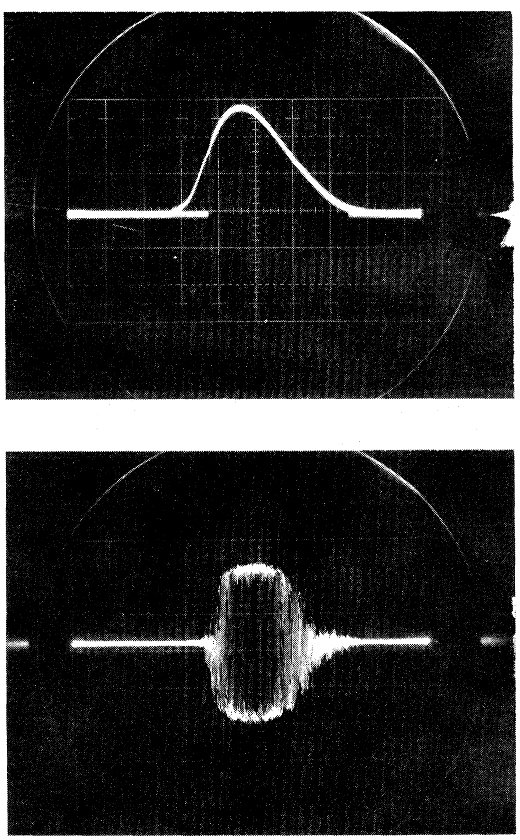

FIG. 4. Same as Fig. 3 except for upper trace: $P_{\rm rms} = 3.5 \times 10^{-4}$ W, and lower trace: vertical scale, 200 μV/div.

2. $H \neq 0$

An external dc magnetic field perpendicular to the films affects the induced voltages in an oscillatory way (but not periodically). At a given microwave power, when the field is increased monotomically, the amplitude of the voltage envelope oscillates between zero and a fixed maximum. At the field larger than 100 G, the oscillation becomes more nearly periodic with a periodicity of about 1 G. Therefore, a spectrum exactly like the lower trace of Fig. 3 can be obtained up to 400 G. Beyond 400 G, the amplitude of the induced voltages gradually decreases and completely disappears at about $H = 0.5$ kG. This is the highest field in which the ac Josephson *tunneling* effect has ever been observed. This magnetic behavior is not understood. A possible explanation is that the field produces a spatial dependence in v which in turn makes the argument of the Bessel function an oscillatory function of magnetic field. A second possibility is that the phase ϕ_0 is a function of dc field. Because of the apparent complexity, we choose not to elaborate any further at this stage. However, we point out that both the zero-voltage dc current and the induced current steps by means of dc bias were *not* observable even in a few gauss.

B. Bad Tunnel Junction

A bad tunnel junction does not exhibit an ideal Giaver quasiparticle current below the gap voltage, and the zero-voltage dc current cannot be completely suppressed to zero by a dc magnetic field of a few gauss. The induced voltages were quite different in this case.

1. $H = 0$

First, the induced voltages are not always quantized. In fact, the poorer the quality of a junction, the smaller chance that a quantized voltage can be induced. Second, the induced dc voltages, quantized or not, do not have symmetrical polarities and are more stable as a function of time (namely, they do not flip between two opposite polarities). Third, the envelope of the induced voltages does not increase monotonically with increasing microwave power as in the case of the good tunnel junction. Accordingly, the V_n-vs-v relation does not obey the one shown in Fig. 1. A typical example of the induced voltage as a function of microwave power (obtained in the same way as in Fig. 3) is shown in the top trace of Fig. 5. As can be seen, the induced voltage is asymmetrical, not quantized, nor sensitive to the varying microwave power.

2. $H \neq 0$

In a large dc magnetic field (its magnitude depending on the quality of the junction), when the

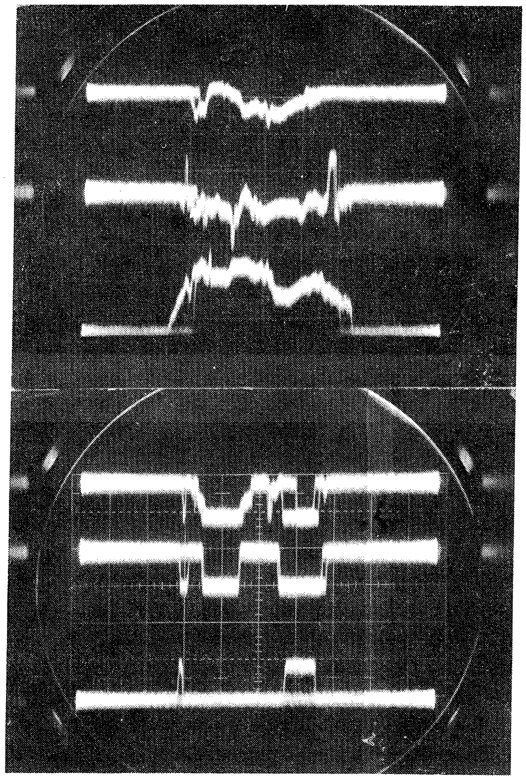

FIG. 5. Induced voltage (across bad junction) vs time (synchronized to the sweep mode of the microwave radiation shown in the upper trace of Fig. 3). $P_{rms} = 5\times10^{-4}$ W. Vertical scale, 20 μV/div. Magnetic field from top to bottom traces 0, 0.1, 0.2, 0.5, 0.6, 0.8 kG. All traces are superposition of eight complete cycles.

"leakage" current at zero voltage is greatly suppressed, the induced voltage becomes quantized. However, the quantum voltages in this case still differ from those of a good junction in the following ways: (i) Quantum voltages of both integer and *half* integer n are observable. (ii) At a fixed microwave power the induced voltage is time independent and stable. (iii) The magnitude of V_n does not increase monotonically with increasing microwave power as described in Fig. 1.

The effects of varying microwave power at fixed magnetic fields are shown in Fig. 5 which is obtained in the same way as Fig. 3, except that the magnetic field is increased in steps from the top trace to the bottom. The effect of the magnetic field at a fixed microwave power is illustrated in Fig. 6 in which the induced (stable) voltage is plotted against magnetic field. In both cases, the tendency of the induced voltages to become quantized in large field is easily seen. Near $H = 0.9$ kG, where the Pb films start to become normal, the whole effect disappears as expected.

The reason that the induced voltages become more quantized in a larger field is probably the weakening of the coupling across the junction which leads to a more sinusoidal current-phase relation.

V. COMPARISONS WITH INDUCED CURRENT STEPS

The agreement between the induced quantum voltages and the patterns predicted in Fig. 1 supports our view that the step voltages in the V-v sweep and the step currents in the I-V sweep are two manifestations of the same mechanism. It also shows that the interaction between the ac Josephson current and the external microwave is a reversible process in which any of the three quantities I, V, and v can be a controlling parameter. There are, however, many differences in properties and in the *experimental conditions* under which they can be observed. Although some of them have been described in Secs. I–IV, we summarize them again as follows (we use V_n to represent the induced quantum voltages in the V-v curve of an *unbiased* experiment and I_n to represent the current steps in the I-V curve of a *biased* experiment):

a. Parameters. In the I_n experiment, there are two independent parameters E and v. The relations

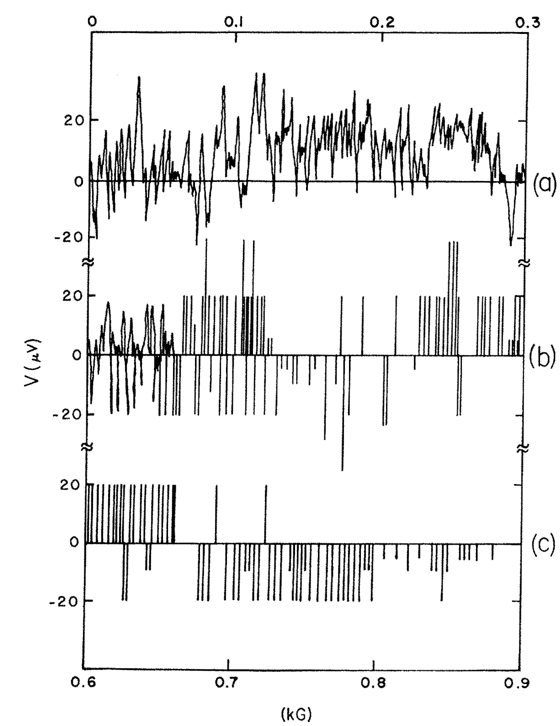

FIG. 6. Induced voltage (across bad junction) vs magnetic field (perpendicular to Pb films). Horizontal axes are (a) 0–0.3 kG; (b) 0.3–0.6 kG; (c) 0.6–0.9 kG. Both microwave power and frequency are fixed, where $P = 3\times10^{-4}$ W and $\nu = 10$ GHz.

among the rest of the (dependent) variables $V, I,$ and ϕ_n are multiple valued. In the V_n experiment, v is the only independent parameter and the relation between I and V is single valued and quantized.

b. Phase locking. Phase locking between the junction and the microwave field is strong in the I_n experiment since the allowable range of I_n is larger and continuous. Accordingly, fluctuations in ϕ_n and v can be accommodated by the junction to allow itself to remain in the same I_n step. On the other hand, the phase locking for the V_n experiments is weak because of the quantized restriction in I and V. Small fluctuations in I could cause V_n to make a transition. The symmetry in polarities, especially, makes V_n very unstable against its counter part V_{-n}. Indeed, the strong phase locking in the I_n experiment is the base for the e/h measurement. The weak-phase-locking property of V_n, however, makes it sensitive to the external radiation. This weak-coupling property could probably be exploited in using the junction as a detector.

c. Dependence on I_J. For the I_n experiment, it is easier to induce the current steps if I_J is large since $I_n \propto I_J$. On the other hand, since V_n is determined by ν the observation of V_n does not crucially depend on I_J (except that the range of R will be affected). This conclusion can be derived from Eqs. (2) and (4).

d. Effect of H. If the junction has trapped flux or is in a dc magnetic field of a few gauss, I_J will be much reduced and it is difficult to observe I_n. However, the V_n can easily be induced in such situations because of its "independence" from the magnitude of I_J (independence in a sense because its effect can be balanced out by R). As has been described previously, V_n can be observed in a field as high as 500 G.

e. Effect of R. V_n can be induced only if R is larger than a certain lower limit depending on I_J, and in addition when the junction is a *good* tunneling barrier. In principle, I_n is independent of R. In experiment, however, because of the inability of a small junction to protect itself from trapping flux, when the junction is externally biased by a constant current source (of large R), it often results in a much reduced I_J and consequently, a much smaller I_n. Also, the whole I-V curve is not reproducible from run to run. This is probably due to the large self-field generated near the tip (i.e., the junction area) by the transient current at the time of closing the switch. This problem in tracing the I-V curve can be eliminated by using a low-resistance current source. However, this low-resistance R is smaller than the lower limit of R required for the V_n experiments. Consequently, we have not been able to make a direct comparison between the power dependences of I_n and V_n in the same range of R.

VI. SUMMARY

Finally, we summarize that the induced voltages are sensitive to the radiation and fluctuation, observable in a large dc magnetic field, and of a systematic power dependence. Therefore, this manifestation of the Josephson effect has advantages in noise and radiation detection.

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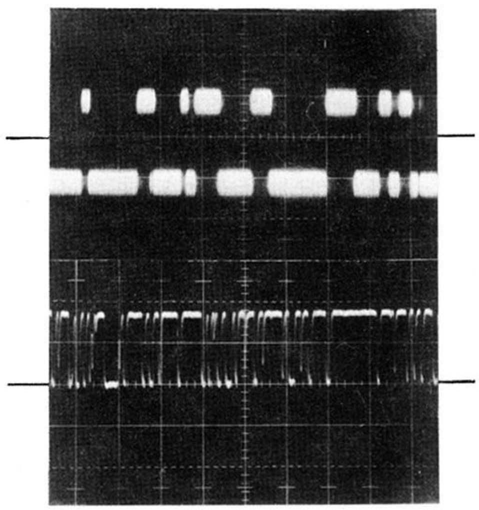

FIG. 2. Induced dc voltages across a Pb—Pb oxide—Pb junction at $T = 1.4$ K and $H = 0$. Here $\nu = 10$ GHz. Upper trace: vertical, 20 μV/div; horizontal, 0.2 sec/div; microwave power, -20 dBm, $n = 1$ and -1. Lower trace: vertical, 0.1 mV/div; horizontal, 0.5 m sec/div; microwave power, -9 dBm, $n = 8$ and 0.

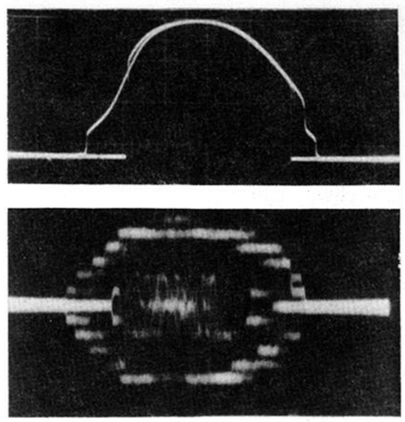

FIG. 3. Upper trace: power spectrum of the klystron output. $P_{rms} = 1.2 \times 10^{-4}$ W. Horizontal sweep rate is 80 Hz, the central frequency 10 GHz, and the signal width 65 MHz. Lower trace: induced quantum voltage vs frequency and time (synchronized to the horizontal of the upper trace). Vertical, 50 μV/div (center is shifted slightly to the left).

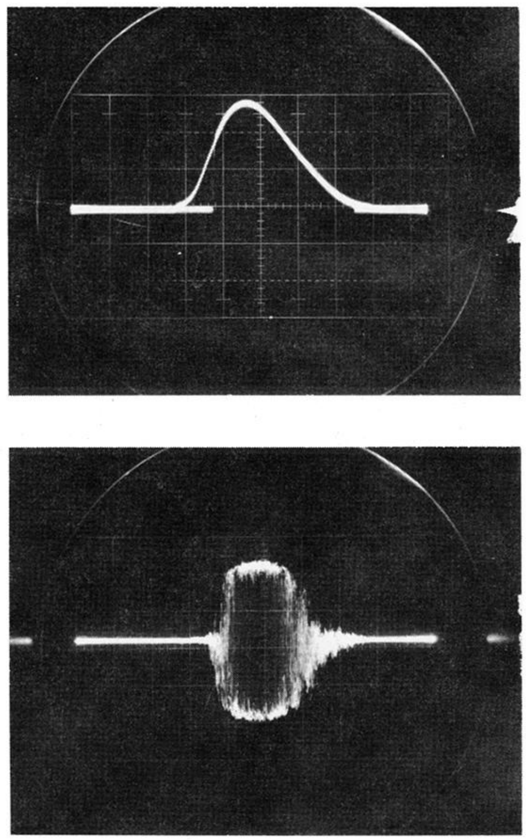

FIG. 4. Same as Fig. 3 except for upper trace: $P_{rms} = 3.5 \times 10^{-4}$ W, and lower trace: vertical scale, 200 μV/div.

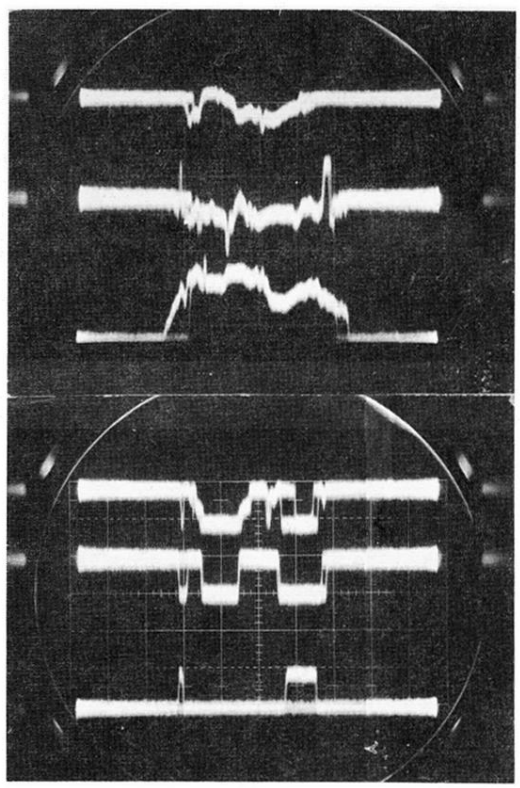

FIG. 5. Induced voltage (across bad junction) vs time (synchronized to the sweep mode of the microwave radiation shown in the upper trace of Fig. 3). $P_{rms} = 5 \times 10^{-4}$ W. Vertical scale, 20 μV/div. Magnetic field from top to bottom traces 0, 0.1, 0.2, 0.5, 0.6, 0.8 kG. All traces are superposition of eight complete cycles.