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INTRODUCTION

The prediction and subsequent discovery of the Josephson[1] effects have given rise to a variety of new devices and techniques. Josephson devices are now widely used in low temperature laboratories for the measurement of tiny low-frequency voltages and magnetic fields, and considerable work is in progress to investigate their use as high frequency detectors and mixers. One of the most important uses of the Josephson effect has been in the precision measurement of e/h, and the maintainence of the standard of emf. All of these uses involve what may be termed "quantum phase effects", that is, effects that explicitly exhibit the macroscopic quantum nature of superconductors. In this article, I have tried to give an account of some of the quantum phase devices which have been developed, and to briefly describe their applications.

SUPERCONDUCTIVITY AND QUANTUM PHASE EFFECTS

According to the microscopic theory of superconductivity of Bardeen, Cooper, and Schrieffer,[2] the electrons in a superconductor are subject to an attractive interaction which gives rise to bound electron pairs. The energetically most favorable state of the system requires that these Cooper pairs have the same center of mass momentum, or, quantum mechanically, that they have the same phase. All the pairs in a superconductor may be described by a single <u>macroscopic</u> wave function or <u>order parameter</u>, and have (in the absence of applied fields) identical quantum mechanical phase, ϕ. The existence of this macroscopic quantum state was first proposed by London.[3] The pairing theory explains the two properties of a superconductor that were first discovered: its zero electrical resistance at zero frequencies, and the Meissner effect, which is the exclusion of a magnetic field from the bulk of the sample by surface currents flowing in a thin skin layer or penetration depth. Both effects rely implicitly on the macroscopic quantum state of a superconductor, but do not demonstrate it explicitly. A third major property, flux quantization, clearly exhibits macroscopic quantum effects. Originally proposed by London,[3] flux quantization was first observed experimentally[4] in 1961. The amount of magnetic flux contained in a superconducting ring cannot be arbitrary, but must be quantized in units of the flux quantum, $\phi_o = h/2e \simeq 2 \times 10^{-7}$ gauss cm^2. If a superconducting ring contains no flux, it is in the $n = 0$ quantum state. A magnetic field applied to this ring will be opposed by a circulating supercurrent that will maintain the ring in the $n = 0$ state.

Another very important manifestation of the macroscopic quantum nature of superconductors is the Josephson[1] effect. A review of this topic by P. W. Anderson appeared in the November 1970 issue of Physics Today, and I shall only briefly mention the essential features.

Josephson[1] considered two superconductors separated by a thin insulating barrier, and proposed that Cooper pairs would be able to tunnel through the barrier without developing a voltage across it. The flow of pairs constitutes a supercurrent. The supercurrent j_S generates a difference $\Delta\phi$ between the phases of the order parameters in the two superconductors according to the relation[5]

$$j_S = j_1 \sin(\Delta\phi). \quad (1)$$

The dc Josephson effect occurs for $j_S \leqslant j_1$; for $j_S > j_1$, a finite voltage is developed across the barrier. The effect was first observed by Anderson and Rowell[6] in a crossed-film tunnel junction similar to the one shown in Fig. 1(a). A typical current-voltage (i-v) characteristic is shown in Fig. 2(a).

At finite voltages, the ac Josephson effect occurs, and the supercurrent oscillates with time. Eq. (1) is still valid, but $\Delta\phi$ evolves with time according to the relation

$$\frac{d}{dt}(\Delta\phi) = \omega = 2\Delta\mu/\hbar, \quad (2)$$

where $\Delta\mu$ is the electrochemical potential difference across the junction. If this potential difference is purely electrostatic in origin, $\Delta\mu = eV$. A voltage of 1μV corresponds to a frequency of about 484 MHz. Notice that Eq. (2), with $\Delta\mu = eV$, can be written as $V = (h/2e)\nu = \phi_o\nu$, so that the Josephson voltage-frequency relation and flux quantization are intimately related.

The coupling energy[5,6] of a junction is $E_c = -\phi_o j_1/(2\pi)$. If j_1 is of order 1mA, E_c is about 2eV, appreciably less than the binding energy of a single hydrogen atom. It is for this reason that a Josephson junction may be used as the basis of a very sensitive device.

Other types of junction that have been investigated are shown in Figs. 2(a) - (f). They all have a zero voltage supercurrent up to a well-defined maximum known as the critical current (see Fig. 2(b)), and all obey Eq. (2) at finite voltages. The most useful junctions for device work have been the point contact[10] (Fig. 2(e)), the proximity effect bridge[9] (Fig. 2(d)), and the Slug[11] (Fig. 2(f)). Fabrication of reliable junctions has been a major difficulty in this field. However, recent work on tunnel junctions prepared in a glow discharge, mechanically robust point contacts, proximity effect bridges, and variants of the Dayem bridge,[8] suggest that the situation is improving.

QUANTUM PHASE DEVICES

1. Magnetometers

One family of Josephson devices relies on the double-junction[12] interferometer illustrated in Fig. 3(a). Two junctions are connected on a superconducting ring, and their total critical current monitored by means of a room temperature amplifier. The critical current is a periodic function of a magnetic flux applied to the ring as shown in Fig. 3(b), with a period of one flux quantum, ϕ_o. This interference effect, first performed by Jaklevic, Lambe, Silver, and Mercereau,[12] is an elegant demonstration of the macroscopic quantum state in a superconductor. When the junctions are in a finite voltage regime (as they must be to enable the critical current to be measured), flux quanta can pass through them into the ring. As the applied flux is increased, the interferometer moves through a succession of quantum states, n = 0, 1, 2 ... .

For practical reasons, the maximum area of the double junction is about 1 cm^2. Clearly, the device can be used as a digital magnetometer with a maximum field resolution of about 2×10^{-7} gauss. However, one can detect much smaller fields by measuring the small change in the critical current that arises when the applied magnetic flux is changed by a fraction of a flux quantum. Forgacs and Warnick[13] were able to detect magnetic field changes as low as 10^{-9} gauss in a 1 Hz bandwidth with a dc Squid (Superconducting Quantum Interference

Device). The limit was set not by the superconducting device, but rather by noise generated at the input of the room temperature amplifier. However, the present author and James L. Paterson,[14] have recently developed an "asymmetric Squid." In this variation, the current (i in Fig. 3(a)) is fed into the ring in an asymmetric fashion, for example, at two points either side of one of the junctions. As a result, the symmetric oscillations of Fig. 3(b) become skewed into the asymmetric form of Fig. 3(c). On the steeper side of the oscillation, the change in critical current for a given change in magnetic flux may be as much as two orders of magnitude higher than for the symmetric case. It is likely that this simple modification of the dc Squid will appreciably increase its sensitivity.

A number of workers[15-18] have developed single junction quantum interferometers, which have become known as rf Squids. These devices have been preferred over the dc Squids because only one junction is required, and also because the method of readout gives voltage amplification in the helium bath. Rf Squids are now available commercially. If an increasing magnetic field is applied to a superconducting loop containing a single junction, the quantum state of the ring changes as flux quanta move in through the junction. The single junction interferometer can be used as a magnetometer by coupling it to the inductance of a tank circuit, as shown in Fig. 4(a). An ac current (i_o) is applied to the tank circuit at its resonant frequency. The amplitude of the voltage across the tank circuit is periodic in the flux applied to the interferometer, with a period of one flux quantum. The applied flux modulates the effective inductance of the interferometer, and hence the resonant frequency of the tank circuit. The advantage of this technique lies in the amplification obtained in the resonant circuit which is at liquid helium temperatures. The field sensitivity is comparable to or somewhat better than that of the dc Squid. A photograph of an ac Squid made by Mercereau and Nisenoff appears in Fig. 4(b). Zimmerman[19] has made rf Squids with a "fractional-turn loop," an ingenious modification that increases the potential sensitivity of the device by perhaps an order of magnitude.

The magnetic field sensitivity of both dc and rf Squids may be increased by means of the superconducting flux transformer shown in Fig. 5(a). A magnetic field applied to the pickup coil generates a persistent supercurrent in the transformer. This supercurrent in turn applies a magnetic flux to the Squid. If the area of the pickup loop, A_1, is greater than that of the secondary loop, A_2, there will be an enhancement of the magnetic field sensitivity. A simple treatment shows that if $A_1 \gg A_2$, the enhancement is approximately $(A_1/A_2)^{1/2}$. Enhancements of one order of magnitude have so far been achieved.

Magnetometers, usually with transformers, have been used in a variety of applications, for example, in measuring tiny susceptibilities in low magnetic fields. Gollub et al.[20] have measured the fluctuating susceptibility of a superconductor at its transition temperature. Dr. J. E. Mercereau has reported susceptibility measurements on chemical proteins. The sample is inserted into the magnetometer in a small dewar, and its temperature can be varied from 1K to 300K. This technique represents an order-of-magnitude improvement over present methods. A further application of the magnetometer is to detect very small displacements of a magnetic body. This instrument has potential as a gravimeter.

A flux transformer may also be used to measure magnetic field gradients, as shown in Fig. 5(b). Gradient sensitivities of better than 10^{-10} gauss/cm have been reported. Zimmerman and Frederick[21,22] have used a gradiometer to take magnetocardiograms by placing a portable cryostat containing the gradiometer on the patient's chest. The tiny magnetic fields generated by the heartbeat were picked up by the gradiometer, amplified, and displayed on an oscilloscope.

2. Voltmeters

A magnetometer may be converted into a galvanometer by coupling it to a superconducting loop. A variation on this principle is the Slug[11] (Superconducting Low-inductance Undulatory Galvanometer, Fig. 1(f)), whose critical current is modulated by a current in the niobium wire. This form of coupling is equivalent to passing the current along one of the superconducting arms of the interferometer shown in Fig. 3(a). These galvanometers are used as voltmeters by connecting a resistance in series with the coil, as in Fig. 6. The voltmeters are almost invariably used as null-seeking devices in a feedback system. If the resolution of the galvanometer is ΔI, the coil inductance L, and the series resistance R, the voltage sensitivity is $\Delta V = R\Delta I$, and the time-constant $\tau = L/R$. The lowest inductance that can be achieved in a circuit with a single turn loop and discrete components appears to be about 10^{-8} H. For a time-constant of 1s, the lowest value of R is correspondingly $10^{-8}\Omega$. The resolution of the galvanometers is in the vicinity of $10^{-8} - 10^{-9}$A, and the voltage resolution therefore $10^{-16} - 10^{-17}$ V. However, the Nyquist noise generated in a resistance of $10^{-8}\Omega$ at 4K, with a circuit time-constant of 1s, is about 8×10^{-16}V. Consequently, the resolution is limited by Nyquist noise.

For higher values of circuit resistance, it is usual to impedance-match the voltmeter by using a multiturn coil to give correspondingly higher current resolution without increasing the time-constant, L/R. However, as the resistance increases and a progressively higher turns-ratio is required, the losses multiply, and eventually it is no longer possible to achieve voltage measurement that is limited by Nyquist noise in the resistance at ^{4}He temperatures. The present upper limit of resistance appears to be 10^{-2} - $10^{-1}\Omega$. It is intriguing to realize that there is apparently no way at present to observe Nyquist noise in a ^{4}He temperature resistance in the range of roughly $10^{-1}\Omega$ - 10Ω. Values of resistance above 10Ω can be transformer-matched to room temperature low noise amplifiers.

These voltmeters have been used in Hall effect and thermoelectric measurements at liquid ^{4}He temperatures, and also in detecting voltages due to flux flow in type II superconductors. A further use[23] was to compare the voltages of steps induced on the i-v characteristics of two dissimilar junctions while they were irradiated at the same frequency (see next section). The voltages were found to differ by less than 10^{-17}V, corresponding to 1 part in 10^8.

3. Measurement of e/h

Perhaps[24] the single most important use of the Josephson effect has been in the measurement of the fundamental constant ratio e/h. When a Josephson junction is irradiated with microwaves, a series of constant-current voltage steps is induced on the i-v characteristic,[25] as indicated in Fig. 7. These steps appear at voltages[1]

$$V_n = n\hbar\omega/2e, \tag{3}$$

where ω is the angular frequency of the microwaves, and n is an integer. The applied microwaves beat with the oscillating supercurrents in the junction to produce a zero frequency component whenever the supercurrent frequency is equal to the microwave frequency, or a multiple of it. These zero frequency components are manifested as dc supercurrent steps at finite voltages. By accurately measuring the microwave frequency and the voltages at which these steps appear, one has an estimate of 2e/h.

The measurements are important in three respects. First, they provide a simple and accurate means of maintaining and comparing standards of emf in terms of a frequency. Second, the new value of e/h has had a considerable impact on the values of many fundamental constants. Third, an accurate value of the fine structure constant, α, may be obtained from 2e/h. This value of α is believed to contain no corrections from quantum electrodynamics (QED), and may be used to independently compare QED theory with QED experiments.

Extensive measurements of 2e/h have been made, pioneered by work at the University of Pennsylvania by Langenberg, Parker, and Taylor.[26] The Pennsylvania group have made seven high precision determinations, the NPL in the U.K. three, and the NSL in Australia and the PTB in West Germany, one each. When these values of 2e/h are expressed in terms of the NBS as-maintained volt of 1969, they agree to within ± 1ppm. The latest Pennsylvania result[27] is $2e/h = 483.593718 \pm 0.000060\ \mathrm{MHz}/\mu V_{NBS69}$ (± 0.12 ppm). These results are summarized and discussed in a paper by Finnegan, Denenstein, and Langenberg.[27]

At present, the various national laboratories of the world maintain the standard volt by means of cells. Every three years or so, the cells are taken to the Bureau International du Poids and Mesures (BIPM) in France and intercompared. These transfers often involve some loss of accuracy, because the cells have to be removed from their controlled environment. However, if the voltages of the various standard cells can be expressed as a Josephson frequency, intercomparisons are relatively simple, and do not involve transporting the cells. Dr. B. N. Taylor at the NBS reports that the U.S. legal volt will soon be maintained in terms of a Josephson frequency, and that the standards laboratories of other countries are expected to follow suit.

It should be emphasized that the Josephson junction is not used to define the volt. The standard volt is expressed as a Josephson frequency, which then provides a very convenient and accurate means of re-establishing the volt in another laboratory. The present accuracy of frequency calibration in terms of the as-maintained volt is about 1 part in 10^7, although the absolute volt is known only to ± 2.6 ppm.

The value of 2e/h obtained by Parker et al.[28] was about 38 ± 10 ppm smaller than that given by the 1963 least-squares adjustment of the fundamental constants by Cohen and DuMond.[29] This result led Taylor et al.[30] to perform a new adjustment. A crucial point in their adjustment was the combination of 2e/h with various other quantities (which do not contain significant known QED corrections), to obtain a value of the fine structure constant, α, which is thought to be independent of QED effects. This "non-QED" value for α was 20ppm higher than the 1963 value, which did involve QED effects. The new value of α has resolved a number of discrepancies between QED experiments and theory.[30] Other fundamental constants have also been affected by the new adjustment,[30] for example, h has been increased by 91ppm.

It is striking that a solid containing 10^{22} electrons/cm^3 can yield a high precision measurement of a fundamental constant involving the charge on a single electron. The fact that this measurement is possible is a direct consequence of the macroscopic quantum state in a superconductor.

4. High frequency generators, detectors, and mixers

Considerable effort has been made to use the ac Josephson effect for the generation and detection of high frequency electromagnetic radiation.[31] It now seems unlikely that the Josephson junction will be important as a generator, because of the relatively low power levels available. A major problem is the impedance mismatch between free space (377Ω) and the junction (typically 1Ω). The same mismatch of course arises with detectors, so that relatively little of the incident radiation is actually transferred into the junction. The most successful detectors have been point contacts, although the coupling of radiation to them is not well understood.

Since the application of electromagnetic radiation to a junction modifies the current-voltage characteristic, a variety of detectors are possible. In principle, a detector could be realized by monitoring the height of one of the induced steps (see Fig. 7). Changes in step height are detected by current biasing the junction at a voltage just above the step voltage. The voltage across the junction is then a function of the step height. Unfortunately, in order to achieve high sensitivity, a large amplitude step is required so that a high dynamic resistance appears just above and below the step. As a consequence, this technique is not very useful at low signal levels. However, small signals also modify the critical current ($n = 0$ step) of the junction. Since the condition $V_n = n\hbar\omega/2e$ is satisfied for all ω for $n = 0$, the junction may be used as a broadband detector. At a given frequency, the junction has a square-law response to small signals, but the spectral response is usually complicated.[32] The best detector to date appears to be that of B. Ulrich,[33] at Austin, Texas, who has achieved a noise equivalent power (NEP) of 10^{-14} W/$\sqrt{\text{Hz}}$, at a wavelength of 1mm. Ulrich has used this device in the McDonald observatory at the University of Texas for Astronomical observations.

Richards and Sterling[34] have made a regenerative detector by placing a point contact in a cavity. Radiation emitted by the junction at a resonant frequency of the cavity generates a standing wave which in turn couples energy back into the junction.[35] The result is a self-induced step on the i-v characteristic, somewhat similar in appearance to the radiation-induced steps of Fig. 7. If broadband radiation is admitted to the cavity, there is a large response of the self-induced step to radiation at the corresponding cavity resonant frequency. The response is confined to a narrow band whose central frequency may be adjusted by changing the cavity size and shape. Richards and Sterling achieved an NEP of 10^{-14} W/$\sqrt{\text{Hz}}$ at a wavelength of 1mm.

Yet another type of detector is the heterodyne detector, in which the junction is used as a mixer in conjunction with a local oscillator. If the Josephson frequency is ω_J, the signal frequency ω_S, and the local oscillator frequency ω_L, Grimes and Shapiro[36] showed that steps will appear in the i-v characteristic whenever

$$\omega_J + n\omega_S + m\omega_L = 0, \qquad (4)$$

where n and m are integers. If ω_S is close to ω_L, the combined signals are equivalent to one signal modulated at $\omega_L - \omega_S$. The local oscillator can be made to generate a large step, whose amplitude varies with the signal strength. This technique overcomes the major drawback of the induced-step detector mentioned earlier. It is also possible to mix the signal with a high harmonic of the local oscillator, so that high frequency signals, in the far infrared for example, can be detected with a local oscillator of conveniently low frequency. McDonald et al.[37] have successfully mixed a 891 GHz signal from an HCN laser with the 84th harmonic of an X-band local oscillator.

Josephson detectors have improved the state-of-the-art of high frequency detection by perhaps an order of magnitude at certain wavelengths **at which** conventional bolometers have low absorptivity. The main problems with the Josephson detectors appear to be the lack of suitable completely reliable junctions, and the difficulty of impedance matching them to free space. However, work in these areas is intensive, and one may hope for further improvement.

5. Josephson junction thermometry

Kamper[38,39] has suggested the use of the ac Josephson effect in absolute noise thermometry at ^{4}He temperatures and below. A junction is biased at a low voltage by connecting it across a small resistance R, through which a current is passed. The Johnson noise voltage generated by this resistance at a temperature T modulates the ac Josephson frequency which, as a result, has a linewidth

$$\Delta\nu = \frac{4\pi kTR}{\phi_o^2} . \qquad (5)$$

The linewidth of the radiation emitted by the junction is therefore proportional to the absolute temperature of the resistance. Kamper et al.[40] have used this thermometer down to temperatures of 20 mK, and suggest that temperature measurement down to 1 mK is feasible.

Other noise and fluctuation phenomena could be measured with this technique.

6. Computer elements

Matisoo[41] has shown that a Josephson junction may be switched from a zero-voltage to a finite-voltage state in less than 10^{-9}s, so that the junction could possibly form the basis of a logic element in a computer. He has also used two junctions in parallel (as in Fig. 3(a)) as a flip-flop.[42]

Anderson, Dynes, and Fulton[43] have recently used Josephson junctions in a "flux shuttle", which is a prototype counter or shift register. They constructed a series of junctions in the ladder configuration shown schematically in Fig. 8. The critical current (i_c) of each junction is chosen so that each loop can contain at most one flux quantum, supported by a circulating supercurrent, without externally applied fields or currents. This requirement implies $2\,\phi_0 > Li_c > \phi_0$, where L is the inductance of the loop.

If a current of appropriate magnitude (between i_c and $2i_c$) is applied to A_1A_2, most of it will flow through junction A, which will momentarily be driven into a finite voltage state, and a flux quantum will be admitted into loop 1. The current around loop 1 will be redistributed, and junction A will return to a superconducting state. When the drive current is removed, a flux quantum will remain in loop 1, maintained by a circulating supercurrent $J = \phi_0/L$. If a further current drive is applied to A_1A_2, a second flux quantum will be admitted to loop 1. However, junction B, which cannot sustain sufficient current to maintain two quanta, opens, and admits one of the quanta into loop 2. In this way, a succession of current pulses applied at A_1A_2 will propagate flux quanta along the ladder. The arrival of a quantum at (say) the tenth loop can be sensed by a flux detector. Consequently, the ladder behaves as a counter.

Anderson et al.[43] also demonstrated the use of the device as a shift register. Suppose that loop 1 contains the only flux quantum in the ladder, with a supercurrent J circulating as in Fig. 8. If an appropriate current, less than i_c, is applied to B_2B_1 (i.e. in the direction of J), junction B will open to transfer the quantum into loop 2, where it will remain when the current is removed. On the other hand, if loop 1 was initially "empty", the current applied to B_2B_1 will not exceed i_c, and no flux quantum will be introduced or transferred. In this way, the current pulse applied to B_2B_1 transfers the contents of loop 1 (0 or 1) into loop 2. Notice incidentally, that if both loops 1 and 2 initially contain one flux quantum (of the same polarity), B carries no current. When the current pulse is applied, it is insufficient to "open" B, and no transfer of flux occurs.

By successively applying current pulses to each junction (beginning at the end of the ladder), we can shift the contents of the ladder along one loop. In other words, we have a prototype shift register.

CRYOGENICS

All of the devices described must, of course, be operated at low temperatures, usually in the liquid ^{4}He range, 1 - 4 K. Until recently, this requisite has restricted the use of such devices to low-temperature laboratories. However, small, robust metal cryostats are now being more commonly used, and have opened up the possibility of operating low-temperature devices in more rigorous environments. For example, a cryostat designed by P. L. Richards at Berkeley will remain cold for over 12 hours with 1 liter of liquid helium. The cryostat is about 20 cm high and 16 cm in diameter, and is quite portable.

CONCLUSIONS

Of the devices I have described, the magnetometers and voltmeters are already widely used. They are commercially available, and one may expect their applications to expand. The e/h measurements are now mostly being undertaken in standards laboratories, and will be of continued importance in maintaining voltage standards and determining fundamental constants. The electromagnetic radiation detectors are just beginning to significantly improve the state of the art of high frequency detection. Considerable work remains to be done in this area before the ultimate sensitivity of these devices is attained. Such ingenious new ideas as the flux shuttle offer intriguing possibilities, but require intensive development.

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References

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1. B. D. Josephson, Phys. Letters 1, 251 (1962); for reviews of the Josephson effect see B. D. Josephson in Superconductivity, ed. R. D. Parks (Dekker, New York, 1969), or P. W. Anderson in Progress in Low Temperature Physics, ed. C. J. Gorter (North-Holland, Amsterdam, 1967), Vol. 5.
2. J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. 108, 1175 (1957).
3. F. London, Proc. Roy. Soc. (London) A152, 24 (1935); Phys. Rev. 74, 562 (1948); Superfluids (Wiley, New York, 1950).
4. B. S. Deaver, Jr. and W. M. Fairbank, Phys. Rev. Letters 7, 43 (1961); R. Doll and M. Näbauer, Phys. Rev. Letters 7, 51 (1961).
5. B. D. Josephson, Fellowship thesis, Trinity College, Cambridge, England, 1962 (unpublished); P. W. Anderson in Lectures on the Many-Body Problem, Ravello 1963, edited by E. R. Caianiello (Academic, New York, 1964), Vol. 2, p. 115.
6. P. W. Anderson and J. M. Rowell, Phys. Rev. Letters 10, 230 (1963).
7. J. Clarke, Proc. Roy. Soc. (London) A308, 447 (1969).
8. P. W. Anderson and A. H. Dayem, Phys. Rev. Letters 13, 195 (1964); A. H. Dayem and J. J. Wiegand, Phys. Rev. 155, 419 (1967).
9. H. A. Notarys and J. E. Mercereau, "Proceedings of the International Conference on the Science of Superconductivity," Stanford, California, 1969 (to be published in Physica).
10. J. E. Zimmerman and A. H. Silver, Phys. Rev. 141, 367 (1966).
11. J. Clarke, Phil. Mag. 13, 115 (1966).
12. R. C. Jaklevic, J. Lambe, A. H. Silver, and J. E. Mercereau, Phys. Rev. Letters 12, 159 (1964).

13. R. L. Forgacs and A. Warnick, Rev. Sci. Instr. 38, 214 (1967).

14. J. Clarke and J. L. Paterson, Bull. Am. Phys. Soc. Series II, 16, 399 (1971).

15. J. E. Zimmerman, P. Thiene, and J. T. Harding, J. Appl. Phys. 41, 1572 (1970).

16. J. E. Mercereau, Rev. de Phys. Appl. 5, 13 (1970).

17. M. Nisenoff, Rev. de Phys. Appl. 5, 21 (1970).

18. J. M. Goodkind and D. L. Stolfa, Rev. Sci. Instr. 41, 799 (1970).

19. J. M. Zimmerman, to be published.

20. J. P. Gollub, M. R. Beasley, and M. Tinkham, Phys. Rev. Letters 25, 1646 (1970).

21. J. M. Zimmerman, J. Appl. Phys. 42, 30 (1971).

22. J. E. Zimmerman and N. V. Frederick, to be published.

23. J. Clarke, Phys. Rev. Letters 21, 1566 (1968).

24. For a tutorial review of this subject, see J. Clarke, Am. J. Phys. 38, 1071 (1970).

25. S. Shapiro, Phys. Rev. Letters 11, 80 (1963).

26. D. N. Langenberg, W. H. Parker, and B. N. Taylor, Phys. Rev. 150, 186 (1966).

27. T. F. Finnegan, A. Denenstein, and D. N. Langenberg, to be published in Phys. Rev.

28. W. H. Parker, D. N. Langenberg, A. Denenstein, and B. N. Taylor, Phys. Rev. 177, 639 (1969).

29. E. R. Cohen and J. W. M. DuMond, Rev. Mod. Phys. 37, 537 (1965).

30. B. N. Taylor, W. H. Parker, and D. N. Langenberg, Rev. Mod. Phys. 41, 375 (1969).

31. For a review, see P. L. Richards, "The Josephson Junction as a Detector of Microwave and Far Infrared Radiation," to be published in Physics of II-V Compounds, Vol. G (Academic Press).

32. C. C. Grimes, P. L. Richards, and S. Shapiro, J. Appl. Phys. 39, 3905 (1968).

33. B. Ulrich, 12th International Conference on Low Temperature Physics, Kyoto, Japan (1970).

34. P. L. Richards and S. A. Sterling, Appl. Phys. Letters 14, 394 (1969).

35. M. D. Fiske, Rev. Mod. Phys. 36, 221 (1964).

36. C. C. Grimes and S. Shapiro, Phys. Rev. 169, 397 (1968).

37. D. G. McDonald, A. S. Risley, J. D. Cupp, and K. M. Evenson, Appl. Phys. Letters 18, 162 (1971).

38. R. A. Kamper, Symposium on the Physics of Superconducting Devices, Charlottesville, Virginia (ONR report, 1967) p. M1.

39. R. A. Kamper and J. E. Zimmerman, J. Appl. Phys. 42, 132 (1971).

40. R. A. Kamper, J. D. Siegwarth, R. Radebaugh, and J. E. Zimmerman, to be published.

41. J. Matisoo, Appl. Phys. Letters 9, 167 (1966).

42. J. Matisoo, J. Appl. Phys. 39, 2587 (1968).

43. P. W. Anderson, R. C. Dynes, and T. A. Fulton, Bull. Am. Phys. Soc. Series II, 16, 399 (1971).

Figure Captions

Fig. 1. Types of Josephson junction

(a). Crossed film tunnel junction.[6] The first film of (for example) tin is allowed to oxidize before the second strip is deposited. The junction thus consists of two superconductors separated by a thin layer of metal oxide.

(b). Superconductor-normal metal-superconductor junction,[7] in which the oxide layer of (a) is replaced by a copper film.

(c). Dayem bridge,[8] consisting of a thin superconducting film with a necked-down region forming a weak link.

(d). Proximity effect junction,[9] in which the Dayem bridge is further "weakened" by a normal metal overlay.

(e). Point contact junction.[10]

(f). Slug,[11] consisting of a bead of solder frozen about the oxide coating of a piece of niobium wire.

Fig. 2(a). Current-voltage characteristic of tunnel junction.

(b). Current-voltage characteristic of "weak link" (Slug).

Fig. 3(a). Double junction quantum interferometer: two junctions mounted on a superconducting ring. A magnetic field applied to the plane of the ring modulates the critical current of the two junctions.

(b). Typical plot of critical current vs applied magnetic flux for a double/junction.

(c). Skewed oscillations from an asymmetric double junction.

Fig. 4(a). Single junction quantum interferometer, coupled to which is the inductance of a tank circuit. The amplitude of the voltage (V_o) across the tank circuit is an oscillatory function of the flux Φ applied to the interferometer.

(b). Photograph of an rf Squid.

Fig. 5(a). Superconducting flux transformer. The flux applied to the pick-up loop (1) generates a supercurrent in the transformer, and hence a flux in the Squid (X indicates a weak-link).

(b). Magnetic field gradiometer. The loops (1) and (2) are of equal area but opposite sense. The flux generated in the Squid is proportional to the difference in the fields at (1) and (2).

Fig. 6. Superconducting voltmeter. The current $I = V/R$ induced in the loop of inductance L generates a magnetic flux in the interferometer.

Fig. 7. Constant-voltage current steps induced on Sn-SnO-Sn junction by 4GHz radiation.

Fig. 8. Schematic of flux shuttle as a counter of shift register. Loop 1 contains a single flux quantum maintained by the circulating supercurrent $J = \phi_o/L$, where L is the loop inductance.

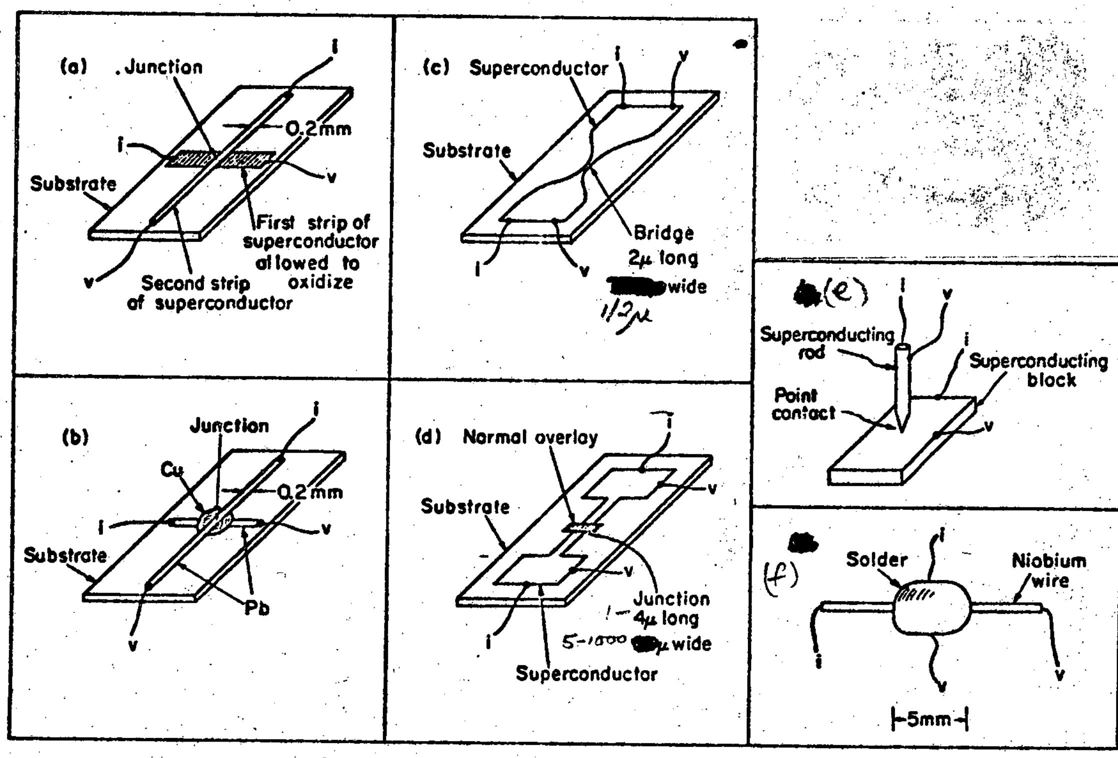

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Fig. 1

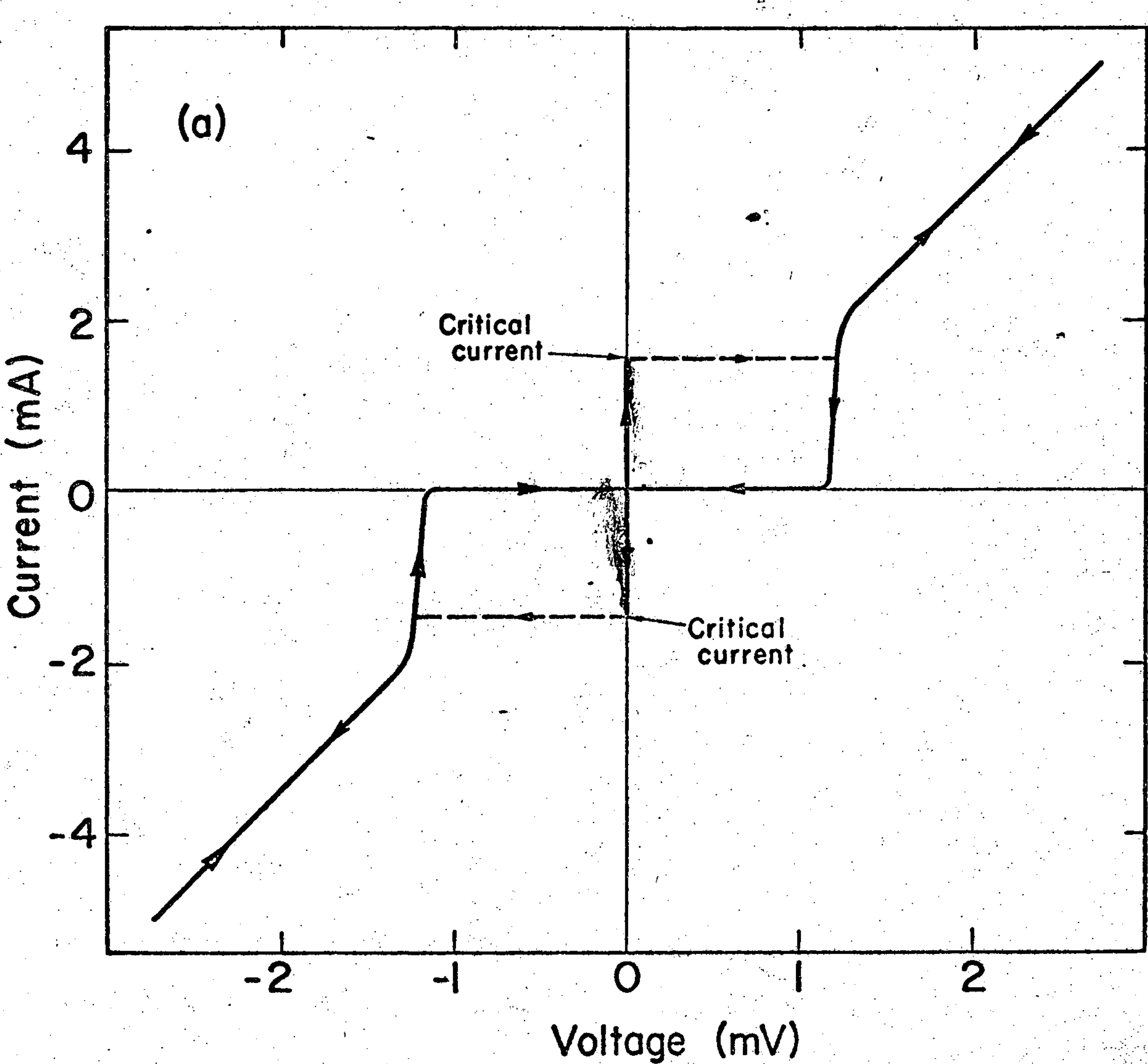

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Fig. 2(a)

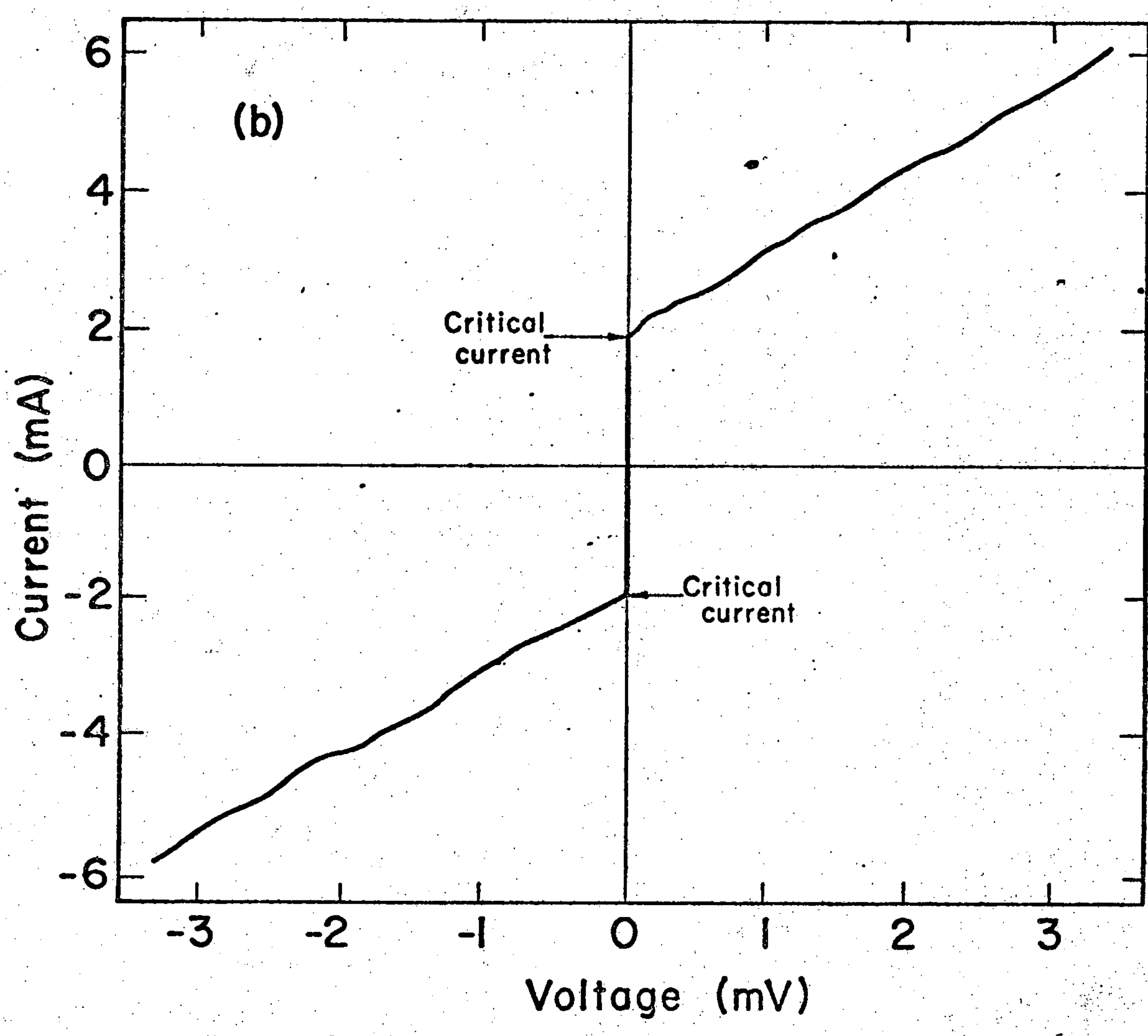

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Fig. 2(b)

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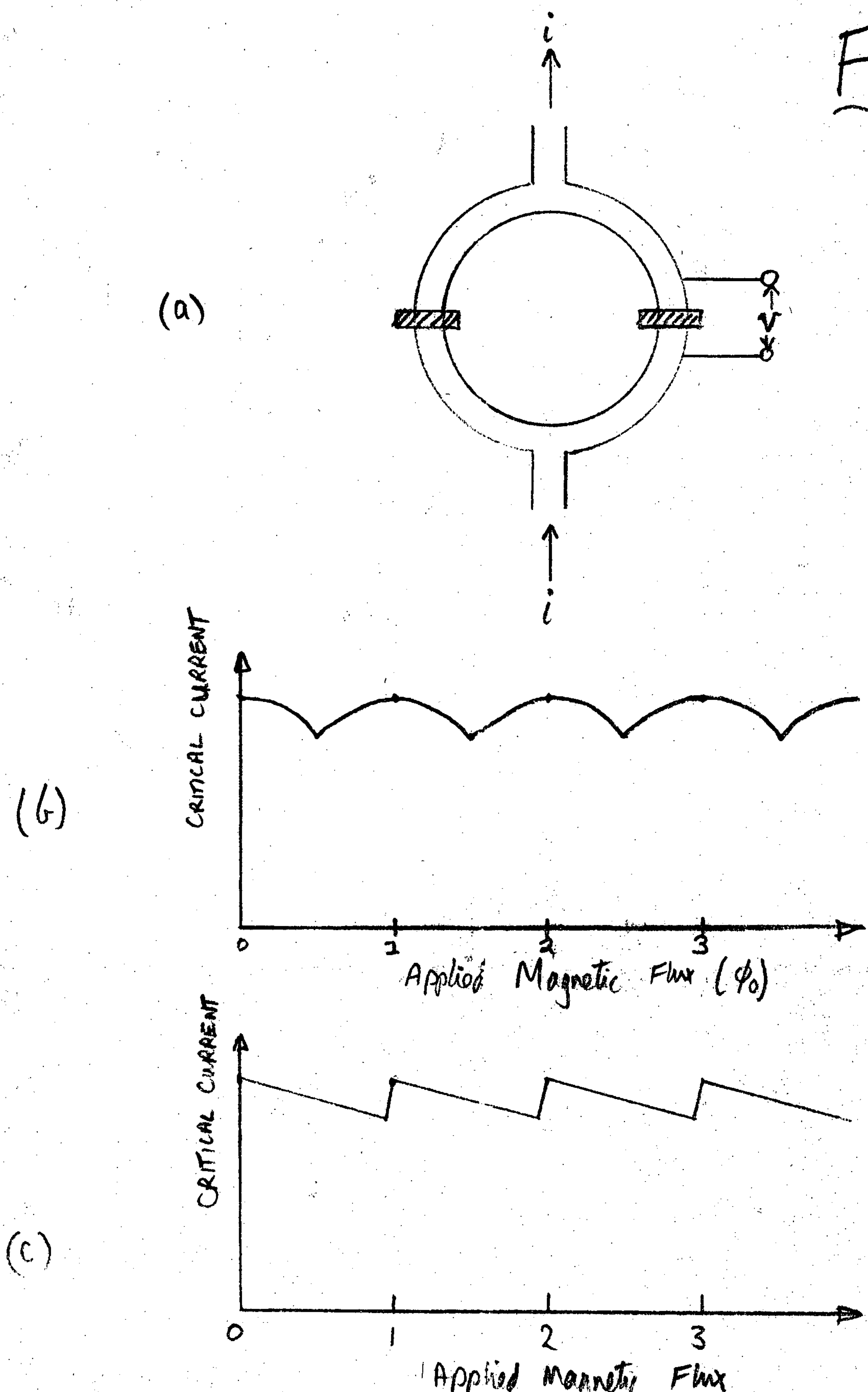
FIG. 3



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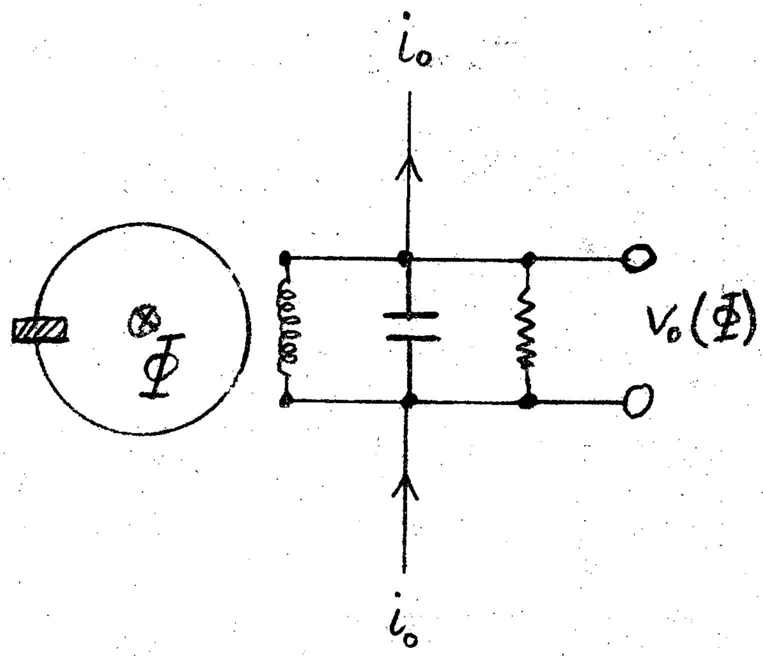

Fig. 4(a)

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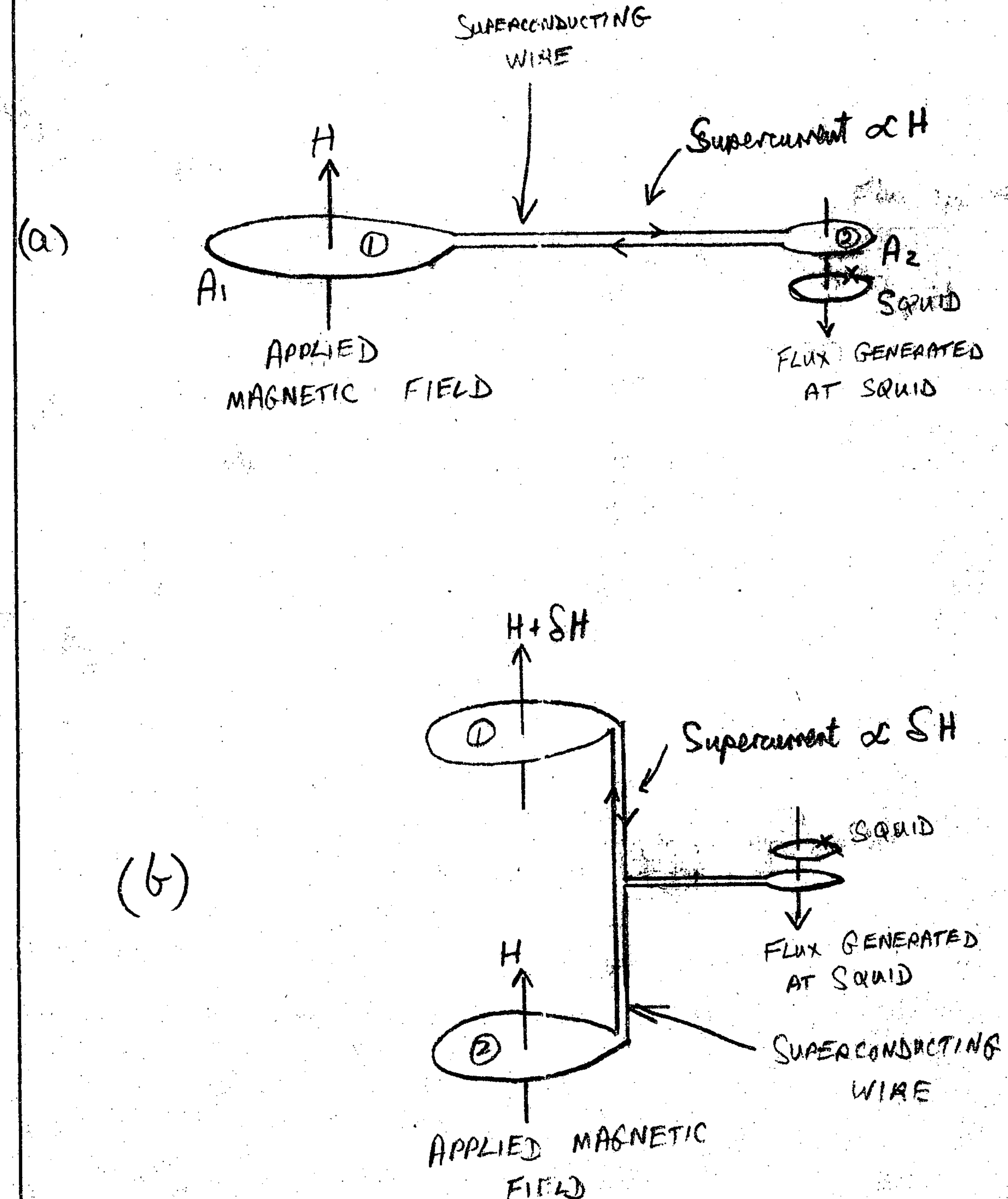

Fig. 5

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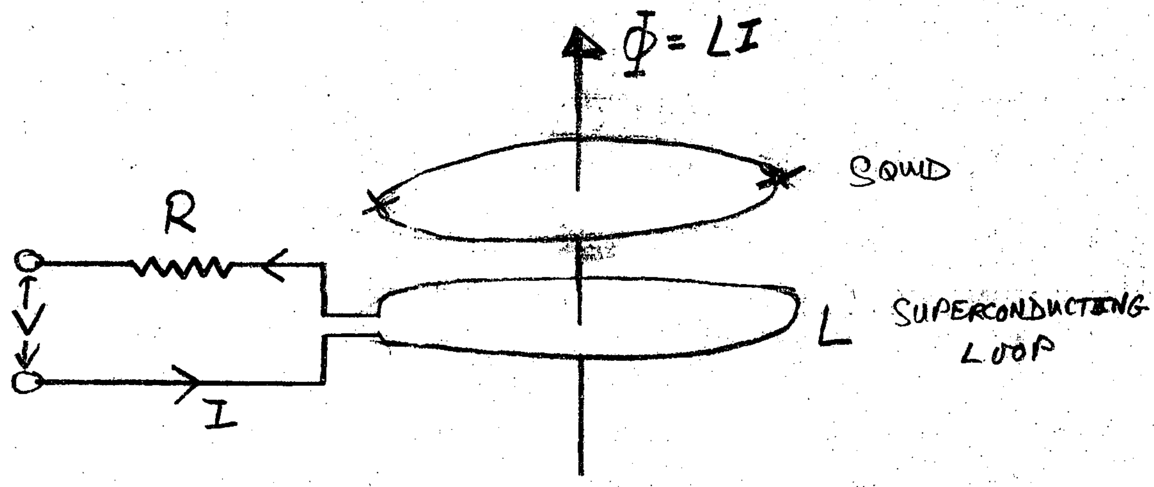

Fig. 6

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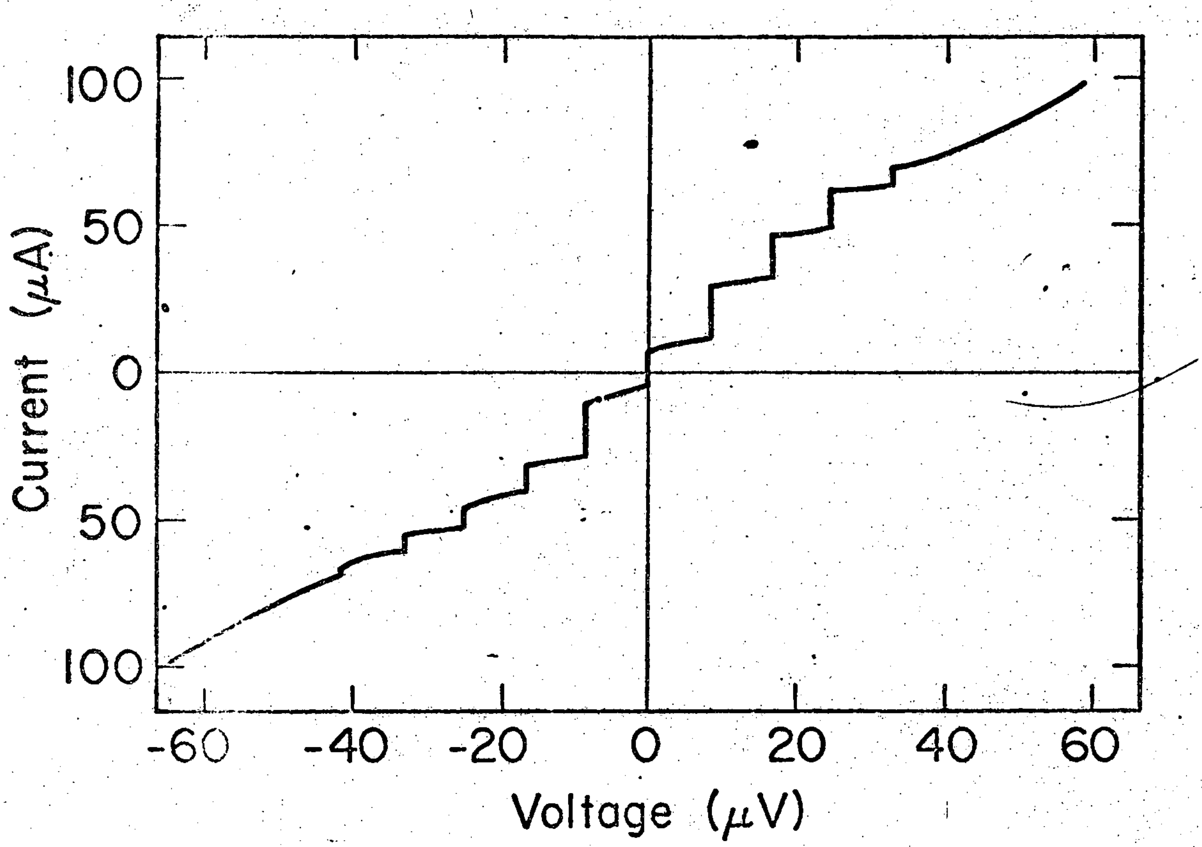

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Fig 7.

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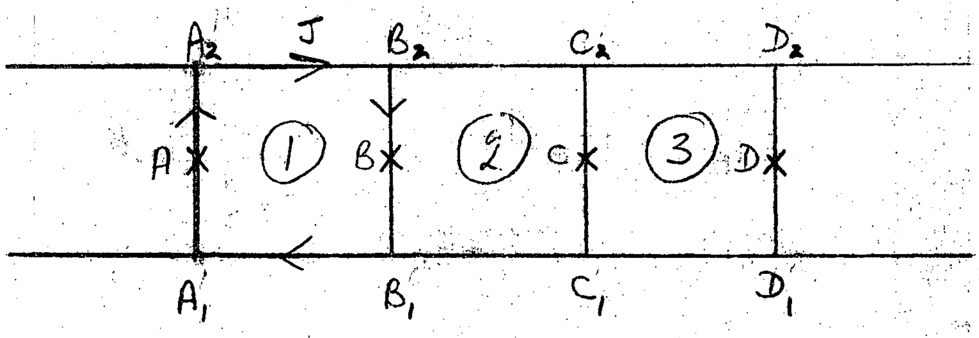

Fig. 8

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