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Publication Date

1968-06-01

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Submitted to Physical Review Letters

UCRL-18330
Preprint

UNIVERSITY OF CALIFORNIA

Lawrence Radiation Laboratory
Berkeley, California

AEC Contract No. W-7405-eng-48

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ABSTRACT

Using the a c Josephson effect we have demonstrated experimentally
that $2e/h$ is identical in lead, tin and indium to within 1 part in 10^{11} .

Josephson¹ showed that when two weakly coupled superconductors are biased at a voltage, V , an alternating supercurrent of frequency

$$\nu = 2eV/h \quad (1)$$

flows between them, e being the electronic charge and h Plank's constant. The effect of electromagnetic radiation of frequency ν upon a Josephson junction or weak link is to induce time-independent constant-voltage current steps² on the current-voltage characteristic. In the case of a pure Josephson junction in which the current through the barrier is related to the difference in the phase of the order parameter (ϕ) across it by the relation¹ $j = j_1 \sin \phi$, the voltage at which the steps appear is given by

$$V_n = nh\nu/(2e), \quad (2)$$

n (the order of the step) being an integer. In the more general case of a metallic bridge or point contact subharmonic steps may also be observed³.

By irradiating junctions at a known frequency and measuring the voltages at which the resultant steps occurred, Parker, Taylor and Langenberg^{4, 5} have deduced an absolute value of e/h with a precision of 6 parts in 10^6 . This result, provided it contains no unsuspected systematic error, resolves a major difficulty in modern electrodynamics, namely the discrepancy between the theoretical and experimental values of the hyperfine splitting of atomic hydrogen. In addition, the method provides a simple and accurate means of comparing and maintaining standards of electromotive force⁶. Consequently it is of importance to establish Eq. 2 as an exact universal relation which is independent of

the superconductors used and the conditions under which the experiment is performed. Parker et al. showed that this was so to within 2 parts in 10^6 . The present experiments, although of low absolute accuracy, demonstrate that the voltage-frequency relation is identical in different materials to 1 part in 10^{11} . The principle of the experiment is to apply the same radiation to two junctions of dissimilar materials and bias each on the induced step of the same order n : by directly comparing the voltages across the two junctions, one may make a very precise differential measurement.

In contrast to the insulating barriers or point contacts used in previous experiments, the present junctions consisted of a normal metal barrier sandwiched between two superconductors⁷. The junctions were made by evaporating successively on to a glass substrate a strip of superconductor (lead, tin or indium), a disc of normal metal (usually copper) and finally a second strip of superconductor at right angles to the first (see Fig. 1(a)). The superconductors were about 0.2 mm wide and $5,000\text{\AA}$ thick; the copper was typically $10,000\text{\AA}$ thick. The current-voltage characteristics of these sandwiches were studied in the four-terminal arrangement. It was shown that the junctions sustained a supercurrent up to a certain critical value, above which a voltage appeared, tending rapidly to a linear dependence on current. Because of the very low electrical resistance of the copper barrier, typically $10^{-7}\ \Omega$, the voltages developed were small and it was convenient to use a superconducting voltmeter⁸ to measure them. The critical current, typically

a few mA, decreased exponentially with increased thickness of copper and rose rapidly as the temperature was lowered⁷. The magnetic field dependence of the critical current indicated that the sandwiches behaved essentially as Josephson junctions.

A sinusoidal R. F. field was applied to the junctions by means of an oscillator driving a small solenoid surrounding them. Current steps were induced on the characteristic; thus both a c and d c Josephson effects are observed in these sandwiches. Steps were seen at frequencies between a few kHz and about 1 MHz, the latter corresponding to a voltage of about 2nV at the first harmonic step. The amplitude of the steps was rapidly attenuated at voltages higher than a few nV, irrespective of the frequency of the applied radiation. Thus with a frequency of 1 MHz only the first harmonic step was visible whereas at 100 kHz, steps were observed up to at least the 10th harmonic. An example of the induced steps is shown in Fig. 1(b). Subharmonic steps were also usually observed, as in the thin film bridges studied by Anderson and Dayem³, indicating that flux flow occurs in the junctions at finite voltages. It is not yet known whether the true a c Josephson effect or a flux flow mechanism is dominant in producing the integer steps. However, the distinction is immaterial for the present purpose since in both processes the same quantity $2e/h$ relates voltage and frequency. The important feature which makes possible the very precise voltage measurements is the extremely low differential resistance of the steps compared with that of other types of junction.

The principle of the comparison experiment is indicated in Fig. 2. The two junctions, of different superconductors, are connected in series with a superconducting switch and a superconducting galvanometer⁸. The junctions are subjected to the same radiation and with the switch open each is biased independently on the same order induced step. The superconducting switch is then closed. If there is any voltage difference between the junctions, a current will flow through the galvanometer. The voltage resolution (ΔV) of the system is IR , where I is the current sensitivity of the galvanometer and R the total differential resistance of the steps on which the junctions are biased. No current flow was detected and an upper limit of 1 part in 10^{11} was set on the voltage difference.

In the initial experiments the junctions were lead-copper-lead and tin-copper-tin; this combination was chosen because lead is a strong-coupling superconductor whereas tin is not. The entire circuit was surrounded by a superconducting can to screen out external magnetic field fluctuations and immersed in a bath of superfluid helium, the temperature of which was stabilized to within 10^{-4}°K . The cryostat was surrounded by a double mu-metal shield to reduce the earth's field to a few milligauss. The inductance of the circuit (L), estimated by introducing a known resistance in series with the galvanometer⁸ and measuring the time-constant, was $(1.0 \pm 0.1) \times 10^{-7}$ H. The resolution of the galvanometer was $0.3 \mu\text{A}$. The superconducting thermal switch was tested with sub-critical currents in the junctions and found to

induce no observable spurious current into the circuit. (The circulating current induced due to flux quantization was no greater than $1/2 \phi_0/L \approx 10$ nA). The frequency of the applied radiation was 500 kHz so that the voltage of the first order induced step, upon which each junction was biased, was approximately 1.06 nV. The amplitude of the steps was typically 0.5 mA. When the switch was closed it was found that no current flowed through the galvanometer and that both junctions remained biased upon their steps. In this state, although there was a voltage across the junctions, the circuit was superconducting in the sense that a magnetic field applied to it induced a circulating supercurrent, provided that its amplitude was insufficient to drive either junction off the induced step. In order to obtain the maximum possible circulating current, junction 1 was current-biased at the lower end of its step and junction 2 at the upper end and the circulating current caused to flow in the same direction as i_1 . An upper limit was set on the value of R by studying the decay of the circulating current. With an induced circulating current of 500 μ A, the decay was less than 0.3 μ A in 1.8×10^3 sec, giving a time-constant (τ) greater than 3×10^6 sec. Thus $R (=L/\tau)$ was less than $3.3 \times 10^{-14} \Omega$ and the voltage resolution at least 10^{-20} volts. We can therefore say that the voltages developed across the junctions were identical to within about 1 part in 10^{11} . The best resolution ever obtained was 6 parts in 10^{12} .

During the course of each measurement, both the frequency and amplitude of the R. F. drifted by about 1 part in 10^5 . The frequency

shift caused the same change in the voltage induced across each junction and the amplitude variation affected the shape of the current-voltage characteristic and the size of the steps. However, neither fluctuation was sufficiently large to drive the junctions off the steps or to introduce any discernable dissipation of the circulating current.

The same null result was obtained when the pairs of superconductors were lead and indium or tin and indium and also when silver was substituted for copper as the barrier in one of the junctions. In addition, the variation of the following parameters, although generally affecting the shape of the current-voltage characteristic and the amplitude of the steps, did not give rise to any observable difference in the voltage across the junctions:

- (i) temperature, from 1.2°K to 2.2°K;
- (ii) the thickness of the barrier;
- (iii) the level of the applied R. F. power, over a factor of 5 (5 parts in 10^{11});
- (iv) the R. F. frequency, from 100 kHz to 500 kHz (5 parts in 10^{11});
- (v) the order of the steps on which both junctions were biased, up to the fourth order (5 parts in 10^{11});
- (vi) the position on the induced step (2 parts in 10^{11});
- (vii) the ambient magnetic field, up to ± 1 Gauss (5 parts in 10^{11});
- (viii) the direction of the bias current through the junctions;
- (ix) the direction of the circulating supercurrent.

In some of these experiments the accuracy was lower (as indicated in parenthesis) because of the reduced size of the induced steps and hence

of the maximum possible circulating supercurrent.

In conclusion we may state that $2e/h$ is identical in lead, tin and indium to within 1 part in 10^{11} and, to a somewhat lower accuracy, remains so when a number of experimental conditions are varied. From these observations we cannot deduce directly that the charge on the pairs⁹ is $2e$ to within these limits. However, it would be truly remarkable if the corrections to the free electron charge were identical for all three metals at this level of precision and it would seem more likely that, at least at this level, there are in fact no corrections to be applied. One might therefore express considerable confidence in the absolute accuracy of the results of Parker et al. at the level of 1 part in 10^6 , as regards both the quantum electrodynamic implications and the proposal for comparing and maintaining standards of voltage. One might further consider the possibility of using the Josephson a. c. effect to define the absolute volt.

The writer would like to acknowledge helpful discussions with Professors J. A. Appelbaum, M. L. Cohen, P. L. Richards and G. I. Rochlin.

This work was supported by the United States Atomic Energy Commission.

FOOTNOTES

1. B. D. Josephson, Phys. Letters 1, 251 (1962); Adv. in Phys. 14, 419 (1965).
2. S. Shapiro, Phys. Rev. Letters 11, 80 (1963).
3. 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).
4. W. H. Parker, B. N. Taylor and D. N. Langenberg, Phys. Rev. Letters 18, 287 (1967).
5. W. H. Parker, Ph.D. Thesis, University of Pennsylvania.
6. B. N. Taylor, W. H. Parker, D. N. Langenberg and A. Denenstein, Metrologia, October 1967.
7. A detailed account of the preparation and properties of these junctions is to be published.
8. The superconducting galvanometer (SLUG) used in all of the experiments has been described elsewhere (J. Clarke, Phil. Mag. 13, 115 (1966)). The galvanometer consists of a pellet of tin-lead solder surrounding a length of niobium wire so as to form a weak link device. The critical current is a function of the current flowing in the wire. To avoid feeding spurious A. C. signals into the cryostat, a D. C. technique (J. W. McWane, J. E. Neighbor and R. S. Newbower, Rev. Sci. Instrum. 37, 1602 (1966)) was used to monitor the critical current and hence detect changes in the current flowing along the niobium wire. In the determination of the characteristics of the Pb-Cu-Pb junctions, a resistance of about $10^{-7} \Omega$ was connected in series with the galvanometer and the voltages measured using a null-reading technique.

9. In his thesis, Parker points out that if higher order correlations of electrons are present (e.g. 4 or 6) these will give rise to subharmonic or lower order harmonic steps and not affect the voltage at which the steps appear.

FIGURE CAPTIONS

- Fig. 1(a) Lead-copper-lead junction configuration.
- (b) The current-voltage characteristic of a lead-copper-lead junction at 4.2°K irradiated at a frequency of 250 kHz.
- Fig. 2 Circuit used for comparing the voltages developed across two junctions of different superconductors irradiated at the same frequency. The currents i_1 and i_2 are adjusted to bias each junction on the same order current step.

Fig. 1

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Fig. 2

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