we have now seen CESR in four metals besides all the alkalis, there is a good possibility for observing spin waves in at least one of them.

[5]S. Schultz and C. Latham, Phys. Rev. Letters 12, 695 (1965); S. Schultz and M. R. Shanabarger, Phys. Rev. Letters 16, 187 (1966).

[6]This is a big "if." In our experiments leakage was typically better than 165 dB, and the actual power in the main spin-wave peak was ≈20 dB above leakage for the data presented in Fig. 1.

[7]Although we have detected the power transmitted, for most purposes it is more convenient to measure the component of the transmitted magnetic field projected on a reference rf field, and all the data shown were taken with the reference field adjusted so as to observe the imaginary part of the complex susceptibility (i.e., the quantity which is called χ'' in the usual resonance terminology.)

[8]For our material $\rho(\text{R.T.})/\rho(4.2°\text{K}) \approx 6000$, and the appropriate $\omega\tau \approx 20$. Making corrections due to the finite $\omega\tau$ does not significantly alter any of the results presented. $T_2 \approx 10^{-6}$ sec.

[9]We have used the value of 1.24 for m^*/m in sodium. C. C. Grimes and A. F. Kip, Phys. Rev. 132, 1991 (1963).

[10]There are, of course, two roots for B_1 in the solution of the equation. One of these is eliminated in that it predicts the location of the spin waves on the wrong side of the CESR.

[11]M. T. Taylor, Phys. Rev. 137, A1145 (1965), and using $m^*/m = 1.24$.

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[13]See Ref. 1 and G. D. Gaspari, Phys. Rev. 151, 215 (1966).

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[15]For the range of sample thicknesses considered, the diffusion time for the spin information is much less than the spin relaxation time. Hence, a free-induction decay measures T_2^*. The same equipment is being used for experiments at higher temperatures where the reverse relationship between the times applies.

MEASUREMENT OF $2e/h$ USING THE ac JOSEPHSON EFFECT AND ITS IMPLICATIONS FOR QUANTUM ELECTRODYNAMICS*

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(Received 23 January 1967)

Using the ac Josephson effect, we have determined that $2e/h = 483.5912 \pm 0.0030$ MHz/μV. The implications of this measurement for quantum electrodynamics are discussed as well as its effect on our knowledge of the fundamental physical constants.

In this Letter, we report a high-accuracy measurement of $2e/h$ using the ac Josephson effect (here, e is the electron charge and h is Planck's constant). When combined with the measured values of other fundamental constants, this measurement yields a new value for the fine-structure constant α which differs by 21 ppm from the presently accepted value. This change in α removes the present discrepancy between the theoretical and experimental values of the hyperfine splitting in the ground state of atomic hydrogen, one of the major unsolved problems of quantum electrodynamics today. We also discuss the effect of this change on our present knowledge of the fundamental physical constants.

The phenomenon used in these experiments was first predicted by Josephson in 1962.[1] He showed theoretically that when two weakly coupled superconductors are maintained at a potential difference V, an ac supercurrent of frequency

$$\nu = (2e/h)V \qquad (1)$$

flows between them. This equation, known as the Josephson frequency-voltage relation, can be shown to follow from quite general assumptions concerning superconductivity,[1,2] and is believed to be exact. In a recent publication[3] we reported an experimental test of this relation which verified that the frequency-voltage ratio was equal to the then best value of $2e/h$ to within the 60-ppm uncertainty of the measurements, and was completely independent of all of the experimental variables tested. This work also demonstrated that the main experimental difficulty with using the ac Josephson effect to make a high-accuracy determination of $2e/h$ was the calibration of the voltage-measuring system. Since then, we have acquired a completely self-calibrating system, and have carried out a new series of measurements with an order-of-magnitude improvement in accuracy.

In these new experiments, measurements were performed on two types of "junctions" which show ac Josephson-effect phenomena—evaporated thin-film tunnel junctions, and point-contact weak links.[3] The particular phenomenon used was that of microwave-induced, constant-voltage current steps[1,2] of the type first observed by Shapiro.[4] Such steps appear as excess dc currents in the current-voltage characteristics of Josephson junctions when they are irradiated with microwave radiation of frequency ν. Physically, this effect arises from the presence of a microwave-induced ac voltage across the junction which frequency-modulates the ac Josephson current. The constant-voltage current steps simply correspond to zero-frequency (dc) sidebands. The relationship between the voltages V_n at which these steps occur and the frequency of the applied radiation is $2eV_n = nh\nu$, where n is the number of the step. A determination of $2e/h$ can thus be made simply by measuring the frequency of the applied microwave radiation and the absolute voltage at which the current steps occur. No other measurements are required except those necessary in calibrating the equipment, and in this sense it is a remarkably straightforward fundamental constant experiment.

The applied microwave radiation was generated by an X-band (8- to 12.4-GHz) oscillator with a stability of one part in 10^8 per hour when phase-locked to a quartz crystal reference. The frequency of the radiation was measured to an accuracy of one part in 10^8 by using an electronic counter and a microwave frequency converter. The reference time base of the counter was maintained to an accuracy of better than one part in 10^8 by regular phase comparisons with the U. S. frequency standard as broadcast by radio station WWVB, Fort Collins, Colorado. Thus, the frequency measurement contributed negligible error (~0.01 ppm) to the measured value of $2e/h$. The over-all accuracy was limited by the voltage-measuring system, i.e., potentiometer and standard reference voltage.

The reference voltage used was the mean voltage of a set of six standard cells, calibrated by the U. S. National Bureau of Standards (NBS), in a constant-temperature air bath. This voltage was known to 1 ppm in terms of the NBS legal volt, the uncertainty being an estimate of the possible changes in the emf of the standard cells due to transporting them from NBS to our laboratory. In order to obtain a value of $2e/h$ in absolute units, it is necessary to convert from the legal volt to absolute volts. The present best value of this conversion factor is 1 NBS legal volt = $1.000\,012 \pm 0.000\,004$ absolute volts, where the 4-ppm uncertainty is intended to represent a 50% confidence level.[5]

The potentiometer used was the Julie Research Laboratories PVP 1001.[6] This nanovolt instrument is self-calibrating in that it has provisions which enable the operator to measure all factors which contribute to the accuracy of a voltage measurement and to make any necessary corrections. Using techniques developed by Julie Research Laboratories[7] and NBS,[8] the 1-mV full-scale range can be calibrated with an rms uncertainty of between 3 and 4 ppm (this was the range normally used since the voltages of the induced current steps rarely exceeded 1 mV). The null detector used with the potentiometer consisted of a photocell amplifier and galvanometer and had a resolution of 1 nV.

In making accurate measurements of such small voltages, great effort is necessary to eliminate or correct for spurious voltages in the measuring circuit. In the measurements described here, the effect of voltages which do not reverse when the current is reversed (thermoelectric voltages, for example) was eliminated by measuring constant-voltage current steps of both polarities. Voltages which

reverse with current (those from Ohmic sources, for example) were shown to be negligible by observing that the voltage in the measuring circuit was constant over the full range of the zero-voltage current arising from the dc Josephson effect.[1] Spurious voltages due to any rectification of the microwaves were also shown to be negligible by observing that the measured value of $2e/h$ was independent of microwave power over a range of 10 dB for a given sample and of 20 dB from sample to sample.

The results of measurments on several thin-film tunnel junctions and point-contact weak links are given in Table I. The standard deviation of a set of measurements obtained during one run[9] on any particular junction, typically 2 ppm, is due to the 1-nV resolution of the null detector, the stability and linearity of the potentiometer, and the stability of the thermoelectric voltages in the measuring circuit (usually of order 100 nV). Within this 2-ppm standard deviation, the measured value of $2e/h$ was found to be independent of a wide variety of experimental conditions, including step number up to $n=40$, magnetic field from 0 to 10 G, microwave frequency from 8 to 12 GHz, and microwave power. All of the measurements were carried out between 1.2 and 1.6°K.

For most of the current steps from which the data were obtained, the voltage was constant to within 1 nV (the resolution of the null detector) over the full range of the step. However, for three of the point contacts (marked by an asterisk in Table I), the voltage was found to increase by 5-10 nV as the current was increased over the range of the step. It was observed that in higher resistance point contacts (several tenths of an ohm rather than several hundredths of an ohm), where the voltage variation was as much as 200 nV, the midcurrent point of the step gave a value of $2e/h$ equal to the average of all the data obtained on the constant-voltage steps. As the resistance was decreased, the voltage variation decreased and the midpoint continued to give a value of $2e/h$ in agreement with the constant-voltage step data. Extrapolating this behavior to contacts with 5- to 10-nV variation, we assume that the midcurrent point corresponds to the voltage at which the step would occur if it were constant. Thus, all measurements on such steps were made at this midpoint.

The average of all of the data in Table I, weighted as the inverse square of the rms uncertainties, gives

$$2e/h = 483.5912 \pm 0.0030 \text{ MHz}/\mu\text{V},$$

or in more conventional terms,

$$h/e = 4.135\,725 \pm 0.000\,026 \times 10^{-15} \text{ J sec/C}$$

$$= 1.379\,529 \pm 0.000\,008 \times 10^{-17} \text{ erg sec/esu}.$$

The quoted uncertainty, about 6 ppm (70% confidence level), is an rms sum of all known sources of error, either systematic or random, and includes the uncertainty in the calibration of the potentiometer, the standard deviation

Table I. Summary of experimental data. Junctions of the form Sn-SnO-*X* are evaporated thin-film tunnel junctions while the others are point-contact weak links. The table entries are in chronological order and the decreasing uncertainty in the potentiometer calibration results from improved techniques.

JUNCTION	UNCORRECTED $n\nu/V$ WITH STD. DEV. MHz/μV	POTENTIOMETER CORRECTION WITH rms UNCERTAINTY ppm	STD. CELL TEMPERATURE CORRECTION ppm	CORRECTED $n\nu/V$ WITH rms UNCERTAINTY MHz/μV
Sn-SnO-Sn	483.610 ± .002	-30 ± 10	—	483.596 ± .005
Sn-Sn	483.6126 ± .0011	-29 ± 7	—	483.5986 ± .0032
Ta-Ta	483.6164 ± .0009	-39 ± 4	-0.5	483.5973 ± .0021
Sn-SnO-Sn	483.6156 ± .0008	-39 ± 4	-0.5	483.5965 ± .0021
Sn-SnO-Sn	483.6158 ± .0007	-42 ± 4	-0.3	483.5955 ± .0021
Sn-SnO-Pb	483.6174 ± .0013	-43 ± 4	-1.0	483.5962 ± .0023
Nb-Ta*	483.6195 ± .0007	-42 ± 4	-1.0	483.5987 ± .0021
Ta-Nb_3Sn*	483.6185 ± .0011	-44 ± 4	-0.5	483.5975 ± .0022
Ta-Ta*	483.6185 ± .0016	-46 ± 4	-0.4	483.5961 ± .0025
Sn-SnO-Sn	483.6194 ± .0005	-45 ± 4	-0.0	483.5976 ± .0020
WEIGHTED AVERAGE OF DATA IN TERMS OF NBS VOLT MHz/μV_{NBS}				483.5971 ± .0022
NBS VOLT TO ABSOLUTE VOLT CONVERSION				-0.0058 ± .0019
FINAL VALUE FOR 2e/h IN ABSOLUTE UNITS MHz/μV				483.5912 ± .0030

of a set of measurements, the uncertainty in the absolute value of the NBS legal volt, and the uncertainty in transferring the NBS volt to our laboratoratory. It should be noted that the standard deviation of the eight most accurate measurements, made over a period of several months, is only 2 ppm, an indication of the high precision of the measurements. To within this 2-ppm precision, the measured value of $2e/h$ is independent of the material and type of junction used.

A value of the fine-structure constant can be derived from our value of $2e/h$ and other directly measured quantities by use of the equation

$$\alpha^{-1}=\left[\frac{c}{4R_\infty\gamma_p}\frac{\mu_p}{\mu_0}\frac{2e}{h}\right]^{1/2}, \tag{2}$$

where c is the velocity of light, R_∞ is the Rydberg constant for infinite mass, γ_p is the gyromagnetic ratio of the proton, and μ_p/μ_0 is the magnetic moment of the proton in units of the Bohr magneton. Taking the best values for these quantities,[10] $c=2.997\,925\times10^8$ m sec^{-1} ±0.3 ppm, $R_\infty=1.097\,373\,1\times10^7$ m$^{-1}\pm0.1$ ppm, $\mu_p/\mu_0=1.521\,032\,5\times10^{-3}\pm0.5$ ppm, $\gamma_p=2.675\,192\times10^8$ rad sec^{-1} T$^{-1}\pm3$ ppm, and $2e/h=4.835\,912\times10^{14}$ Hz V$^{-1}\pm5$ ppm, Eq. (2) gives[11]

$$(\alpha^{-1})_{2e/h}=137.0359\pm0.0004.$$

This value is 21 ± 5 ppm less than the presently accepted value derived from the fine-structure splitting (fs) in deuterium as measured by Treibwasser, Dayhoff, and Lamb,[12,13]

$$(\alpha^{-1})_{\mathrm{fs}}=137.0388\pm0.0006.$$

The new value of α derived here entirely removes the apparent discrepancy between the theoretical and experimental values for the hyperfine splitting (hfs) in the ground state of atomic hydrogen. This splitting (ν_{hfs}) has been measured to the extraordinary accuracy of 2 parts in 10^{11} by Crampton, Kleppner and Ramsey.[14] The quantum-electrodynamic expression for the splitting, which includes all theoretical effects other than the dynamic polarizability of the proton, is believed to be accurate to a few ppm.[15] When this expression is evaluated using $(\alpha^{-1})_{\mathrm{fs}}$, it predicts

$$\frac{\nu_{\mathrm{hfs}}(\mathrm{expt})-\nu_{\mathrm{hfs}}(\mathrm{theory})}{\nu_{\mathrm{hfs}}(\mathrm{expt})}=43\pm12\ \mathrm{ppm}.$$

[The quoted errors include an uncertainty of 2 ppm in the estimate of form factors and 5 ppm in $(\alpha^{-1})_{\mathrm{fs}}$.] If the theoretical expression is evaluated using $(\alpha^{-1})_{2e/h}$, it predicts

$$\frac{\nu_{\mathrm{hfs}}(\mathrm{expt})-\nu_{\mathrm{hfs}}(\mathrm{theory})}{\nu_{\mathrm{hfs}}(\mathrm{expt})}=0\pm8\ \mathrm{ppm}.$$

Although at present it is impossible to calculate the proton polarizability exactly, the best estimates indicate that it would increase ν_{hfs}(theory) by less than 10 ppm.[15] Thus, unless the proton polarizability is much larger than is presently believed, $(\alpha^{-1})_{\mathrm{fs}}$ suggests a breakdown of quantum electrodynamics, while $(\alpha^{-1})_{2e/h}$ is consistent with both quantum electrodynamics and a small proton polarizability.

The change in α implied here is also important because in the 1963 adjustment of the fundamental physical constants by Cohen and DuMond, the value $(\alpha^{-1})_{\mathrm{fs}}$ was used as an input datum. Because of the pivotal role played by α in this adjustment,[16] any change in α will cause large changes in the values of the other fundamental constants. In Table II, we give the values of some of the more important constants which would have resulted if $(\alpha^{-1})_{2e/h}$ had been used as an input datum in the 1963 adjustment.

We might also point out that with this new experimental value for $2e/h$, a new and more reliable value for the x-ray wavelength conversion factor Λ can be obtained. Using the recent experimental data of Spijkerman and Bearden[17] for the voltage-to-wavelength conversion factor, $V\lambda_S$, we find that $\Lambda=1.002\,067\pm0.000\,023$ Å/kxu based on Bearden's new definition of the x unit.[18]

Although we believe that the results reported here are highly reliable, work is continuing to ensure that there is no unknown systematic error in the measurements. To this end, experiments of the type described here are being carried out at higher frequencies (~70 GHz) as well as experiments involving the measurement of the frequency of the radiation emitted by a Josephson tunnel junction when biased to a known voltage. Preliminary results from experiments of the latter type are in complete agreement with the results presented here.

We should like to thank Mr. Loebe Julie for helpful discussions concerning the potentiometer, Mr. A. G. McNish for arranging the cal-

Table II. Changes in some of the fundamental physical constants resulting from substituting $(\alpha^{-1})_{2e/h}$ for $(\alpha^{-1})_{fs}$ in the input data of the 1963 adjustment. (N is Avogadro's number and m is the rest mass of the electron.) The numbers in parentheses are the one-standard-deviation errors in ppm.

Quantity	Units	Value given by 1963 adjustment	Value implied by this measurement	Change (ppm)
α^{-1}	–	137.0388(4)	137.0359(3)	−21
e	10^{-19} C	1.602 10(13)	1.602 20(13)	+63
	10^{-10} esu	4.802 98(13)	4.803 28(13)	
h	10^{-34} J sec	6.625 59(24)	6.626 28(24)	+105
me	10^{-31} kg	9.109 08(14)	9.109 65(14)	+63
N	10^{26} kmole^{-1}	6.022 52(15)	6.022 14(15)	−63

ibration of the standard cells, Dr. E. Richard Cohen and Dr. Jesse W. M. DuMond for their interest and encouragement, Professor S. A. Bludman and Professor D. J. Scalapino for helpful discussions, and Mr. A. Denestein for his excellent technical assistance.

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*A contribution from the Laboratory for Research on the Structure of Matter, University of Pennsylvania, covering research sponsored by the National Science Foundation and Advanced Research Projects Agency.

†Part of this work was performed while the author was at the University of Pennsylvania and part while at RCA Laboratories.

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