Investigation of Electron Emission from Superconductors

FERNAND BEDARD,* HANS MEISSNER, AND GEORGE E. OWEN
Department of Physics, Johns Hopkins University, Baltimore, Maryland
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Electron emission from a superconducting tin surface at low electric field strengths was sought for. The sample was the cathode of an electron gun, which was focused on a NaI(Tl) crystal. A photomultiplier tube and associated pulse-counting equipment was used as a detector for light pulses. The measurements indicate that at a field strength of 570 v/cm the order of magnitude of such emission is less than 100 electrons/cm^2-sec, under the surface conditions used.

I. INTRODUCTION

MEASUREMENTS of the contact resistance between two superconductors and between a superconductor and a normal conductor separated by an insulating barrier[1–3] indicate: (1) for two superconducting members, the disappearance of the barrier resistance below a critical current at a temperature below the critical temperatures of both elements; (2) for one superconducting member, the reduction of the barrier resistance below a critical current at a temperature below the critical temperature of this member.

The current transfer through the barrier in these cases, as well as in the case of two normal conducting members,[4] has been interpreted as being due to tunnel effect. It appears that the presence of a superconductor on one side of the barrier makes the penetration of the electrons easier.

Therefore the question arises whether electron emission from a superconducting surface under the influence of electric fields is possible at field strengths too small to give rise to ordinary field emission. Gomer and Hulm[5] have already shown that the field emission current does not change by more than an amount corresponding to a change of 0.001 ev in effective work function when a metal becomes superconducting.

II. EXPERIMENTAL METHOD

An electron gun was constructed (see Fig. 1) in which the cathode was a tin sample. If electrons are emitted by the cathode, they are accelerated by the plane-parallel field of a grid, further accelerated and focused onto a NaI(Tl) crystal. The ensuing scintillations of the crystal are converted into voltage pulses by a photomultiplier tube, amplified and counted. In the last runs provision was made for placing the grid at a negative repelling potential in order to establish whether increases in counting rate were due to electrons emitted by the sample.

The specimen, tin of 99.998% purity, was cast in a copper holder. Its surface was etched in HCl and observed to be composed of essentially three large crystals, after which it was electropolished until shiny and smooth.

The specimen holder was screwed into a copper shaft on the base plate of the electron gun (see Fig. 2) and the base plate soldered into place with indium-tin solder.

Located directly above the specimen was a movable electrode whose lower end was covered with a 400-mesh copper grid which served to place a plane field on the specimen. This electrode, along with the other three, formed three electron lenses which focused the beam. The fourth electrode was kept at a potential of 12 kv in order to give the electrons sufficient energy to be easily detected.

A NaI(Tl) crystal, glued by Gelva rosin to the Lucite light pipe, was used as a scintillator to detect the particles. In all runs except the fifth one, the back of the crystal was covered by an opaque 1500 A nickel foil.

In order to lengthen the running time, a 16 in. long, 1 in. diameter, commercially pure aluminum shaft was attached to the copper shaft on the base plate, thus

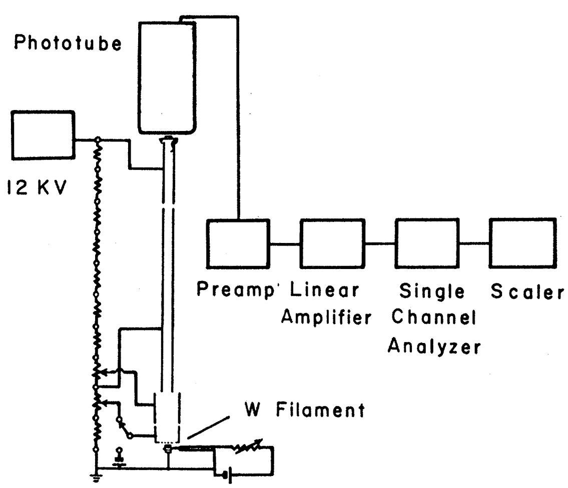

FIG. 1. Block diagram of experiment for measuring electron emission from superconducting Sn.

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[1] R. Holm and W. Meissner, Z. Physik **74**, 715 (1932).
[2] I. Dietrich, Z. Physik **133**, 499 (1952).
[3] F. Bedard and H. Meissner, Phys. Rev. **101**, 26 (1956).
[4] R. Holm, *Electric Contact* (Hugo Gebers Vörlag, Stockholm, 1940).
[5] R. Gomer and J. K. Hulm, J. Chem. Phys. **20**, 1500 (1952).

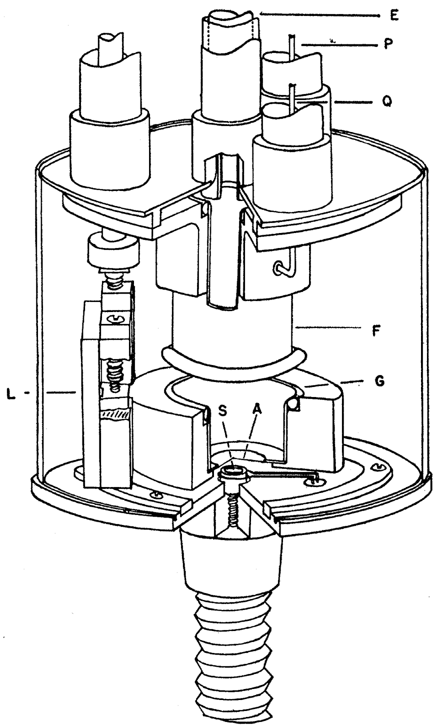

FIG. 2. Electron gun chamber. E—third electrode of electron gun; F—second electrode; G—first electrode; S—specimen; P—potential lead to first electrode; Q—potential lead to second electrode; L—lift assembly; A—accelerating grid.

allowing the use of a larger Dewar vessel (see Fig. 3). This necessitated, however, the installation of a carbon resistance thermometer attached to the specimen support in order to determine the specimen temperature.

III. CALIBRATION PROCEDURE

(a) Electron Gun

A tungsten filament, which covered the same area as the specimen, was heated to a temperature sufficiently high to obtain an emission current measurable by a meter. Then, under different grid voltage conditions, the current reaching a collector assembly was measured. This was done for different collector potentials in order to obtain the energy distribution of the electrons passing through the foil. This data is shown in Table I. It was later found that focus condition β burned a hole through the foil. Under this condition, the efficiency of the electron gun was again measured, producing data α' and β'.

The negative currents indicated for small potentials on the collector electrode are undoubtedly due to an ionization of the residual gas in the collector chamber by the high beam currents.

(b) Detection

Calibration of the mounted crystal and the phototube was accomplished with a Cd^{109} source of 22-kev γ rays. Because spurious pulses were produced by the mounted phototube whenever the high-voltage supply was turned on or off, it was necessary to check the counting efficiency as a function of applied voltage. Comparative pulse-height distributions were made with an intense Cs^{137} source of 660-kev γ rays for 0 kv and 10 kv on the electron gun. These data indicated no difference in pulse height or counting rate of the phototube between these conditions.

A tungsten wire loop around the specimen provided a means of calibrating the pulse height while the system was completely assembled for a run. With this filament heated and high voltage on the electron gun, a pulse-height distribution of the electrons striking the crystal could be made, and the pulse height corresponding to 12-kev electrons determined.

(c) Operating Procedure

Both Dewars (see Fig. 3) were filled with liquid nitrogen, and then the nitrogen was siphoned out of the helium Dewar by helium gas pressure. This Dewar was then filled with liquid helium up to the level of the top depth gauge resistor, $5\frac{1}{2}$ liters of liquid being necessary to fill the vessel with approximately 2 liters.

Table II lists representative measurements of counting rate at different grid potentials and temperatures, both above and below the critical temperature of tin.

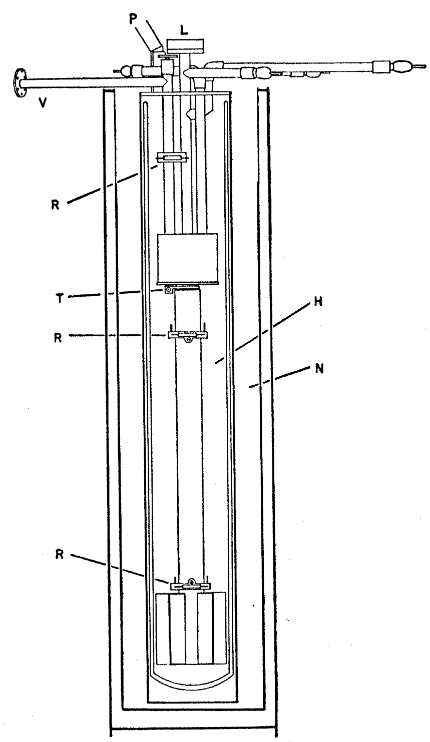

FIG. 3. Experimental assembly. P—to helium pump; V—to high vacuum pumps; L—Lucite crystal mount; T—carbon thermometer; R—carbon resistance depth gauge; H—helium Dewar; N—nitrogen Dewar.

IV. RESULTS

A total of five runs at liquid helium temperatures was made. Of these, the first two were made with a puncture in the nickel foil at a corner of the crystal. Since it was later found, in run 5, that some sporadic discharge phenomenon occurred, it appears reasonable to neglect these runs. For no verification was obtained of the observed counting rate changes in the first two runs, since there was no provision for placing the grid at a repelling potential.

From the data in Table II we see that there is no difference between the counting rates for the grid accelerating *versus* decelerating conditions.

In run 5, which was performed without a foil, sporadic discharges necessitated 1-minute measurements of counting rates. However, there still appears to be no difference between the measurements under the two grid conditions. This absence of a current change is real, in spite of discharges; because there is no background rate change when the grid potential is changed from an accelerating condition to a decelerating condition. This is shown by the fact that counting rate differences between the two grid conditions, accelerating and decelerating, show no dependence upon the accelerating potential.

TABLE I. Measurements of efficiency of electron gun.

Grid potential (volts)	Collector voltage kv	Filament emission μa	Collector current μa
1400(α)	12	63.0	0.44
	9.6		0.28
	7.2		0.12
	6.0		0.09
	2.4		0.03
200(β)	12	34.0	8.3
1400(α')	12	64.5	0.26
	9.6		0.16
	7.2		−0.047
	4.8		−0.047
	2.4		−0.047
200(β')	12	38.0	11.0
	9.6		9.4
	7.2		−1.9
	4.8		−3.1
	2.4		−3.1

Table III lists the limits of sensitivity of the experiment for detection of electrons emitted by the specimen of superconducting tin. They were calculated using the root mean square error of the measured background rate as the limit of sensitivity of detection, divided by the efficiency of the electron gun. Since the area of the sample was 0.079 cm^2, the sensitivity can then be given in electrons/cm^2-sec.

TABLE II. Measurements of counting rate.

Run	Temperature (°K) Bath	Resistor[a]	Grid potential (volts)	Counts/min	Efficiency
3	4.21	4.21	1400	40.9±1.6	0.12% (for accelerating potentials)
	4.21	4.21	−1.5	47.0±1.8	
	4.21	4.21	1400	51.0±1.8	
	3.57–3.52	3.80–3.78	1400	38.6±1.6	
	3.12–2.97	3.31–3.28	1400	41.3±1.7	
	2.66–2.53	3.02–3.00	1400	40.9±1.6	
	2.36–2.22	2.84–2.82	1400	38.5±1.6	
	2.20	2.82–2.80	−1.5	39.4±1.6	
4	2.22–2.18	<2.5 (est)	1400	102.5±2.6	0.16% (for accelerating potentials)
	2.19		−1.5	115.3±2.8	
	2.20		1400	102.0±2.6	
	2.18		−1.5	74.2±2.2	
	2.18–2.17	<2.6 (est.)	1400	72.0±2.2	
	2.18–2.10		1400	48.2±1.8	
	2.13–2.10		−1.5	50.7±1.8	
5	2.26	<3.0 (est.)	200	223±15	24% (for accelerating potentials)
			−1.5	144±12	
			−1.5	146±12	
			200	144±12	
			200	120±11	
			200	148±12	
			−1.5	110±11	
			−1.5	99±10	

[a] The resistor temperature is assumed to be the temperature of the specimen. The critical temperature of tin is $T_c=3.73$°K.

V. CONCLUSIONS

The usual theoretical treatment of the current transfer through a normal conducting contact with a barrier in between considers the bulk properties of the materials involved. For instance, if the barrier material is an insulator, it is assumed that also a very thin layer of it is insulating and that the thickness of this layer is the gap width through which current transfer by tunnel effect takes place (see reference 4). It must be pointed out, however, that this treatment gives results which do not always agree with experiment.[6] No attempts have been made yet to explain the reduction of the barrier resistance if one side becomes superconducting. There is strong evidence that the electronic states change if a metal becomes superconducting, although it is not quite clear just how they do change. The possibility therefore exists, that this change of the electronic states makes the tunnel penetration easier. However, this assumption seems to imply an asymmetry in current conduction, i.e., a rectification, which is not observed. Furthermore, it is just this assumption which would lead one to expect electron emission from superconductors under the influence of a weak electric field. Without a detailed theory, however, it is of course impossible to give numerical values for such expected emission. In addition, it is not quite certain that the surface conditions used

TABLE III. Analysis of electron emission from Sn sample.

Run	Grid voltage volts	Sample field strength volts/cm	Temperature °K	Emission in electrons/sec-cm^2
5	200	570	<3.0	<15
3	1400	3800	2.80	<250
5	7200	20 000	<3.0	<1000

[6] I. Dietrich, Z. Physik 132, 231 (1952).

represent those of an ideal superconducting surface. Nevertheless, this type of experiment seems capable of giving information about the electronic states in a superconductor.

The technique of measuring currents from approximately 10^{-20} ampere to 10^{-17} ampere with a charged particle counter extends the range of measurements in many electron emission experiments. For instance, studies of weak thermionic emission and weak field emission are two examples of experiments which can be done with this method. Various counters could be employed; Geiger counters, scintillation counters, or electron multiplier assemblies. Such a program is now being set up.

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Magnetic Measurements on Individual Microscopic Ferrite Particles Near the Single-Domain Size

A. H. MORRISH AND S. P. YU
University of Minnesota, Minneapolis, Minnesota
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A novel quartz-fiber torsion balance is employed to make magnetic measurements on individual microscopic ferrite particles. A very direct experimental test provides strong evidence for the existence of single-domain magnetic particles. Further, the results confirm theoretical calculations of the critical single-domain size within a small factor.

INTRODUCTION

ON theoretical grounds, there is strong reason for believing that a sufficiently small particle of ferromagnetic material will exist as a single domain. This configuration will result if the associated magnetostatic energy is less than the energy required to form either Bloch walls or else a circular arrangement of the atomic spins. Either of the latter configurations would reduce or remove the magnetostatic energy.

The experimental evidence for the existence of single-domain particles has been obtained by measurements made on powders or suspensions containing many small particles. The evidence presented so far has been at best indirect, and further, can usually be criticized on some additional grounds.

It was thought that an experiment in which an individual microscopic magnetic particle was investigated might provide very direct experimental evidence on whether or not single-domain particles exist. Measurements on an individual particle eliminate several of the factors present in powders. Chief among these are the interparticle interactions and the averaging effect due to the different orientations of the powder particles. Therefore, a novel quartz-fiber torsion balance was constructed.[1] This balance permitted measurements to be made on an individual micron-sized magnetic particle. The relative remanent magnetization of a particle was determined by noting the deflection of the balance in some inhomogeneous magnetic field.

The idea underlying the experiment is as follows. A single-domain particle will have only two, or some small multiple of two, directions along which the magnetization vector will lie. Therefore, the deflection, in the inhomogeneous field, will only be able to assume certain constant values that differ from each other by some relatively large discrete amount. On the other hand, with a multidomain particle, one would expect that the net remanent magnetization, and therefore also the deflection, could be varied in a continuous fashion, up to of course, some maximum amount.

This idea is closely related to the fundamental properties of single-domain particles investigated theoretically by Stoner and Wohlfarth.[2]

PREVIOUS EXPERIMENTS

It is pertinent to consider the previous experimental evidence for the existence of single-domain particles.

Frequently it is supposed[3] that the large coercive force observed for powders containing small particles is evidence for single-domain behavior. This is not conclusive for a variety of reasons. The coercive force increases as the particle size decreases, even in the multidomain region. No evidence has been put forward that there is a sudden discontinuity in the coercive force as the critical size is reached. In fact, there is some evidence that the coercive force continues to increase for particles smaller than the critical size. Further, the absolute value of the coercive force obtained for supposedly single-domain powders is usually considerably less than that predicted by theory.

Another experiment has been carried out by Kittel

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