Superconductivity

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Properties of superconductors are measured and investigated. Critical temperatures of lead, niobium, and vanadium samples are characterized. Persistent current in a superconducting sample is demonstrated. The energy gap predicted by BCS theory is measured in a niobium Josephson junction. The same junction is used to estimate the fundamental flux quantum.

I. INTRODUCTION

Superconductivity was first observed by Heike Kamerlingh Onnes in 1911 while inspecting the low-temperature properties of solid mercury. He discovered that the resistance of the metal dropped sharply to zero below a certain temperature. In the following decades, a number of other effects were observed, including a total expulsion of magnetic fields known as the Meissner effect. A theoretical explanation of superconductivity was not available until the 1950s when Bardeen, Cooper, and Schreiffer[1] developed a microscopic explanation relying on long-distance attraction between electrons. In the 1970s, Josephson[2] discovered that currents could tunnel between superconductors through an insulating barrier at zero voltage. These Josephson effects created a new range of applications for superconductors in quantum circuits and magnetic field sensors. Here, we demonstrate properties of superconductors that stem from BCS theory, including measurements of critical temperature, persistent current effects, and tunneling currents.

II. THEORY

II.1. Superconductivity Transition

In metals not in a superconducting phase, free electrons traveling because of an electric field scatter off phonons and defects in the ion lattice, causing energy to be lost as heat. This is the phenomenon known as electrical resistance. As the temperature drops, the number of phonons decreases, so the resistance of the material also decreases; however, at non-zero temperature there are always some phonons, so there is always some electrical resistance.

In some metals, electron-phonon interactions can cause long-range attractions between two electrons. These two electrons form a bound state, called a Cooper pair, that behaves as a boson. At sufficiently low temperatures, the Cooper pairs condense into their ground state. The energy spectrum of the Cooper pairs has a band gap between the ground state and the first excited state, so if the scattering energy is less than the bandgap, the Cooper pairs will not scatter and the material will have zero resistance (among other properties); i.e., it will be a superconductor.

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II.2. Effects of Magnetic Fields

Superconductors are distinguished from perfect conductors by their total exclusion of magnetic fields. A non-superconducting material with zero resistance (a perfect conductor) will obey Maxwell's equations, and the restriction on its magnetic field will be $\dot{B} = 0$. However, a superconductor has a an additional restriction, first discovered by Meissner in 1933 and phenomenologically explained by London and London in 1935. In a superconductor, not only must the time derivative of the magnetic field must be zero, but the magnetic field itself must be zero. In other words, superconductors are perfectly diamagnetic and will produce surface currents to cancel out an external magnetic field. There is a small region at the surface of a superconductor that has non-zero magnetic field, and the depth of this region is known as the London penetration depth.

This means that the Gibbs energy of the superconducting phase depends on the external magnetic field according to

$$G = -\mu_0 \int_0^{H_0} M dH \tag{1}$$

where M is the field from the superconductor and H_0 is the external field. So the Gibbs energy of the superconducting phase is $\mu_0 H_0^2$, while the Gibbs energy of the normally conducting phase is independent of the magnetic field. Thus, above a critical magnetic field (B_c), the superconductor will revert to the normally conducting phase.

Some superconductors, known as type 2 superconductors, have two critical fields. At the lower critical field, magnetic vortices begin to thread through the superconductor, and at the higher field, the material stops superconducting. This phenomenon occurs when the London penetration depth is longer than the correlation distance between electrons in Cooper pairs. Type 2 superconductors are usually composites, but vanadium and niobium, used in this experiment, are also type 2.

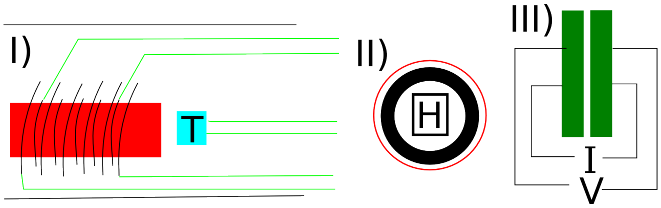

FIG. 1. The three probes used in the experiment. Probe I has two solenoids wound around a removable sample. By measuring the power transfer between the solenoids, a change in the permeability of the sample that marks the superconducting transition can be detected. Probe II has a single solenoid wound around a fixed lead toroid. A Hall effect sensor detects the magnetic field inside the toroid, which remains constant when the lead is in its superconducting state regardless of the state of the solenoid. Probe III consists of a Josephson junction chip. A Josephson junction, shown here (not to scale) consists of two layers of niobium sandwiching a thin insulating layer. Cooper pairs can tunnel across this barrier.

II.3. Josephson Junction

A Josephson junction consists of two superconducting electrodes separated by a very thin insulating layer. If the two electrodes were normal conductors, electrons would tunnel through the barrier with the current a linear function of voltage.

As described earlier, Cooper pairs in a superconductor can travel unimpeded through the lattice because the gap in the energy spectrum between the ground state and the first excited state is so big that phonons in a cold lattice do not possess enough energy to excite the electrons. This implies that if the voltage across the junction is sufficiently low, the Cooper pairs will not be able to gain energy that would allow them to tunnel accross the barrier. Therefore, until the voltage across the barrier is at least $2\Delta/e$, no DC current will flow across the junction. By measuring the current-voltage properties of the junction, the energy gap can be found.

Furthermore, when zero voltage is applied to the junction, a high-frequency alternating current passes through the junction because of phase differences in the Cooper pair wavefunctions on either side. Placing the junction in an external magnetic field causes a phase shift perpendicular to the magnetic field, and when the flux through the junction equals the fundamental flux quantum, the current across the junction goes to zero.

III. EQUIPMENT & PROCEDURE

III.1. Probe I: Measurement of T_c

Measuring very low resistances can be difficult because the resistances of any connections to the low-resistance sample become important. In addition, thermal cycling can damage the connections over time and cause increased resistance if not outright failure of the probe.

Instead of directly measuring the resistance, the sample is inserted as the core of a transformer. The power transfer between the primary and secondary coils is a function of the magnetic flux through the core. When the sample transitions to the superconducting phase, the flux through the core becomes zero and the voltage across the secondary should drop sharply.

The primary and secondary coils are wrapped on top of each other and inserted into a steel pipe approximately a meter long. A cylindrical metal sample is inserted as the core of the transformer. This pipe is inserted into a liquid helium dewar until the transformer is slightly above the liquid helium bath. A vacuum pump draws cold helium vapor through the pipe, which cools the sample closer to the liquid helium temperature. A thermocouple mounted approximately 1 cm above the sample measures the temperature. The temperature is modulated by manually changing the flow rate on the pump, and measured with the thermocouple.

III.2. Probe II: Persistent Current

A common use of superconductors[**?**] is as permanent magnets. Inducing a current in a toroidal superconductor, then cooling it to below its critical temperature freezes the current at a certain value. This maintains a magnetic field in the center of the toroid, and as long as the superconductor stays cold, it behaves like a permanent magnet. Certain alloys, especially those of niobium, have critical magnetic fields in the tens of Tesla, making superconducting magnets ideal for strong permanent magnets.

In Probe II, a solenoid is wound around a toroidal superconductor. A DC current is passed through the solenoid when the superconductor is above the critical temperature, which induces surface currents in the superconductor that act to nullify the field inside the superconductor. When the external magnetic field is shut off, nothing absorbs the energy in these currents, and they continue to flow, maintaining the magnetic field in the center of the toroid. The magnetic field is measured using a semiconducting Hall effect sensor mounted in the center of the toroid.

III.3. Probe III: Josephson Junction

Probe III contains an integrated circuit with 81 Josephson junctions, one of which is used in this experiment. The junction consists of two circular niobium disks with a diameter of 15 µm sandwiching a layer of aluminum oxide approximately 2 nm thick. To measure the energy gap, an alternating current is applied to the Josephson junction, and a sensitive voltage preamplifier measures the corresponding voltage across the junction. Most applied currents can exist either at zero volts or at

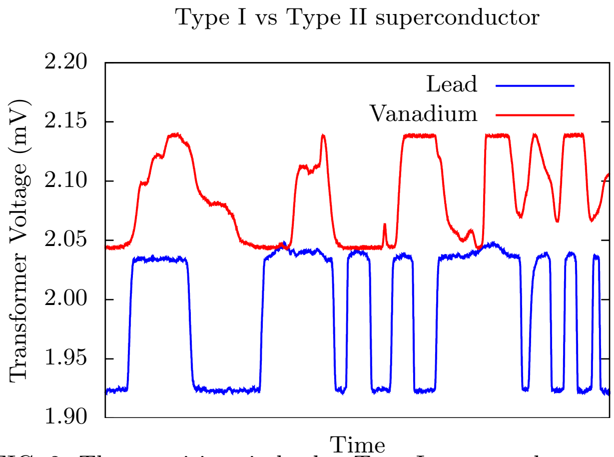

FIG. 2. The transitions in lead, a Type I superconductor, are much sharper than those in vanadium, a Type II superconductor (the temperature modulation was different for the two samples, so the transitions do not line up)

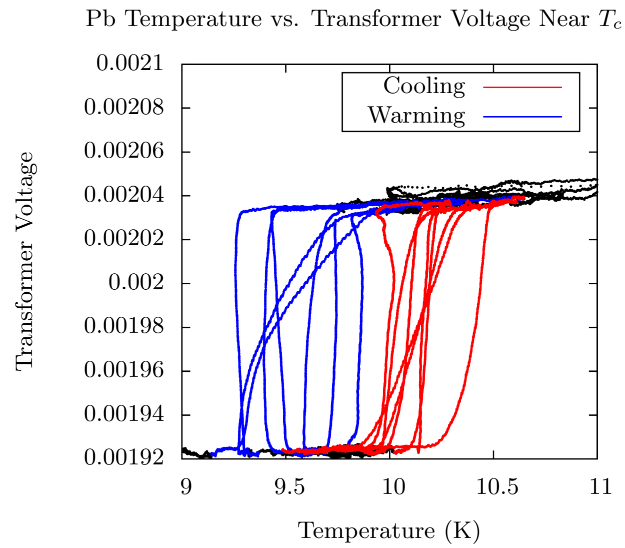

FIG. 3. Examining transitions between the normal and superconducting states of lead reveals hysteresis in the thermocouple-superconductor system

$2\Delta/e$ volts, so the I-V curve shows a hysteresis relationship as the junction transitions between these states. The energy gap Δ can be determined from the gap between voltages with non-zero currents

The flux quantum is measured by applying current to a solenoid wrapped around the Josephson junction chip. The current is swept through a 100 mA range over 40 seconds, which corresponds to three peaks in the height of the zero-voltage current. The locations of the zeros are measured and converted to flux units based on the dimensions of the solenoid and the Josephson junction to determine the flux quantum.

IV. RESULTS

IV.1. Critical Temperature Determination

Samples of niobium, vanadium, and lead were placed in Probe I and immersed in the liquid helium dewar. The temperature was modulated using the method given in III.1 around the critical temperature. The raw data shown in Figure 2 demonstrates the difference between Type I and Type II superconductors. Lead, a Type I superconductor, has very sharp transitions between the superconducting and normally conducting phases, while vanadium, a Type II superconductor, has more gradual transitions that exhibit intermediate levels of superconductivity.

The critical point can be more clearly observed by plotting the temperature against the solenoid voltage, as is done for lead in Figure 3. Naïvely, the critical temperature can be determined by treating each of the transitions as a data point and finding the mean.

As seen in Figure 4, every transition temperature recorded while the sample was warming is warmer than every transition recorded while the sample was cooling.

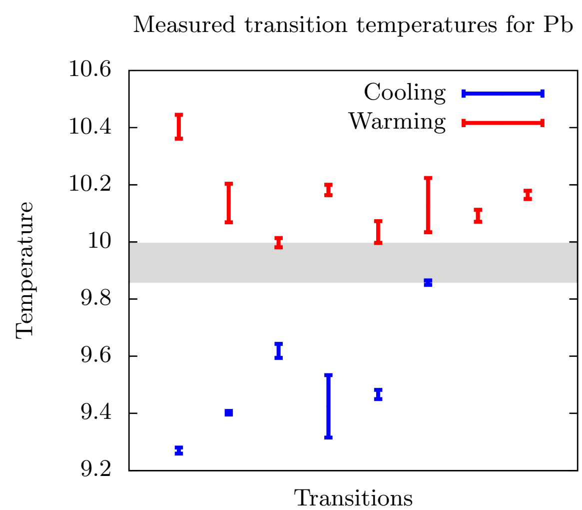

FIG. 4. The real transition temperature can be constrained to be in the gray box, between the coolest warming transition and the warmest cooling transition. The error bars represent the slope of the transition.

Therefore, the transition temperature can be constrained to be within the coolest warming transition temperature and the warmest cooling transition temperature.

This gives a transition temperature of $9.92 \pm 0.13_{\text{stat}}$K for lead, $12.7 \pm 0.3_{\text{stat}}$K for niobium, and $7.0 \pm 0.2_{\text{stat}}$ for vanadium.

Systematic errors discussed in **??** cause a significant overestimation each of these critical temperatures.

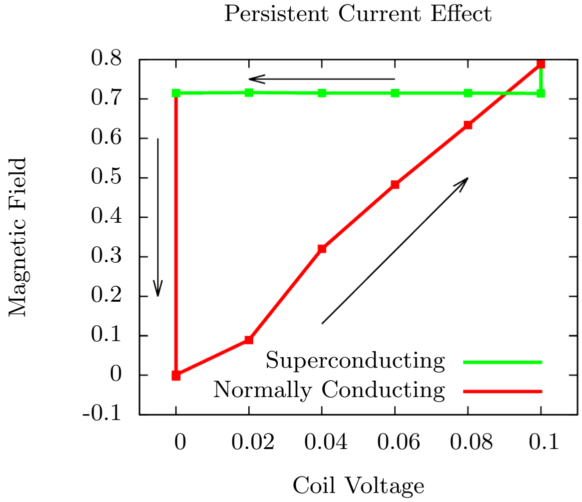

FIG. 5. persistent current

IV.2. Demonstration of Persistent Current Effect

Probe II was used as described in III.2 to store energy in a cylindrical lead shell. As seen in Figure 5, the magnetic field in the interior of the superconducting shell was maintained even when the coil current is turned off, and was quenched as soon as the temperature is raised above T_c.

IV.3. Energy Gap

The Josephson junction in Probe III was cooled to approximately 7 K and an AC current was passed through the junction. The corresponding voltage was measured and plotted against the current, as shown in 6. The energy gap is found to be 1.3 ± 0.1 meV, . This agrees with accepted values, which range from $1 - 2$meV[3].

IV.4. Flux Quantum

While the Josephson junction in the superconducting state, a DC magnetic field was slowly swept over a range of approximately 100 G. The London penetration depth of niobium is known to be 38 nm, which is added to the size of the insulating layer, 2 nm and multiplied by the length of the junction and the applied field to determine the flux through the junction. The size of the peaks, as shown in Figure 7, determines the flux quantum to be 2.4 ± 0.3 fWb, which is within one standard deviation of the accepted value, which is 2.1 fWb.x

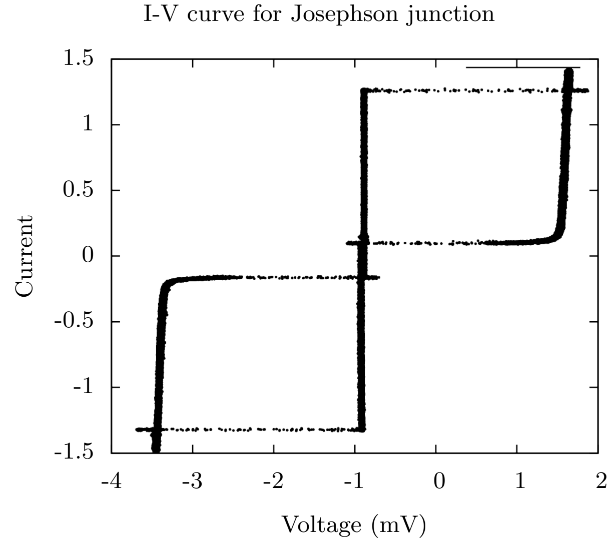

FIG. 6. The I-V curve for a niobium Josephson junction has two interesting features. First, a very high frequency AC current appears when zero voltage is applied. Secondly, no DC current flows until the applied voltage is $2\Delta/e$, where Δ is the superconducting energy gap.

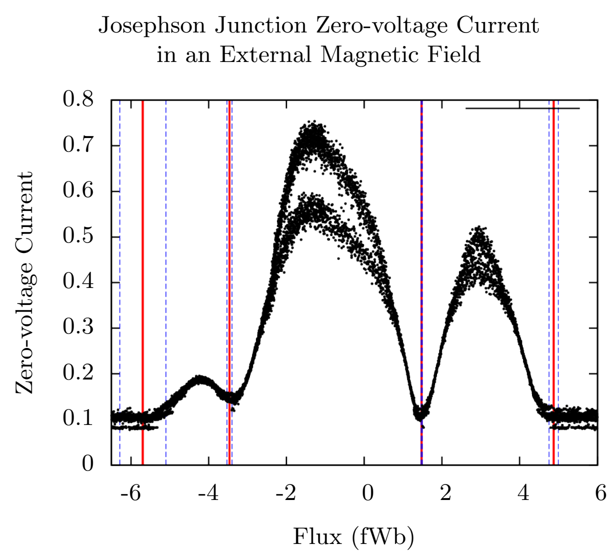

FIG. 7. The flux quantum is measured to be 3.4 ± 0.2 fWb by varying an external magnetic field and measuring the zero-voltage current through a Josephson junction. The flux quantum is the distance between zeros of the smaller peaks.

Sample	Measured	Accepted
Lead	10 ± 1 K	7.2 K
Vanadium	7 ± 1 K	5.4 K
Niobium	12 ± 1 K	9.2 K

TABLE I. Measured and accepted T_c for lead, vanadium, and niobium

V. UNCERTAINTIES

The most significant source of uncertainty in determining the critical temperature was measuring the sample temperature. Each of the measured critical temperatures were significantly higher than the known temperatures, as shown in Table I. The temperature probe was placed approximately 1 cm above the sample. This likely caused a thermal gradient between the sample and the temperature probe that lead to it overestimating the temperature. The probe also had an uncertainty of $\pm 1\,\mathrm{K}$, which has been added to the uncertainties in Table I.

The primary source of systematic uncertainty in measuring the bandgap was again uncertainty in the temperature. The zero-temperature bandgap is reduced by $1 - \frac{T}{T_C}$ at non-zero temperatures. As with Probe I, the temperature could not be measured precisely with Probe III, which contributed a ten percent error that overshadowed any statistical error. This could be overcome by immersing the probe in liquid helium, which would set the temperature to precisely $4.2\,\mathrm{K}$.

Finally, the flux quantum measurement produced a very lopsided looking diffraction curve (Figure 7). It is unclear exactly why this appears, but it creates a large amount of systematic uncertainty. It may be an effect of the slow magnetic field ramp that allows a flux quantum to become "trapped" inside the junction. Faster or discontinuous ramps of the magnetic field are worth exploring to reduce this problem.

VI. CONCLUSION

We measure several properties of superconductors, including critical temperature, the energy gap, and the flux quantum. These properties are hallmarks of BCS theory, which provides a theoretical explanation of superconductivity. We also demonstrate the use of a superconductor as a permanent magnet using the persistent current effect, a common industrial technique that enables compact high-strength magnets in a variety of applications including NMR spectroscopy.

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