High-Temperature Superconductors

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Outline

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2. Theory of superconductivity
3. Electrical resistance
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Introduction

Definition of superconductivity

Superconductivity is a phenomenon of **(a) exactly zero electrical resistance** and **(b) expulsion of magnetic flux fields** occurring in certain materials, called superconductors, when cooled below a characteristic **critical temperature** $\boldsymbol{T_c}$.

Theory of superconductivity

Continuous phase transition

Superconducting phenomenon is a **continuous phase transition.**

Bardeen–Cooper–Schrieffer (BCS) theory

I. The "attractive" interaction between electrons allows the formation of "Cooper pairs" which do not follow the Pauli exclusion principle.

II. The superconducting system is equivalent to an XY-lattice model. The dimension of order parameter is 2 (the amplitude & phase of wave function).

Classification

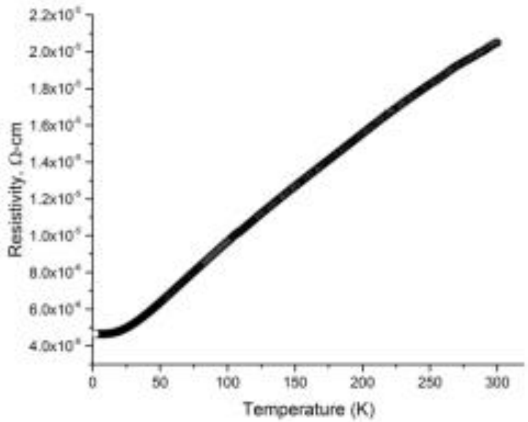
I. Type-I (e.g., mercury): the "attractive" interaction is s-wave and is symmetric.

II. Type-II (e.g., bismuth strontium calcium copper oxide (BSCCO)): high-temperature, d-wave, penetration of magnetic field.

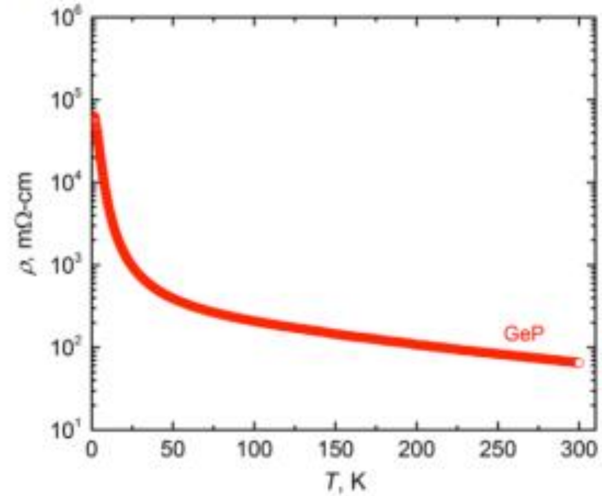
Electrical resistance

Characterization

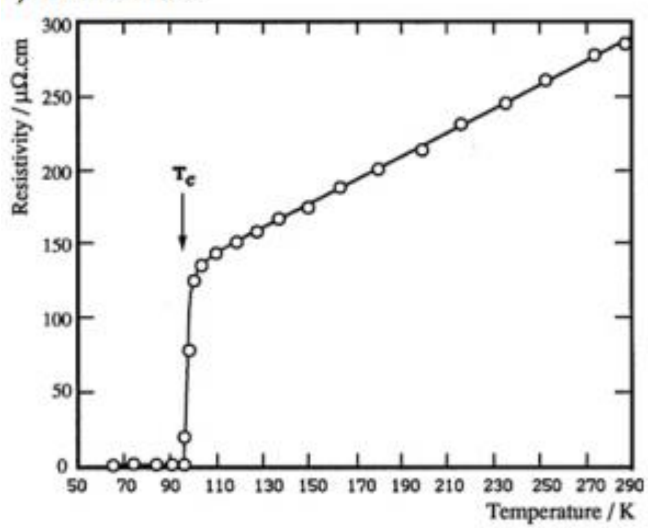
a) CuSnB



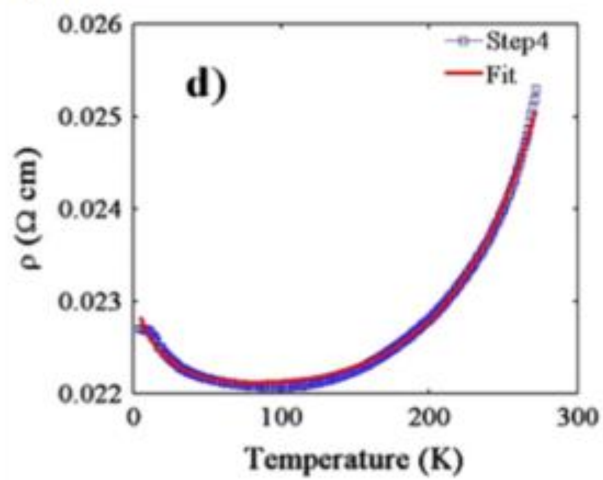
b) GeP



c) $YBa_2Cu_3O_7$



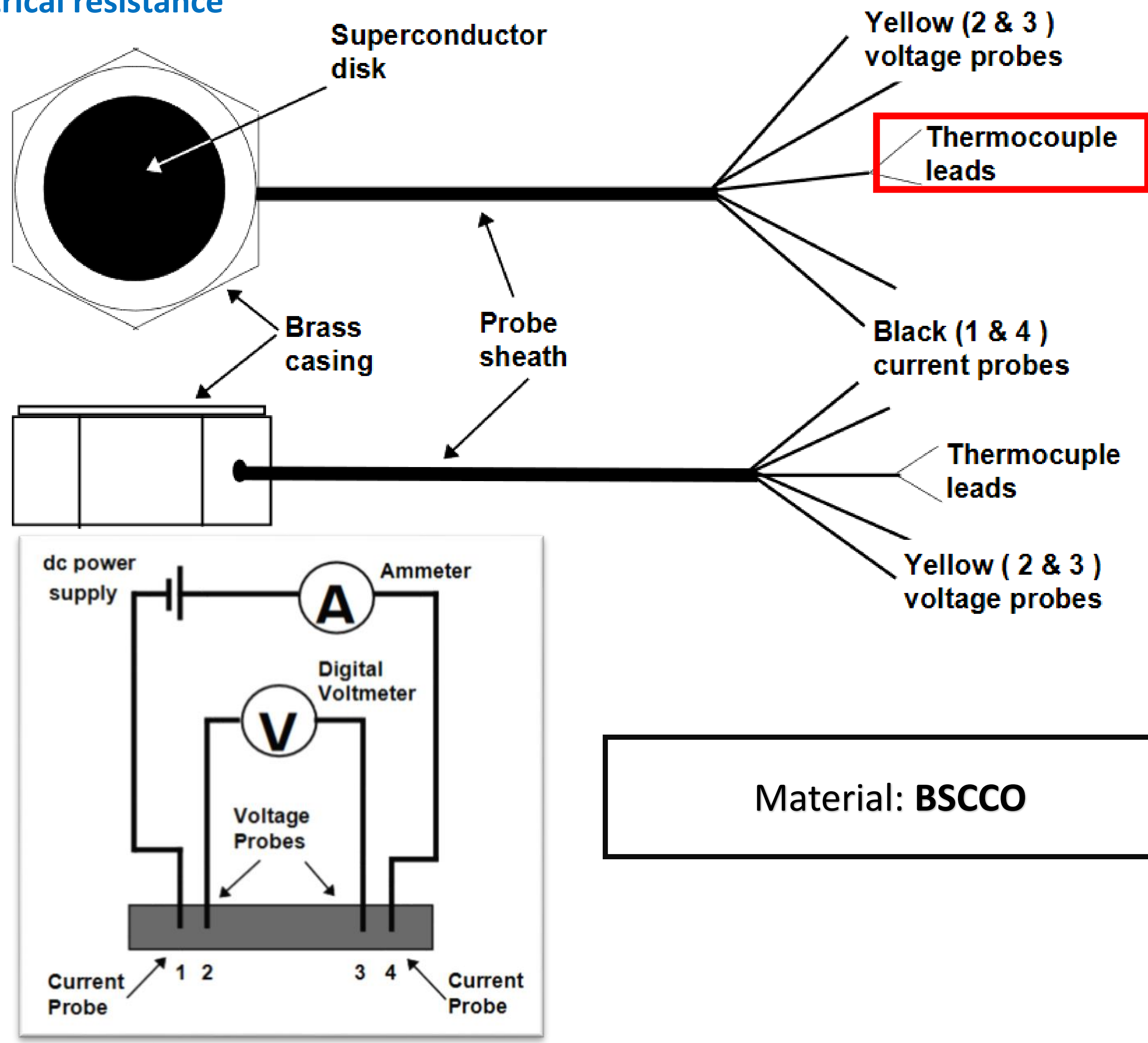
d) In_2O_3



Conductor
vs. Semiconductor
vs. Superconductor

Electrical resistance

Electrical resistance



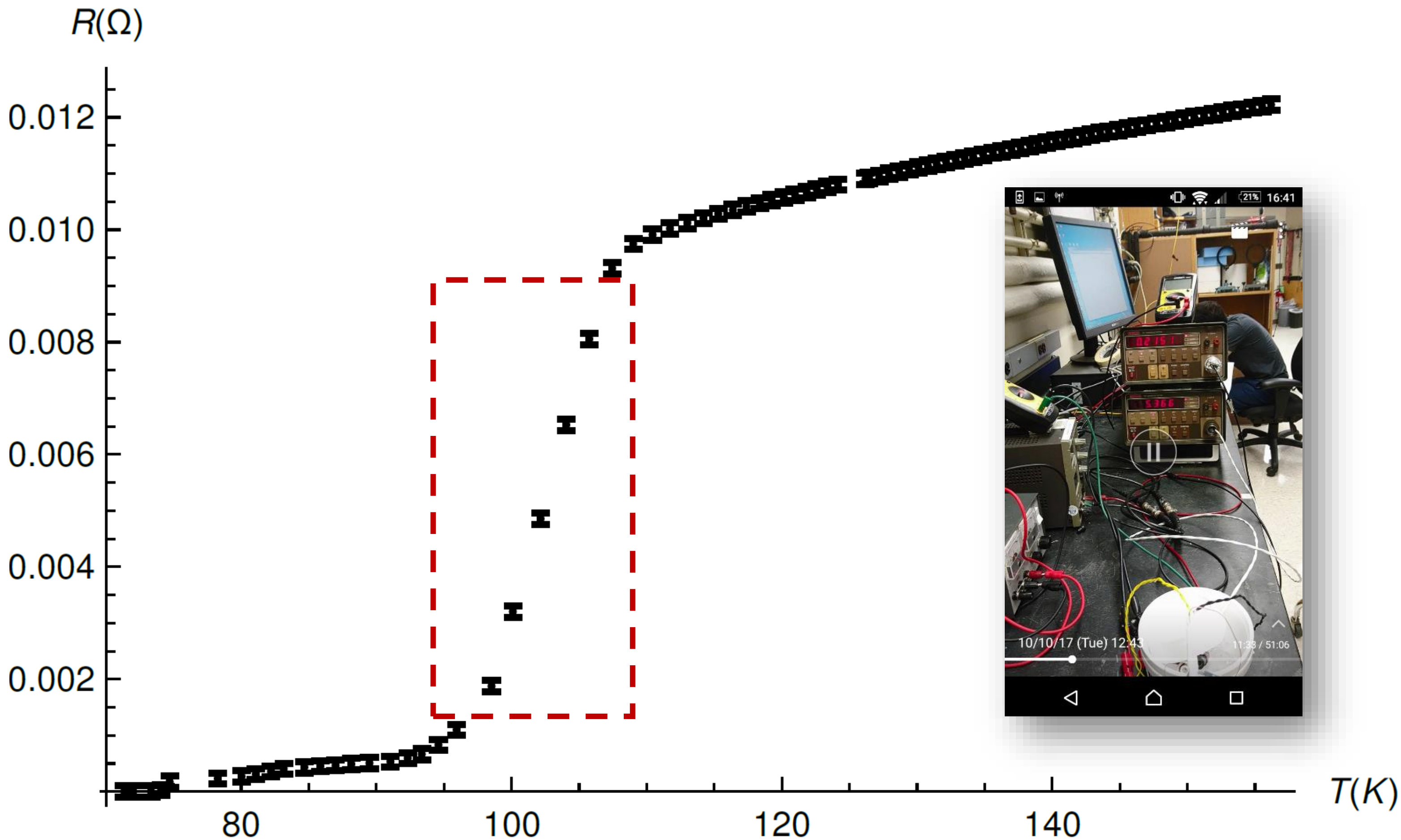
Put leads into 0°C ice-water mixture.

Material: **BSCCO**

Electrical resistance

Electrical resistance

Data was taken by recording a video using a smartphone.



The critical temperature of the BSCCO sample is $T_c \approx 103$ K, with a transition width of 6 K.

Electrical resistance

Electrical resistance

Scaling behavior

Given $\varepsilon = (T - T_c)/T_c$, we know that the correlation length and the correlation time should scale as

$$\xi \sim \varepsilon^{-\nu}, \tau \sim \xi^{z} \sim \varepsilon^{-z\nu}.$$

The London's equation and Maxwell's equation suggest

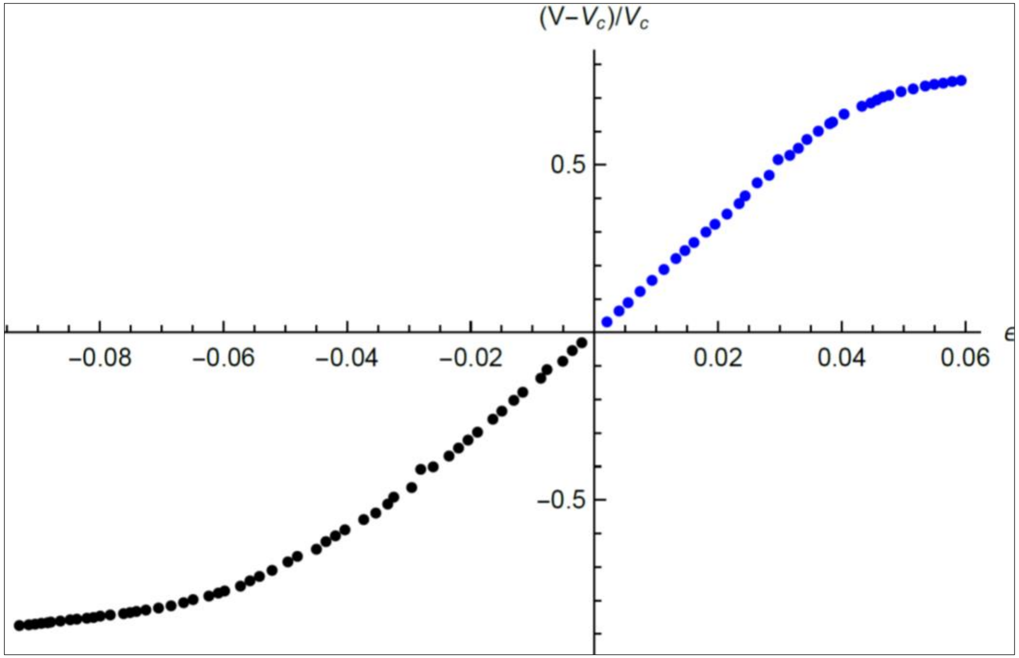
$$\mathrm{B} \sim \xi^{-2}, E/\xi \sim \mathrm{B}/\tau.$$

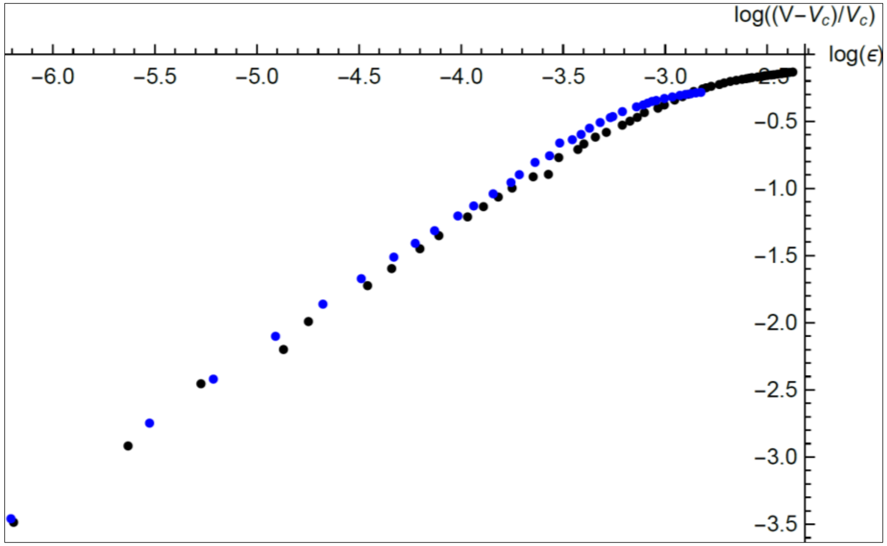
So, the voltage V (or electric field E) scales like

$$E \sim \varepsilon^{\nu(1+z)}.$$

Electrical resistance

Electrical resistance





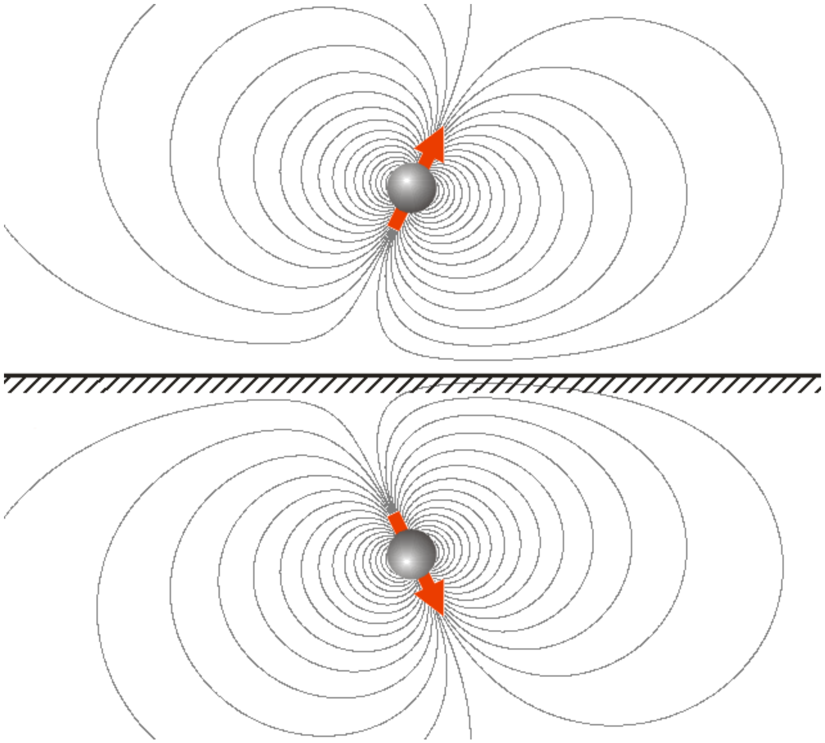
Zoom-in of the critical transition region.

We find the slope $\nu(1+z) \approx 0.9$. (Mean-field theory predicts $\nu = 0.5$ and $z = 2$.)

Meissner effect

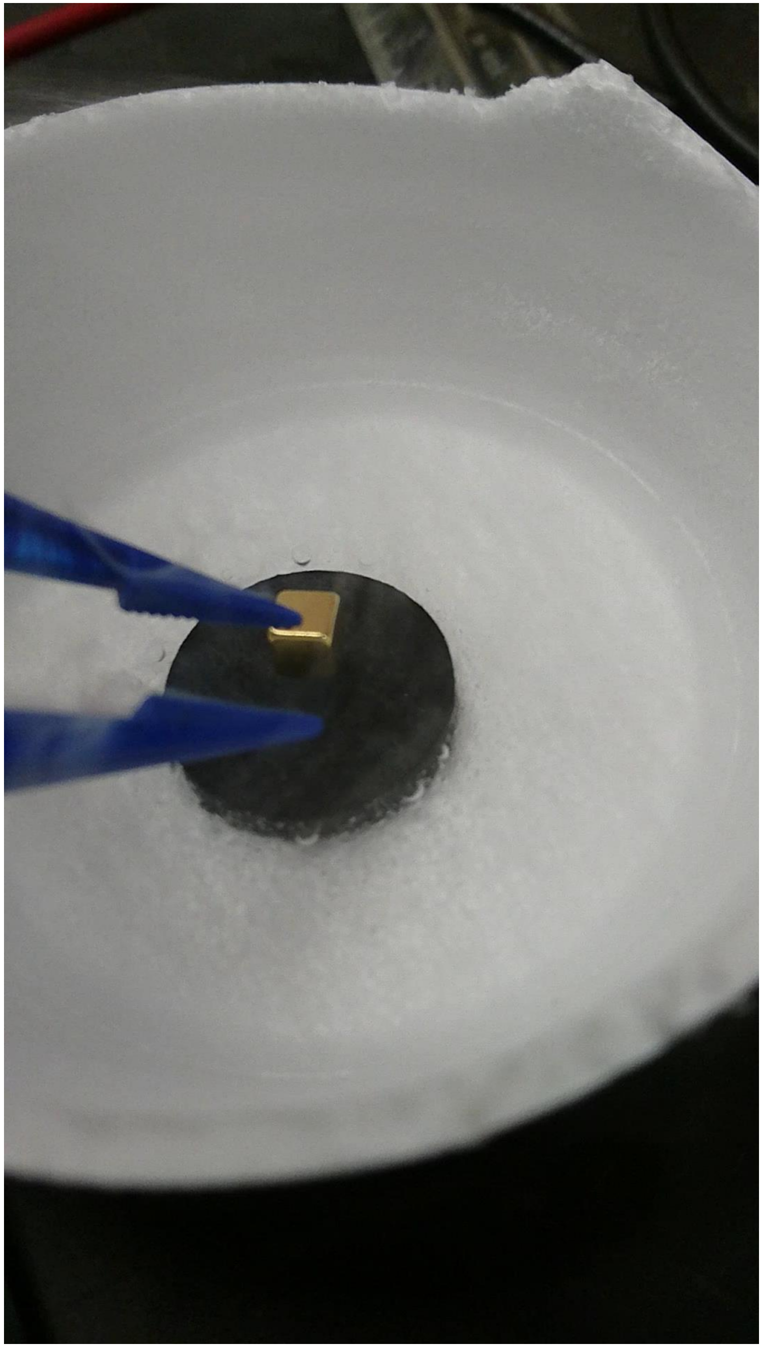
Meissner effect

Method of mirror images



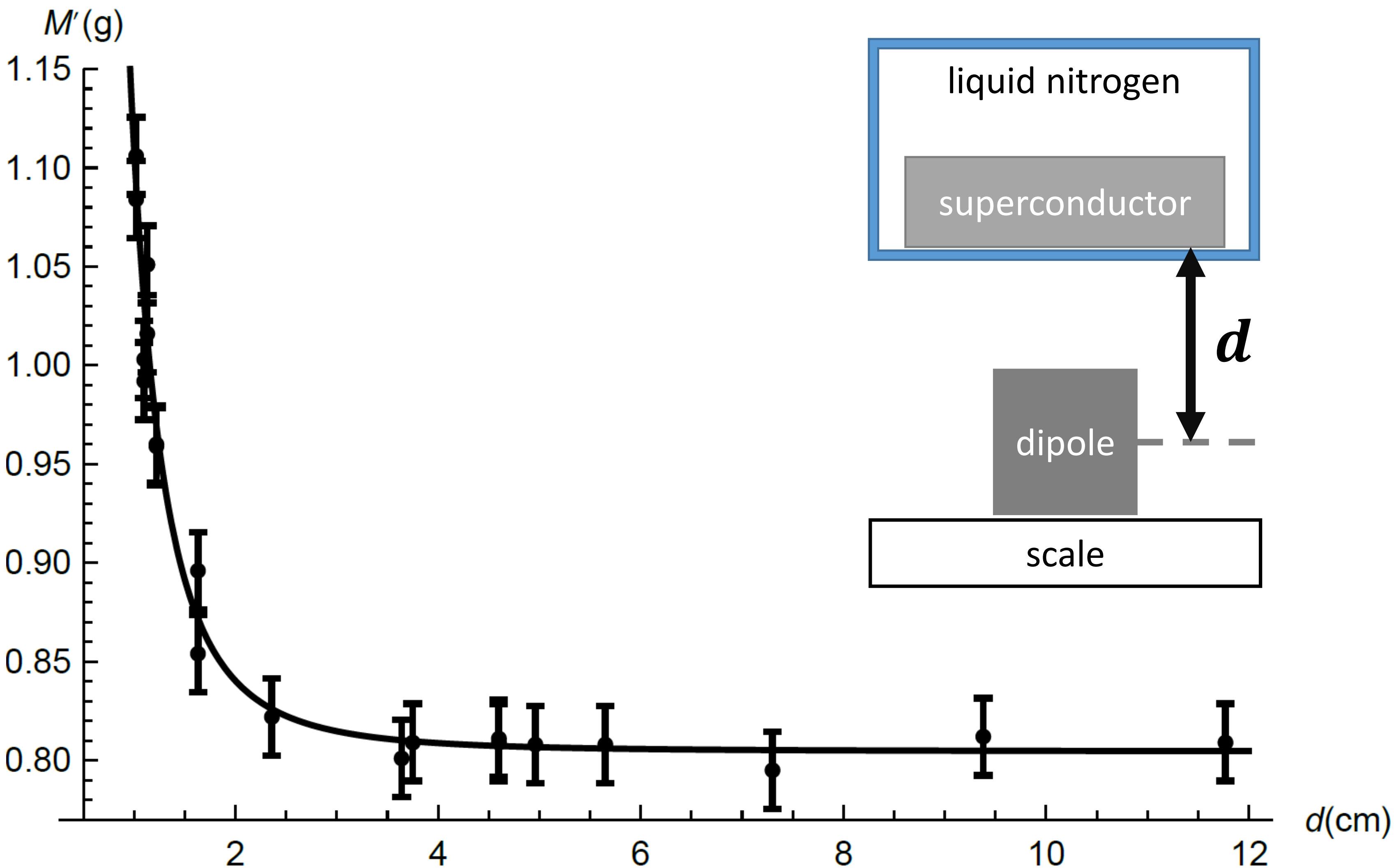
The length dimension of $F_{\text{dipole-dipole}}$ must be $[L^{-2}]$.

So, $F_{\text{dipole-dipole}} \propto m^2/d^4$, with dipole moment m.



Meissner effect

Meissner effect



We find $F_{\text{dipole-dipole}} \propto d^{-\gamma}$, where $\gamma = 3.09 \pm 0.39$ is smaller than what we expected.

Summary

Systematic error & future work

Systematic error:

- (Electrical resistance) Impurity of the sample lowers the critical temperature.
- (Meissner effect) The superconducting surface is not infinitely large.
- (Meissner effect) The scale is made of “iron”.

The next group could work on…

- Characteristics of yttrium barium copper oxide (YBCO) material.
- Measurement of critical magnetic field.

References

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2. Strachan, D. R., Sullivan, M. C. & Lobb, C. J. Probing the limits of superconductivity. in (eds. Bozovic, I. & Pavuna, D.) **4811,** 65 (2002).
3. Koch, R. H. *et al.* Experimental evidence for vortex-glass superconductivity in Y-Ba-Cu-O. *Phys. Rev. Lett.* **63,** 1511–1514 (1989).