From the Meissner Effect to the Isotope Effect: Precursors to the Microscopic Theory of Superconductivity

Brian Schwartz
The Graduate Center of Cuny

A Century of Superconductivity

1- 1908-1930, Discovery of Superconductivity

2- 1930-1955, Meissner Effect, Experimental Data, Isotope Effect and Phenomenological Theories

3-1955-1960, BCS Theory, Energy Gap, Theoretical Formulations and Experimental Confirmations

4- 1960-1985, Tunneling, AC-DC Josephson Effect, Flux Quantization, SQUIDs, High Magnetic Field Superconductors, Magnetic Impurities, Gapless, Heavy ion, Devices, Applications

5- 1985- High T_C Materials, Exotic Materials

Outline of Talk

- Review Meissner Effect
- Short Bio on Meissner
- Macroscopic Theories of Superconductivity
- Experimental Results on Superconductors
- Why Superconductivity Was Hard to Solve
- Failed Theories Prior to BCS
- Considerable Physics Post-BCS

Recent References Used

A Focus on Discoveries

Rudolf P.Huebener and Heinz Luebbig

World Scientific, Singapore, 2008

History of the Physikalisch-Technische Bundesanstalt

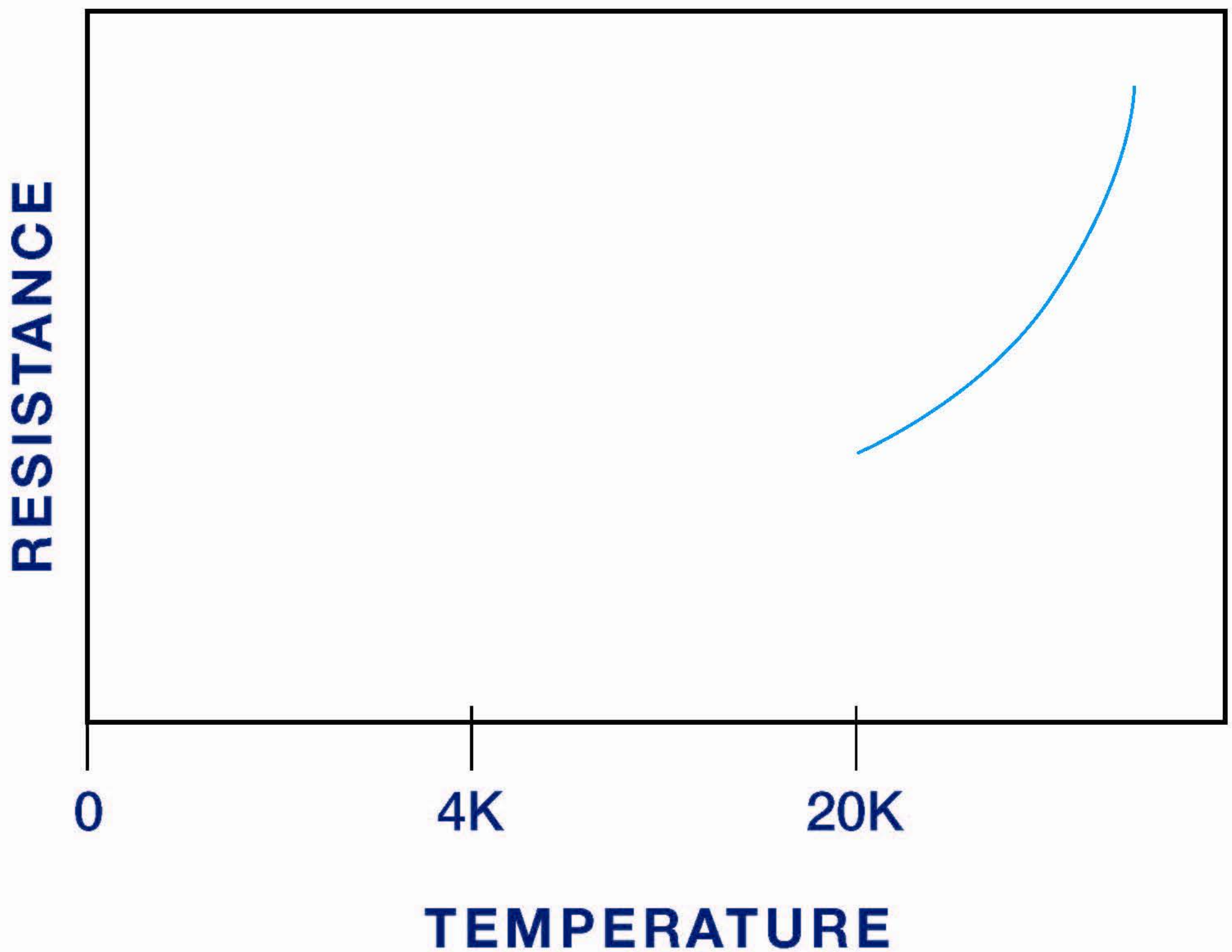
and Physikalisch-Technische Reichsanstalt

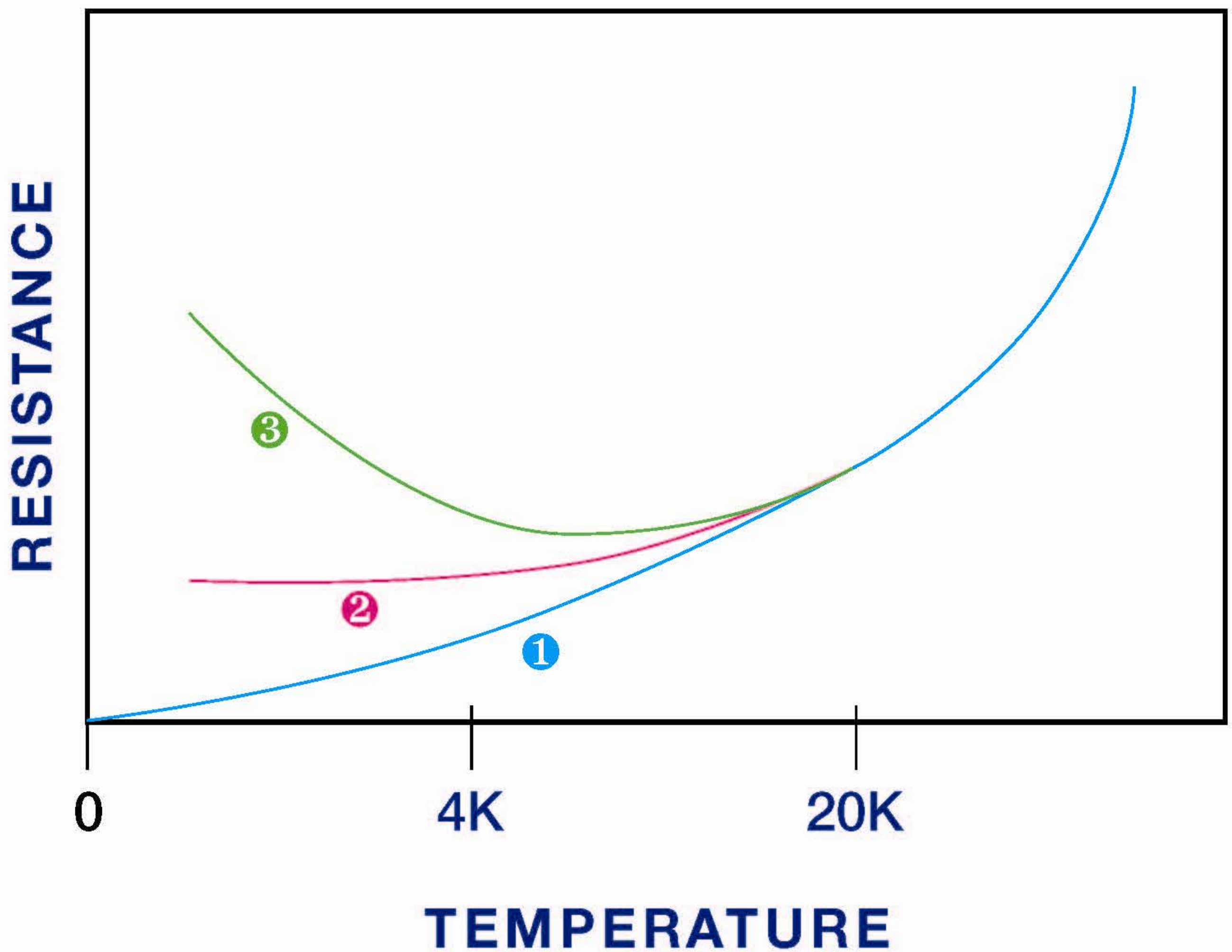
BSC: 50 Years

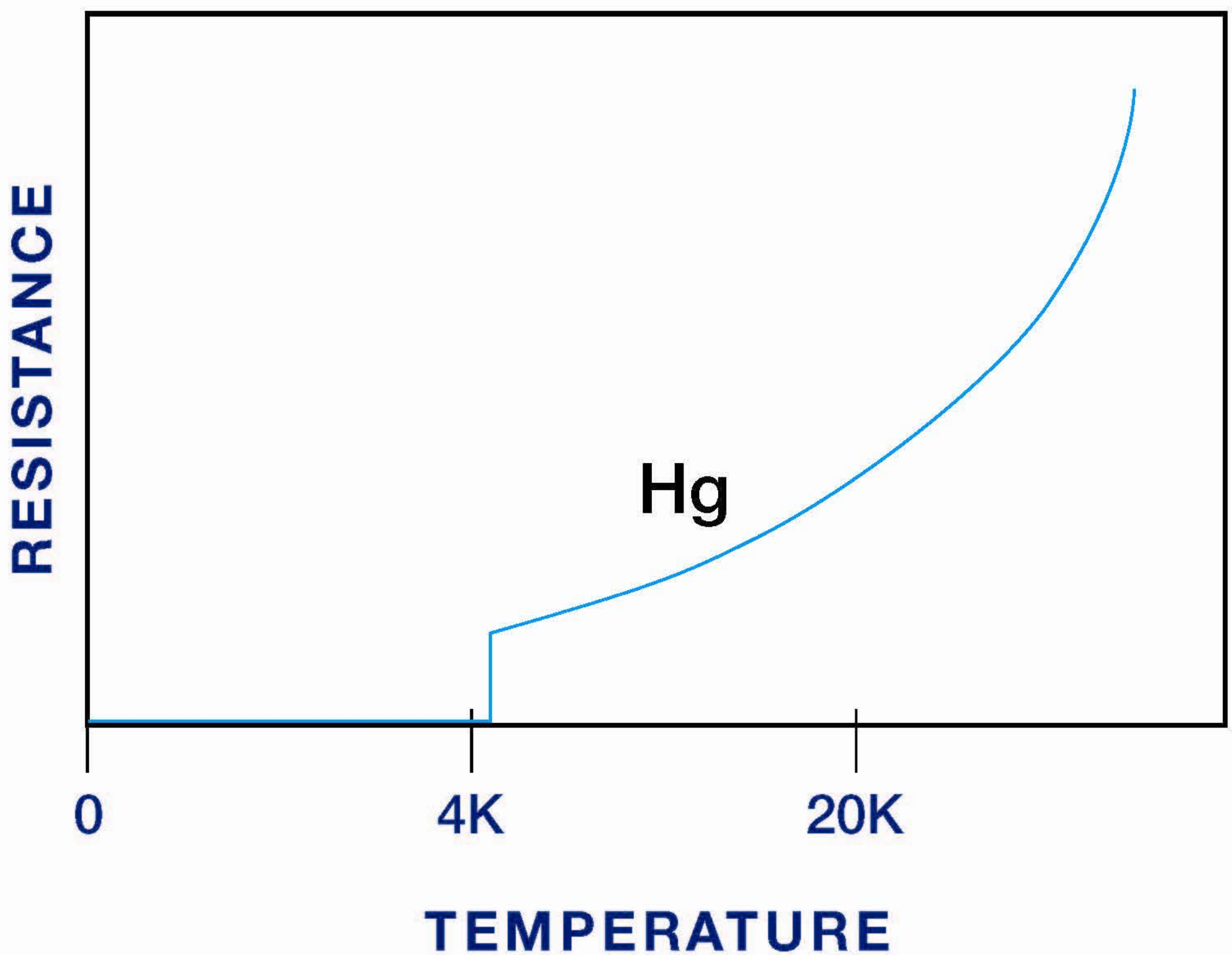
Edited by Leon N. Cooper and Dmitri Feldman

World Scientific, Singapore, 2011

Various Articles on BCS by Lillian Hoddeson, et al.


RESISTANCE
0
4K
20K
TEMPERATURE


RESISTANCE
3
2
1
0
4K
20K
TEMPERATURE


RESISTANCE
Hg
0
4K
20K
TEMPERATURE

Career and Bio of Walther Meissner

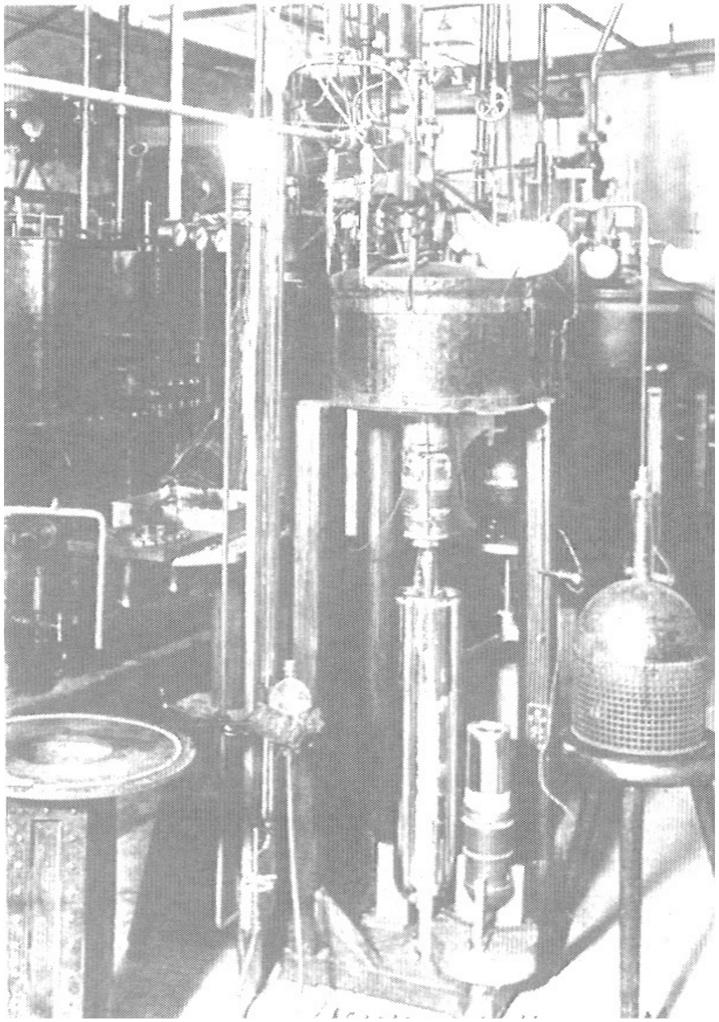
•Born in Berlin 1978
• 1901-06 First studied mechanical engineering and then physics and mathematics at the Technische Hochschule
• 1907 Doctoral supervisor Max Planck
Ph.D. Thesis topic “On the Theory of Radiation Pressure”
• 1908-13 Pyrometry ay the Physikalisch Technische Bundesanstalt in Berlin
• 1913-22 Worked in the Electric Research Laboratory and after WW1 conducted electrical measurements and developed facility to liquefy hydrogen
• 1922-25, He established the world's third largest helium-liquefier (others in Leiden and Toronto)

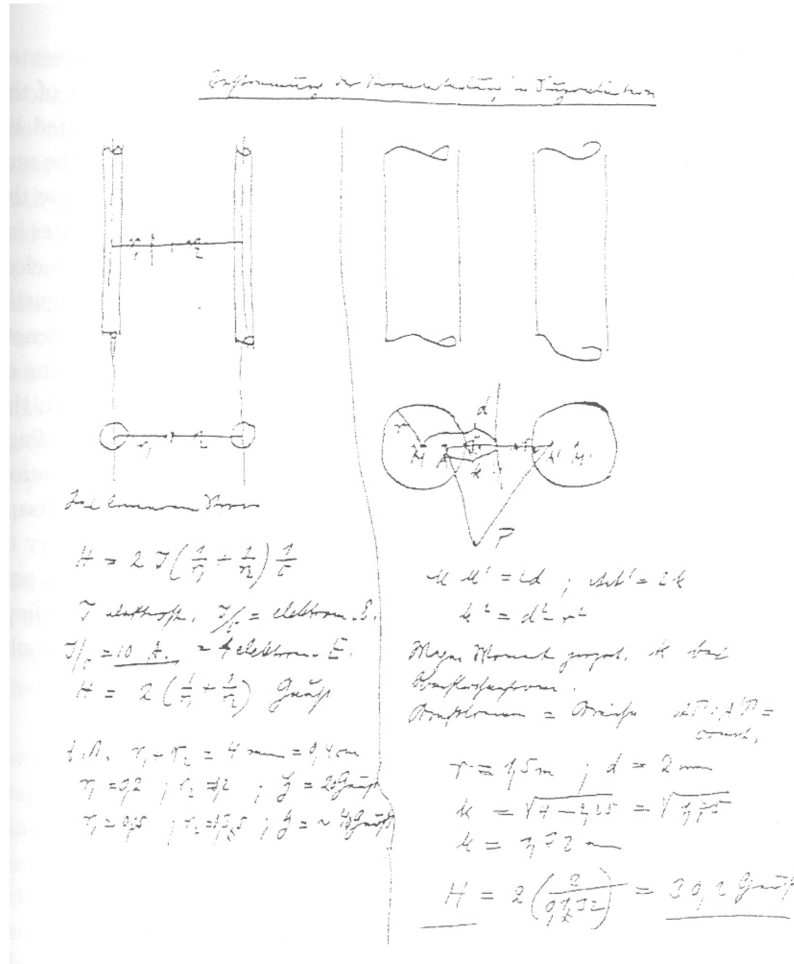
Career and Bio of Walther Meissner

- 1927-30 Resistance measurements on non-superconducting metals and known superconductors Pb, Sn, Hg, Tl and In
- 1928-30 Discovered superconductivity in Tantalum, Thorium, Titanium and Niobium and the first compound Copper Sulfide
- 1931 studied S-S junctions, Sn-Sn, Pb-Pb, Sn-Pb

- 1932-33 discovered perfect diamagnetism in superconductors, Meissner-Ochsenfeld effect Experiments encouraged by Max von Laue

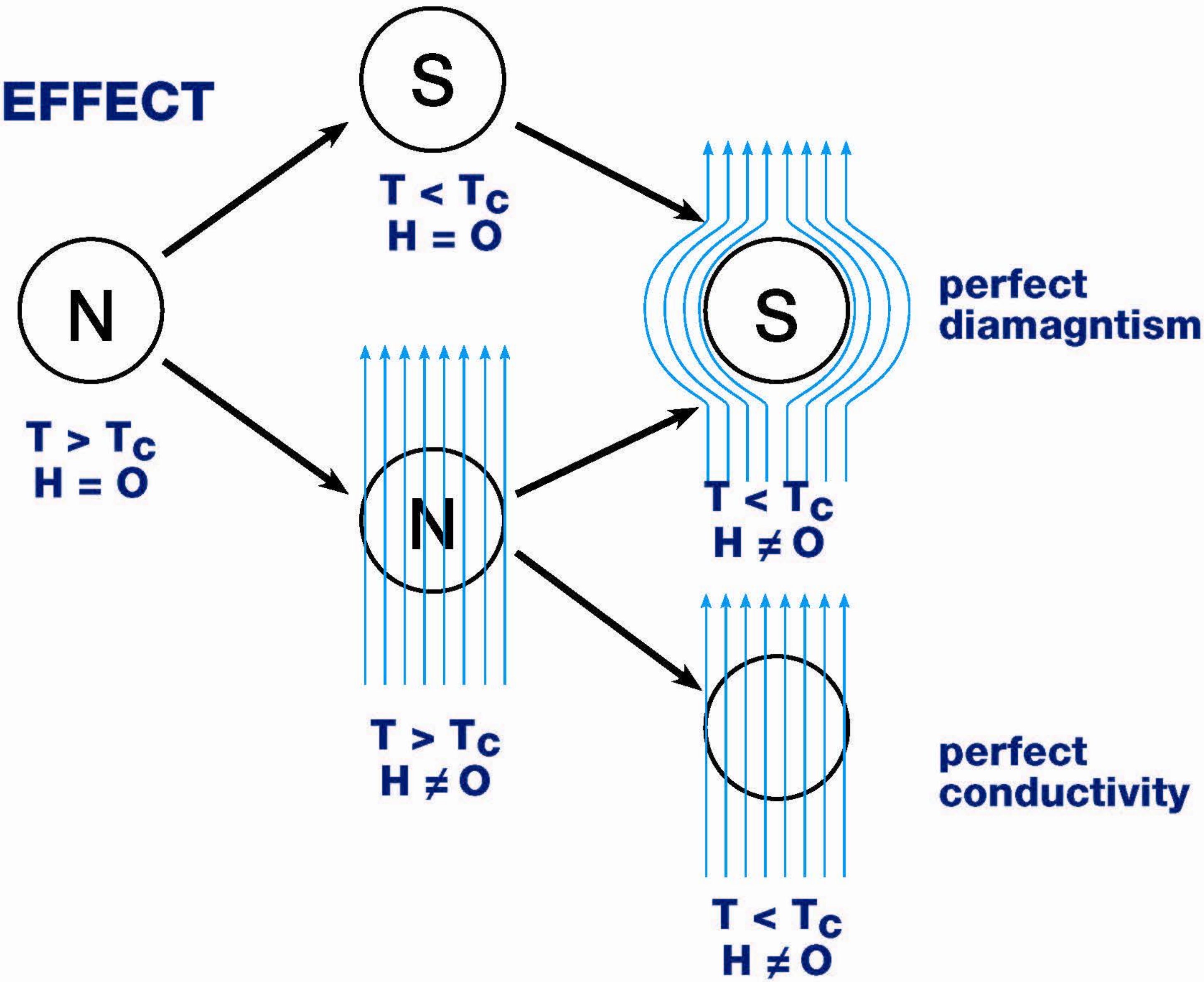
Walter Meissner Robert Ochsenfeld





He Liqiuefaction Plant **Sketch of Magnetic Field Calculation**

MEISSNER EFFECT



Naturwissenschaften
Volume 21, Number 44, 787-788,
W. Meissner and R. Ochsenfeld

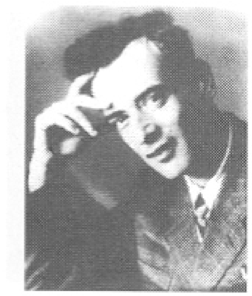
Ein neuer Effekt bei Eintritt der Supraleitfähigkeit

A new Effect upon the Entry of Superconductivity

Albert Einstein
(1879-1955)

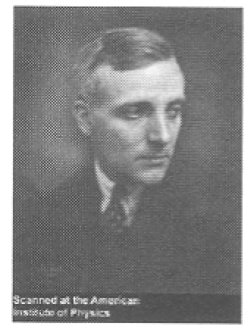
Niels Bohr
(1885-1962)

Ralph Kronig
(1905-1995)



Lev D. Landau
(1908-1968)

Felix Bloch
(1905-1983)



Léon Brillouin
(1889 -1969)

Physicists Who Proposed Theories of Superconductivity Prior to Meissner-Ochsenfeld Experiment

From ***Failed Theories of Superconductivity***, Jörg Schmalian

Reproduction of a slide made in 1955 by John Bardeen to illustrate the status of the theory at that time

QUANTUM THEORY

↙ ↓ ↘

Summerfeld-Bloch
Normal Metals

Electron-Vibration Interaction
(Isotope Effect)

Coulomb Interactions
(Heisenberg-Koppe)

?↓?

ENERGY GAP MODEL

↙ ↘

Pippard Theory
↑
London Theory

↑

ELECTROMAGNETIC PROPERTIES
E=0, **B**=0

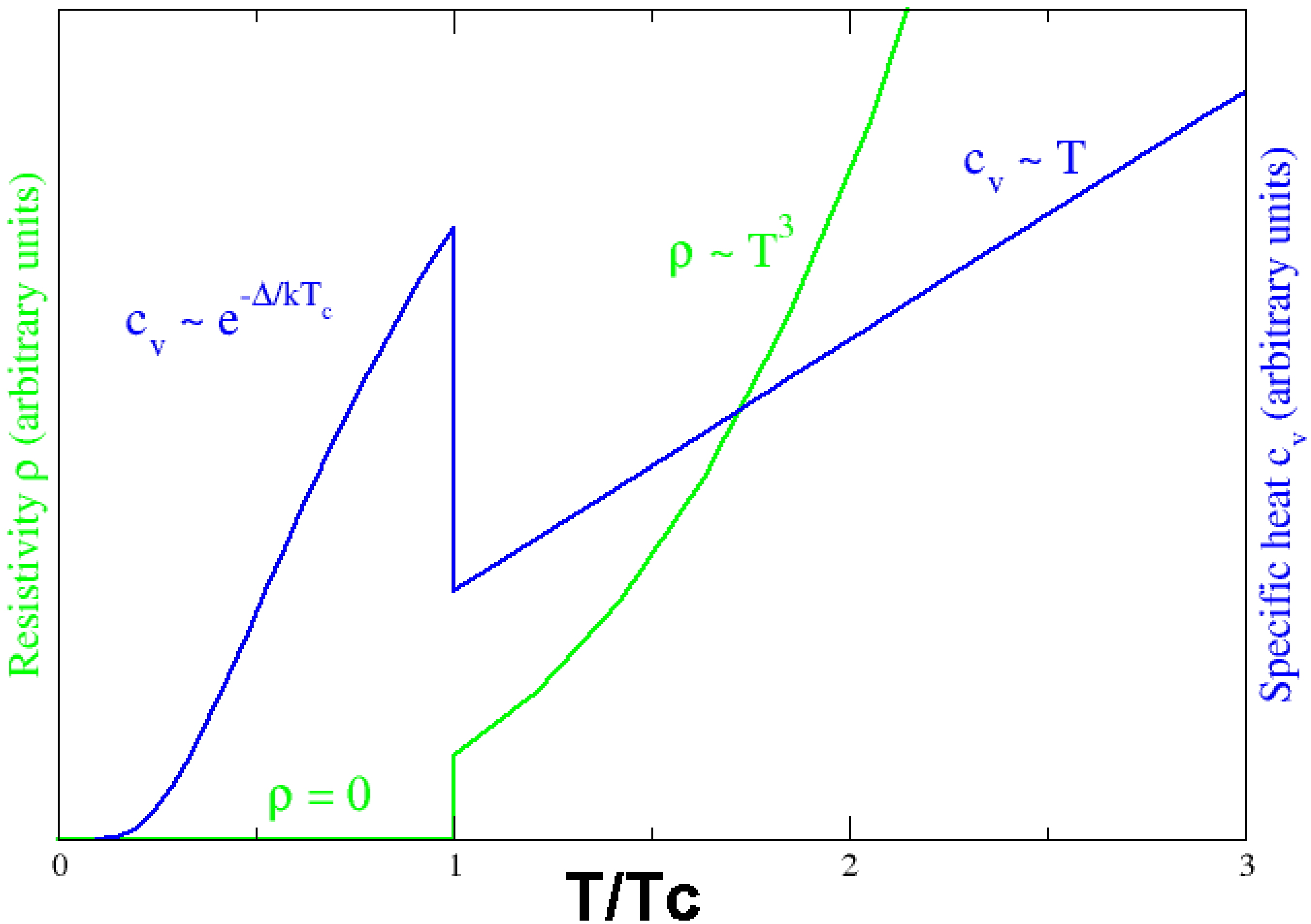
Two Fluid Model
(Gorter-Casimir, etc.)
↑

↑

THERMAL PROPERTIES
(Specific Heat, Thermal Conductivity, etc.)

Macroscopic Theories of Superconductivity

1. Gorter-Casimir Two Fluid Model
2. London Equations, Penetration Depth and Stiffness of the Wavefunction
3. Pippard non-local Theory of the Penetration Depth and Introduction of a Coherence Length
4. Ginzburg-Landau Phenomenological Theory



Resistance and Specific heat

COR GORTER

HENDRIK CASIMIR

The Two-Fluid Model

In 1934 Gorter and Casimir developed the two-fluid model from the thermodynamic properties of superconductors. A finite fraction of the electrons are condensed into a superfluid. At zero temperature the fraction is 1. As the temperature increases, the fraction of the electrons in the superfluid decreases. At T_C the fraction of superfluid electrons goes to zero. The system experiences a second-order phase transition. From the specific heat behavior Gorter and Casimir developed a formula relating the number of electrons in the superfluid to temperature

.

$$\psi_S^2(T) = n_s = n\left[1 - \left(\frac{T}{T_c}\right)^4\right]$$

Where $n_s(T)$ is the fraction of electrons in the superfluid at temperature T and $\psi_S{}^2(T)$ will later be related to the superconducting order parameter.

Heitz and Fritz London

London Equations

Perfect diamagnetism implies that not only is the time derivative of B= 0 but B itself equals zero

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} \qquad \frac{\partial \mathbf{j}_s}{\partial t} = \frac{n_s e^2}{m}\mathbf{E}, \qquad \nabla \times \mathbf{j}_s = -\frac{n_s e^2}{mc}\mathbf{B}.$$

$$\nabla \times \mathbf{B} = \frac{4\pi \mathbf{j}}{c} \qquad \nabla^2 \mathbf{B} = \frac{1}{\lambda^2}\mathbf{B}, \qquad \lambda \equiv \sqrt{\frac{mc^2}{4\pi n_s e^2}}.$$

London realized that in a bulk superconductor with a hole in it, the flux would be trapped

$$\mathbf{j}_s = -\frac{n_s e_s^2}{mc}\mathbf{A}, \qquad \mathbf{v} = \frac{1}{m}\left(\mathbf{p} - \frac{e}{c}\mathbf{A}\right).$$

SIR BRIAN PIPPARD

Pippard Non-Local λ

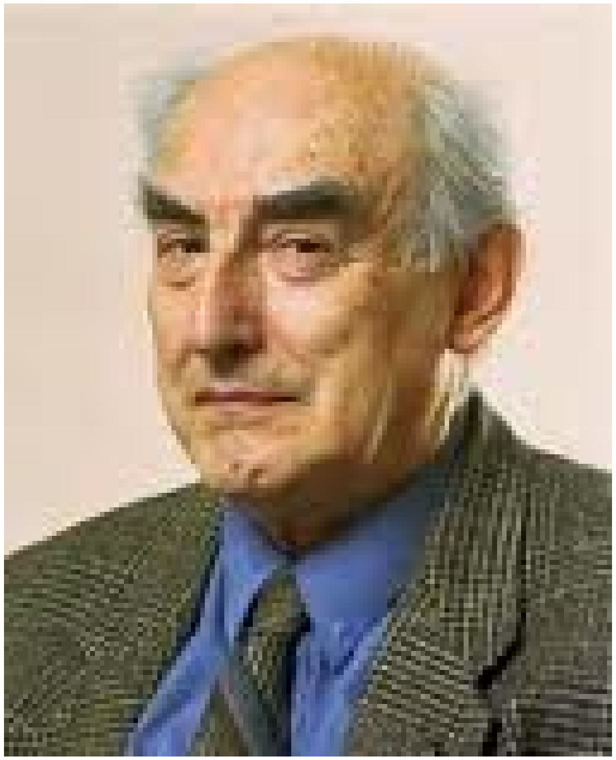
$\lambda_L = (mc^2/4\pi ne^2)^{1/2} \sim 500Å$

λ_{exp} was measured to be longer

By analogy with the anomalous skin effect in metals when $\omega^{-1} \sim \delta < l$

Pippard had to introduce a coherence length $\xi_O \sim 10^{-4}$ cm

ξ_O was interpreted as the distance over which the superconducting state was correlated



V. L. Ginzburg

Lev Landau

Ginzburg-Landau Equations

Obtained from a minimization of the free energy expresses in terms of a order parameter

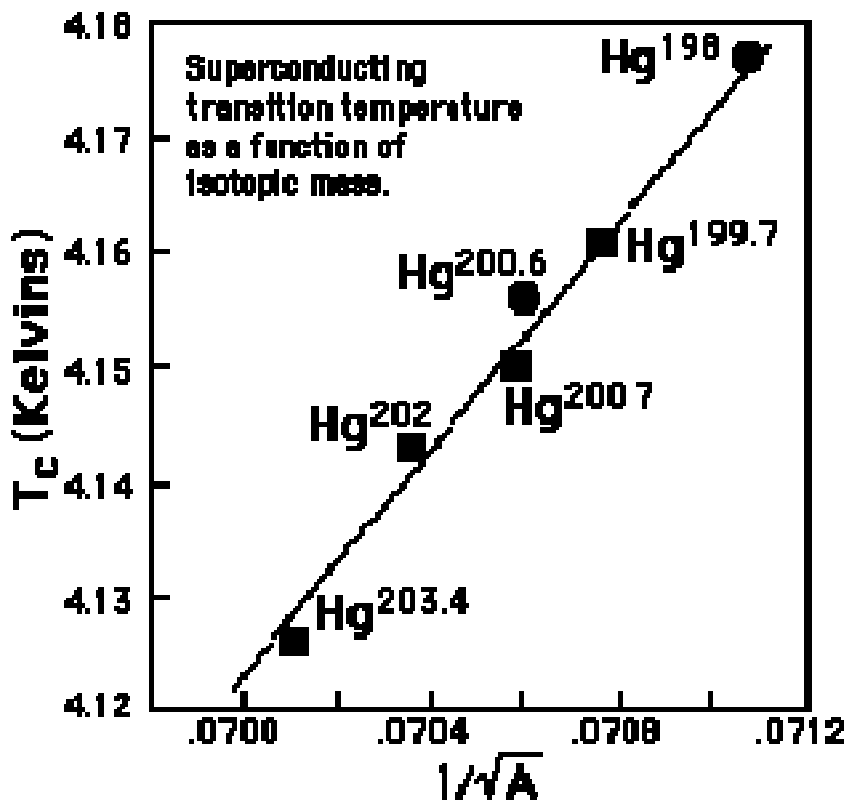
$$\alpha\psi + \beta|\psi|^2\psi + \frac{1}{2m}\left(-i\hbar\nabla - 2e\mathbf{A}\right)^2\psi = 0$$

$$\mathbf{j} = \frac{2e}{m}\mathrm{Re}\left\{\psi^*\left(-i\hbar\nabla - 2e\mathbf{A}\right)\psi\right\}$$

Abrikosov used these equations to explain vortices in type II superconductors

EMANUEL MAXWELL

BERNARD SERIN



Isotope Effect in Superconductors

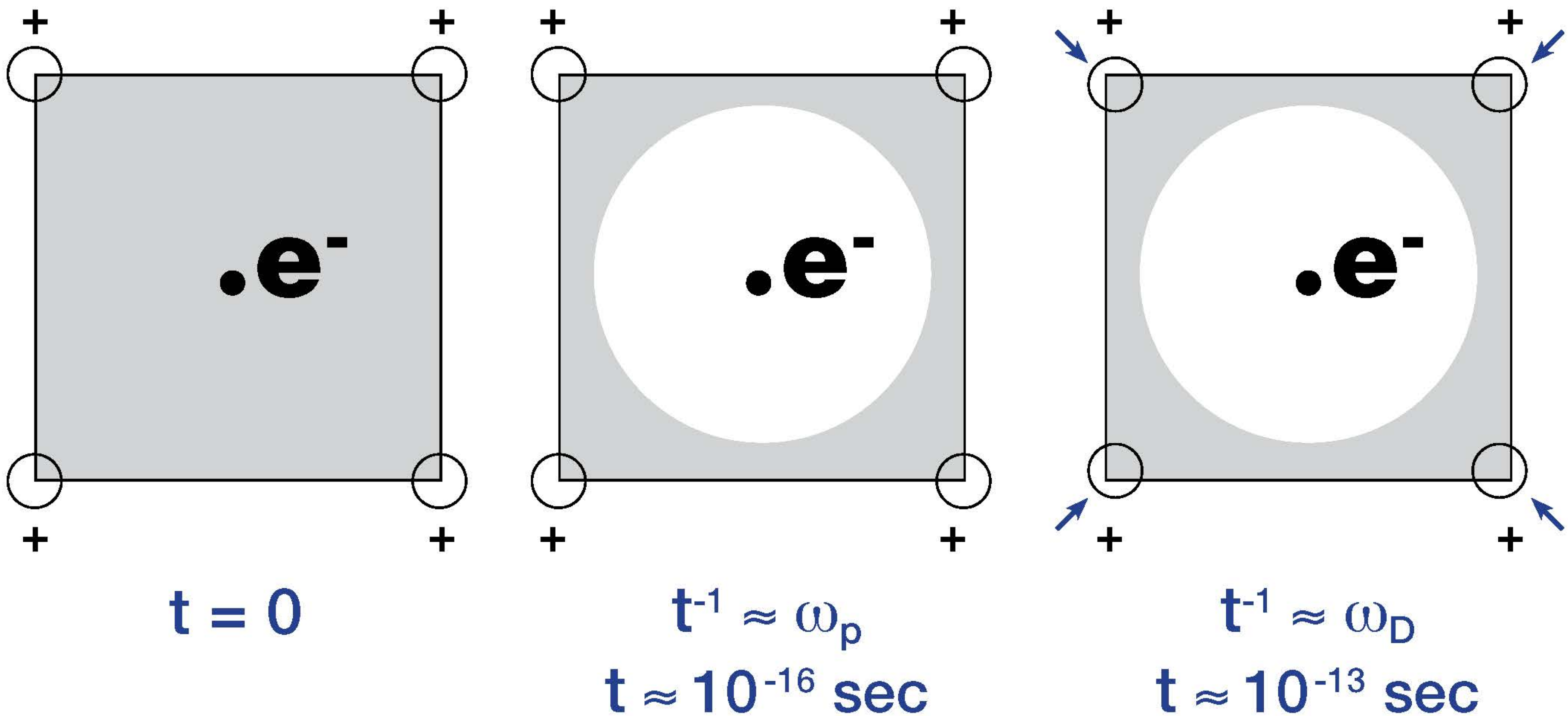
Isotope Effect in the Superconductivity of Mercury

Emanuel Maxwell, Phys. Rev. **78**, 477 (1950)

Superconductivity of Isotopes of Mercury, C. A. Reynolds, B. Serin, W. H. Wright, and L. B. Nesbitt

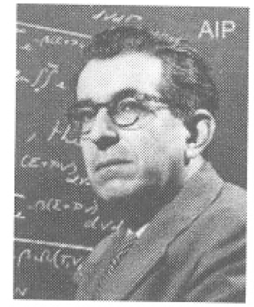
Phys. Rev. **78**, 487 (1950)

ELECTRON–PHONON INTERACTION



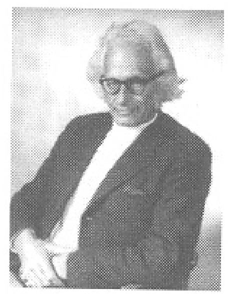
John Bardeen
(1908-1991)

Werner Heisenberg
(1901-1976)



Fritz London
(1900-1954)

Max Born
(1882-1970)



Herbert Fröhlich
(1905-1991)

Richard Feynman
(1918-1988)

Physicists Who Proposed Unsuccessful Microscopic Theories Prior to BSC

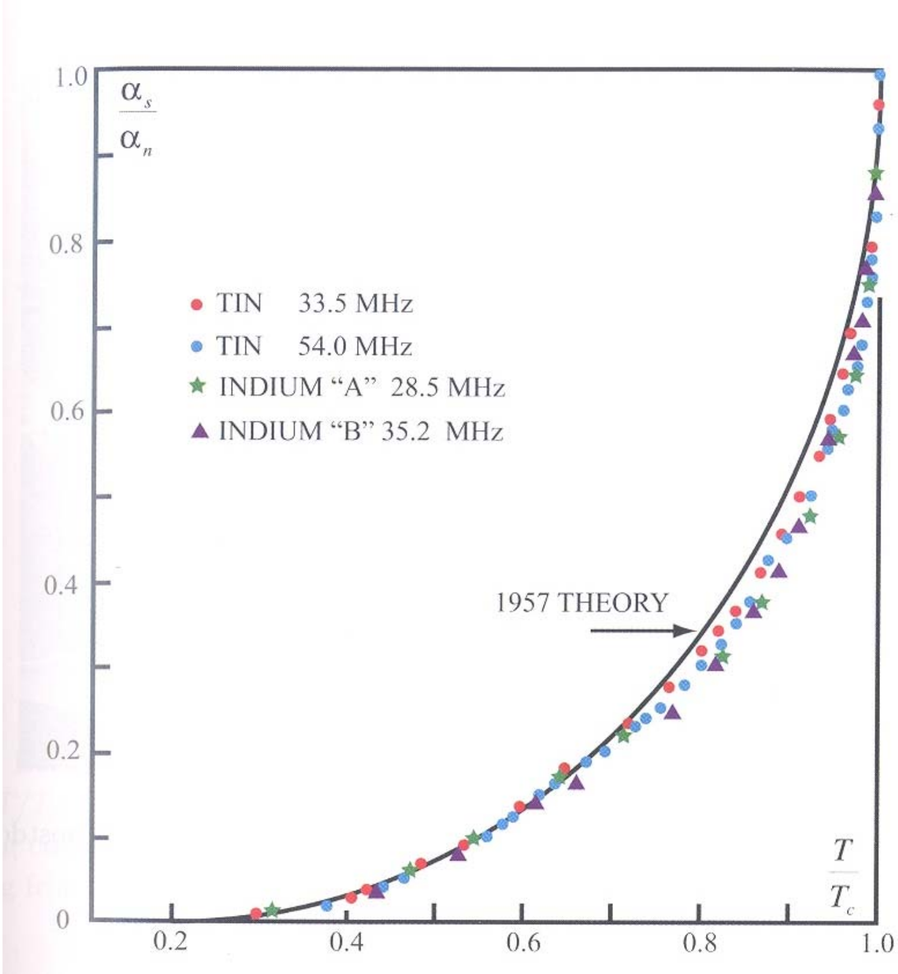
From ***Failed Theories of Superconductivity***, Jörg Schmalian

Experimental Results on Superconductors

- Meissner Effect
- Specific Heat
- Ultrasonic Absorption
- Magnetic Resonance
- Isotope Effect

Evidence for an Energy Gap

- Exponential Drop in Thermal Conductivity (1953)
- Low Temperature Specific Heat ~ $e^{-(Tc/T)}$ (1954)
- Decrease in Ultrasonic Attenuation
- Decrease in Spin-Lattice Relaxation Time
- Microwave Absorption at $h\omega \sim kT_C$
- Transmission of Microwave and Far Infrared Radiation



Temperature-Dependent Ultrasonic Absorption in the Superconducting State, Morse and Bohm

Why Theory Was So Difficult

- Bloch Theorem ". . . that every theory of superconductivity can be disproved."
- Free Energy Difference Between Superconducting and Normal State is $(H_{CB})^2/(8\pi)$ or 1 part in 10^8
- Perturbation Theory in Powers of the Interaction Strength V Could Not be Used:

$$\Delta(E) \sim \exp(-1/(N(0)V))$$

- T_C was a fraction of the Debye Frequency

$$kT_C \sim \hbar\omega_D \exp(-1/(N(0)V))$$

Reproduction of a slide made in 1955 by John Bardeen to illustrate the status of the theory at that time

QUANTUM THEORY

↙ ↓ ↘

Summerfeld-Bloch Normal Metals

Electron-Vibration Interaction (Isotope Effect)

Coulomb Interactions (Heisenberg-Koppe)

?↓?

ENERGY GAP MODEL

↙ ↘

Pippard Theory

↑

London Theory

↑

ELECTROMAGNETIC PROPERTIES

E=0, **B**=0

Two Fluid Model (Gorter-Casimir, etc.)

↑

↑

THERMAL PROPERTIES

(Specific Heat, Thermal Conductivity, etc.)

Classic Books on Superconductivity

Superconductivity, Shoenberg, D. (David)
Cambridge University Press, 1938, 2d ed. 1952

Superfluids, London, Fritz
New York, Wiley, 1950-1954

Superconductivity, Experimental Part, Serin, B
Handbuch der Physik (Berlin: Springer, 1956), Vol. 15:210-273.

Superconductivity, Theory
Handbuch der Physik (Berlin: Springer, 1956), Vol. 15, 274-369

Superconductivity, Lynton, E. A. (Ernest Albert)
London, Methuen; New York, Wiley, 1962, 3rd ed.1969

Superconductivity, Tinkham, Michael.
New York, Gordon and Breach 1965

Superconductivity of Metals and Alloys, Gennes, Pierre-Gilles de
Translated by P.A. Pincus,New York, W.A. Benjamin, 1966

Superconductivity, edited by R. D. Parks
New York, M. Dekker, 1969

Career and Bio of Walther Meissner

- 1934 Appointed Chair technical physics at the Technical University of Munich.
- After World War II, President of the Bavarian Academy of Sciences and Humanities
- Appointed director of the academy's first low temperature research commission.
- Meissner lived alone with his two dogs for the last several years of his life. Meissner died in Munich in 1974 at age 92

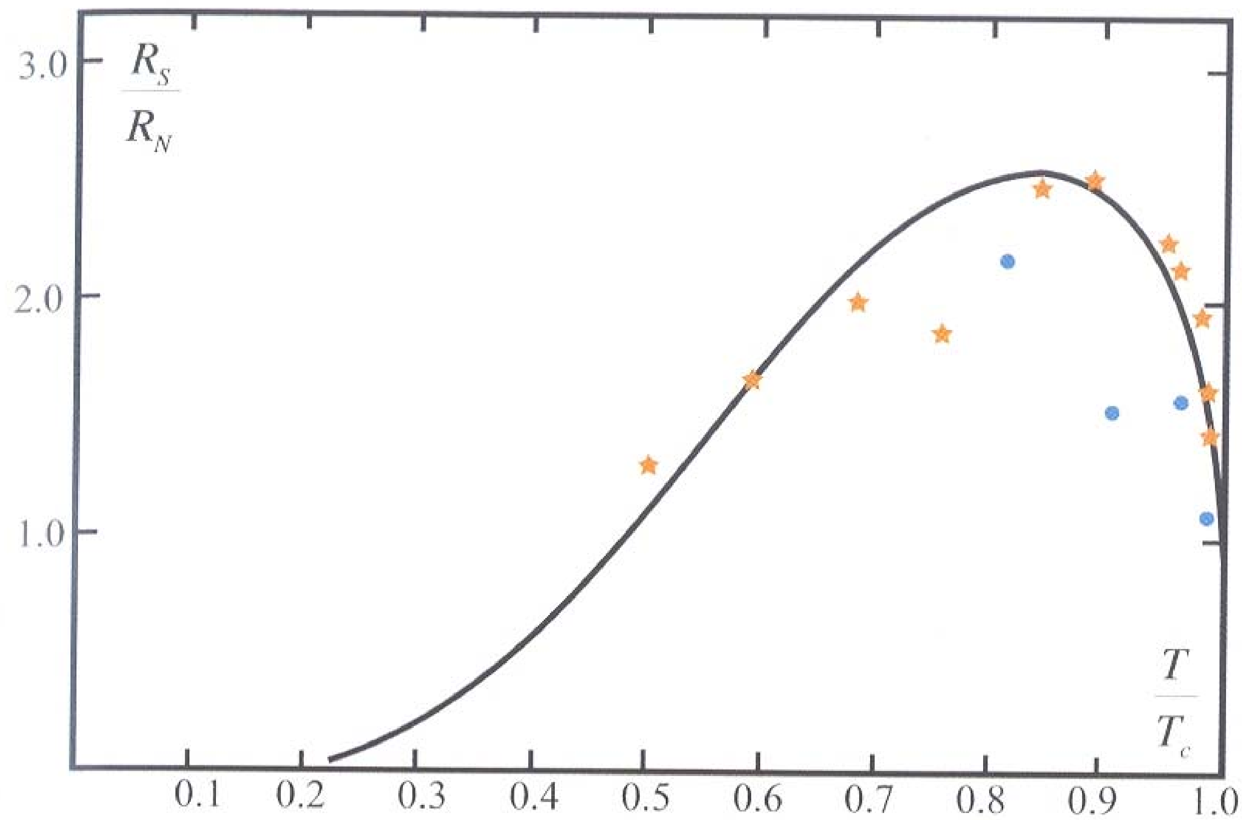
- Robert Ochsenfeld , German physicist, born May 18, 1901
- 1933 Co-discoverer of the Meissner-Ocsenfeld Effect.
- Died on December 5, 1993

Walther Meissner

Born: December 16, 1882
Berlin, Germany

Died: November 16, 1974
Munich, Germany

Robert Ochsenfeld was a German physicist born on May 18, 1901 in Hilchenbach (Helberhausen quarter). In 1933 he discovered with Walter Meissner the Meißner-Ochsenfeld effect.
He died on December 5, 1993 in Hilchenbach.



Temperature-Dependent NMR in the Superconducting State – Data Hebel and Slichter Redfield

London Equations

Perfect diamagnetism implies that not only is the time derivative of B= 0 but B itself equals zero,

$$\frac{\partial \mathbf{j}_s}{\partial t} = \frac{n_s e^2}{m}\mathbf{E}, \qquad \nabla \times \mathbf{j}_s = -\frac{n_s e^2}{mc}\mathbf{B}. \qquad \mathbf{j}_s = -\frac{n_s e^2}{mc}\mathbf{A}. \qquad \nabla \times \mathbf{B} = \frac{4\pi \mathbf{j}}{c}$$

$$\nabla^2 \mathbf{B} = \frac{1}{\lambda^2}\mathbf{B}, \qquad \lambda = \sqrt{\frac{mc^2}{4\pi n_s e^2}}. \qquad B_z(x) = B_0 e^{-x/\lambda}. \qquad \nabla \times \mathbf{B} = \frac{4\pi \mathbf{j}}{c}$$

$$\mathbf{F} = e\mathbf{E} + \frac{e}{c}\mathbf{v} \times \mathbf{B} \qquad \nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$

$$\frac{\partial}{\partial t}\left(\nabla \times \mathbf{j}_s + \frac{n_s e^2}{mc}\mathbf{B}\right) = 0.$$

Not only was the time derivative of the above expression equal to zero, but also that the expression in the parentheses must be identically zero

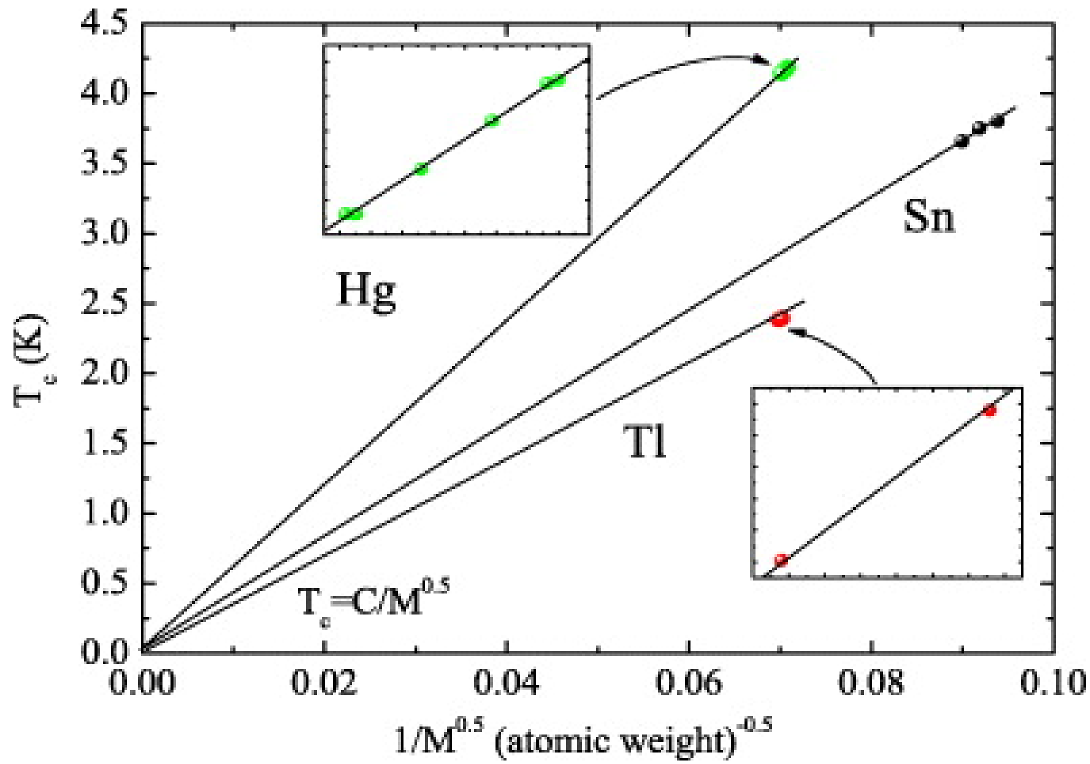
$$\mathbf{j}_s = n_s e \mathbf{v}. \qquad \mathbf{v} = \frac{1}{m}\left(\mathbf{p} - \frac{e}{c}\mathbf{A}\right). \qquad \mathbf{j}_s = -\frac{n_s e_s^2}{mc}\mathbf{A},$$

London Equations

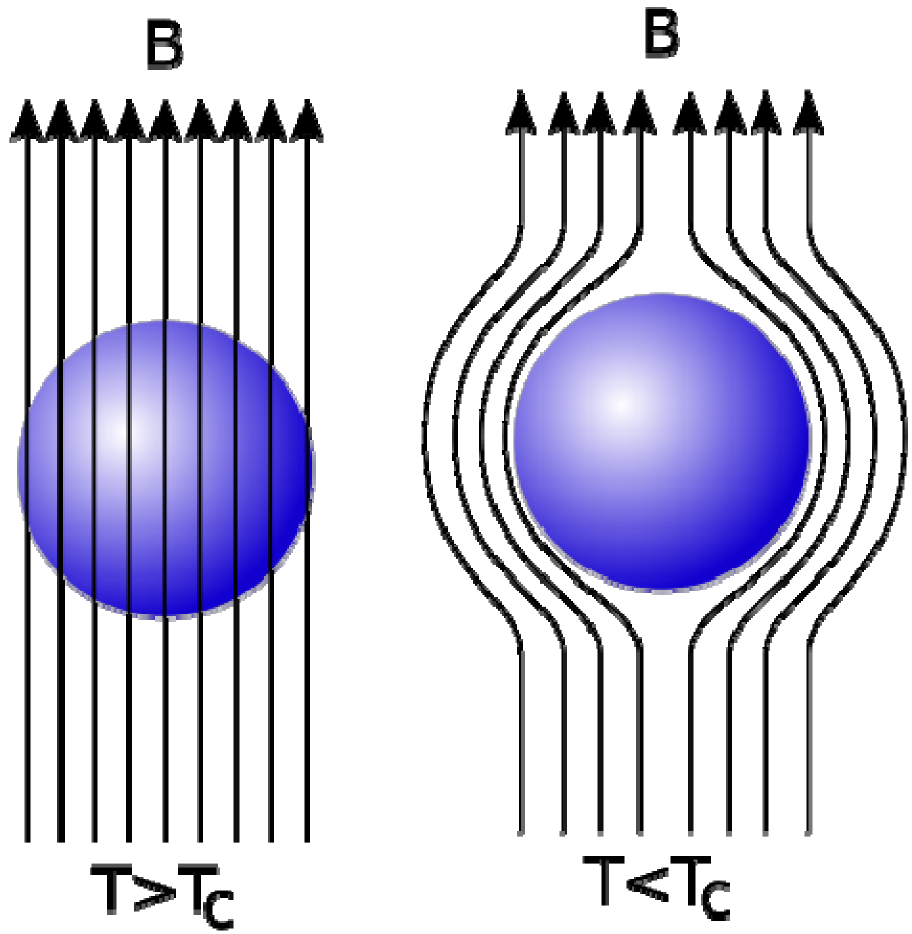
There are two London equations when expressed in terms of measurable fields: Here j_s is the superconducting current

$$\frac{\partial \mathbf{j}_s}{\partial t} = \frac{n_s e^2}{m}\mathbf{E}, \qquad \nabla \times \mathbf{j}_s = -\frac{n_s e^2}{mc}\mathbf{B}.$$

$\mathbf{j}_s$



Isotope Effect in Hg, Sn and Tl



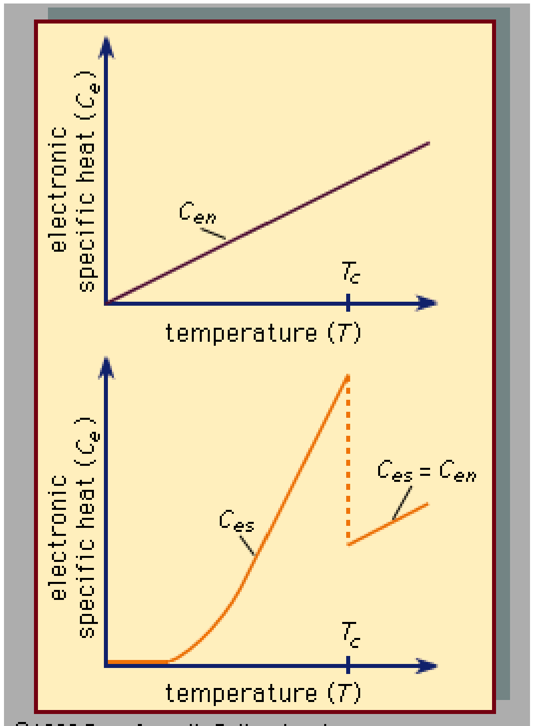
Meissner Effect

The Two-Fluid Model

In 1934 physicists Gorter and Casimir developed the two-fluid model of superconductivity in order to help explain the thermodynamic properties of superconductors. A finite fraction of the electrons are condensed into a sort of superfluid. At zero temperature there is complete condensation and all electrons participate in forming the superfluid. As the temperature of the system is increased from zero, a fraction of the electrons in the superfluid form a normal fluid, As the temperature increases to T_c the fraction of electrons contained in the superfluid goes to zero and the system experiences a second-order phase transition from the superconducting to the normal state. From the specific heat behavior Gorter and Casimir developed a formula relating the number of electrons in the superfluid to temperature.

$$\psi_S\,(T) = n_s = n\left[1 - (\frac{T}{T_c})^4\right]$$

Where $n_s(T)$ is the fraction of electrons in the superfluid at temperature T.


electronic specific heat (C_e)
C_{en}
T_c
temperature (T)
electronic specific heat (C_e)
C_{es}
$C_{es} = C_{en}$
T_c
temperature (T)