Phys 798S Superconductivity
Fall 2025

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Physics Department
University of Maryland

Lecture 1

Nobel Prizes in Superconductivity

The Nobel Prize in Physics 1913
Heike Kamerlingh Onnes "for his investigations on the properties of matter at low temperatures which led, inter alia, to the production of liquid helium"

The Nobel Prize in Physics 1962
Lev Davidovich Landau "for his pioneering theories for condensed matter, especially liquid helium"

The Nobel Prize in Physics 1972
John Bardeen, Leon Neil Cooper and John Robert Schrieffer "for their jointly developed theory of superconductivity, usually called the BCS-theory"

The Nobel Prize in Physics 1973
Leo Esaki and Ivar Giaever "for their experimental discoveries regarding tunneling phenomena in semiconductors and superconductors, respectively"
Brian David Josephson "for his theoretical predictions of the properties of a supercurrent through a tunnel barrier, in particular those phenomena which are generally known as the Josephson effects"

The Nobel Prize in Physics 1987
J. Georg Bednorz and K. Alexander Müller "for their important break-through in the discovery of superconductivity in ceramic materials"

The Nobel Prize in Physics 1991
Pierre-Gilles de Gennes "for discovering that methods developed for studying order phenomena in simple systems can be generalized to more complex forms of matter, in particular to liquid crystals and polymers"

The Nobel Prize in Physics 2003
Alexei A. Abrikosov, Vitaly L. Ginzburg and Anthony J. Leggett "for pioneering contributions to the theory of superconductors and superfluids"

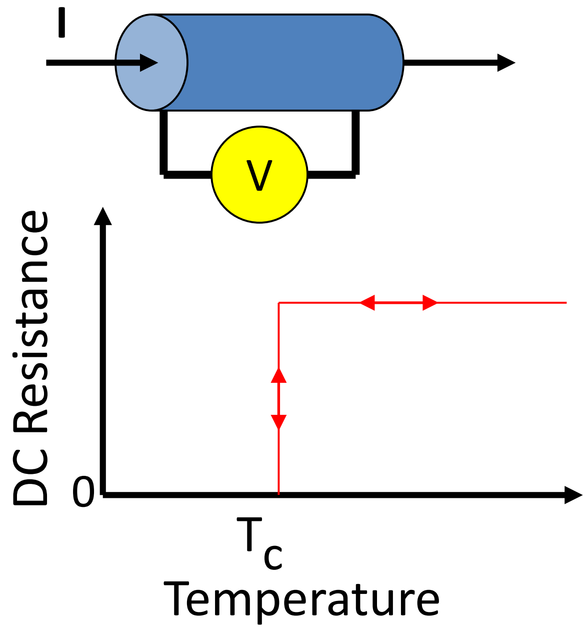
The Nobel Prize in Physics 20??
Your name here

The Three Hallmarks of Superconductivity

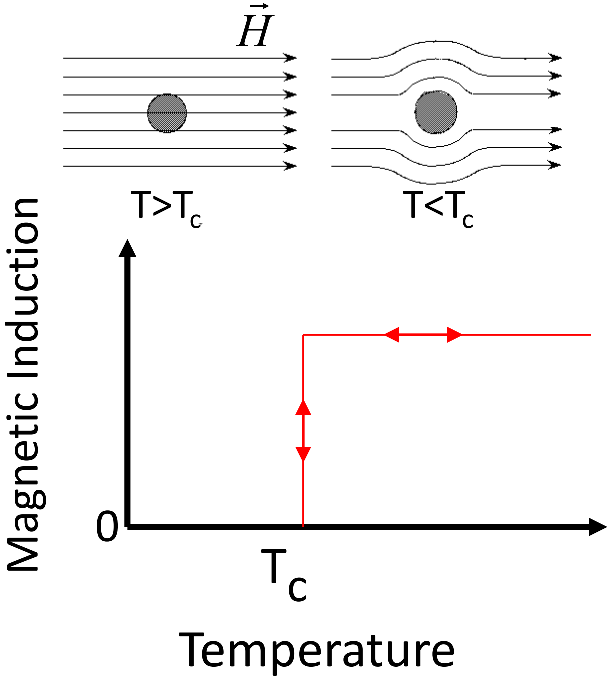
1) Zero Resistance
2) Meissner Effect
3) Macroscopic Quantum Effects

The Three Hallmarks of Superconductivity

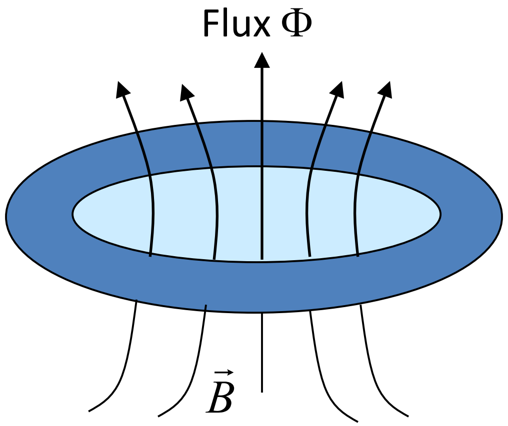
Zero Resistance



Complete Diamagnetism

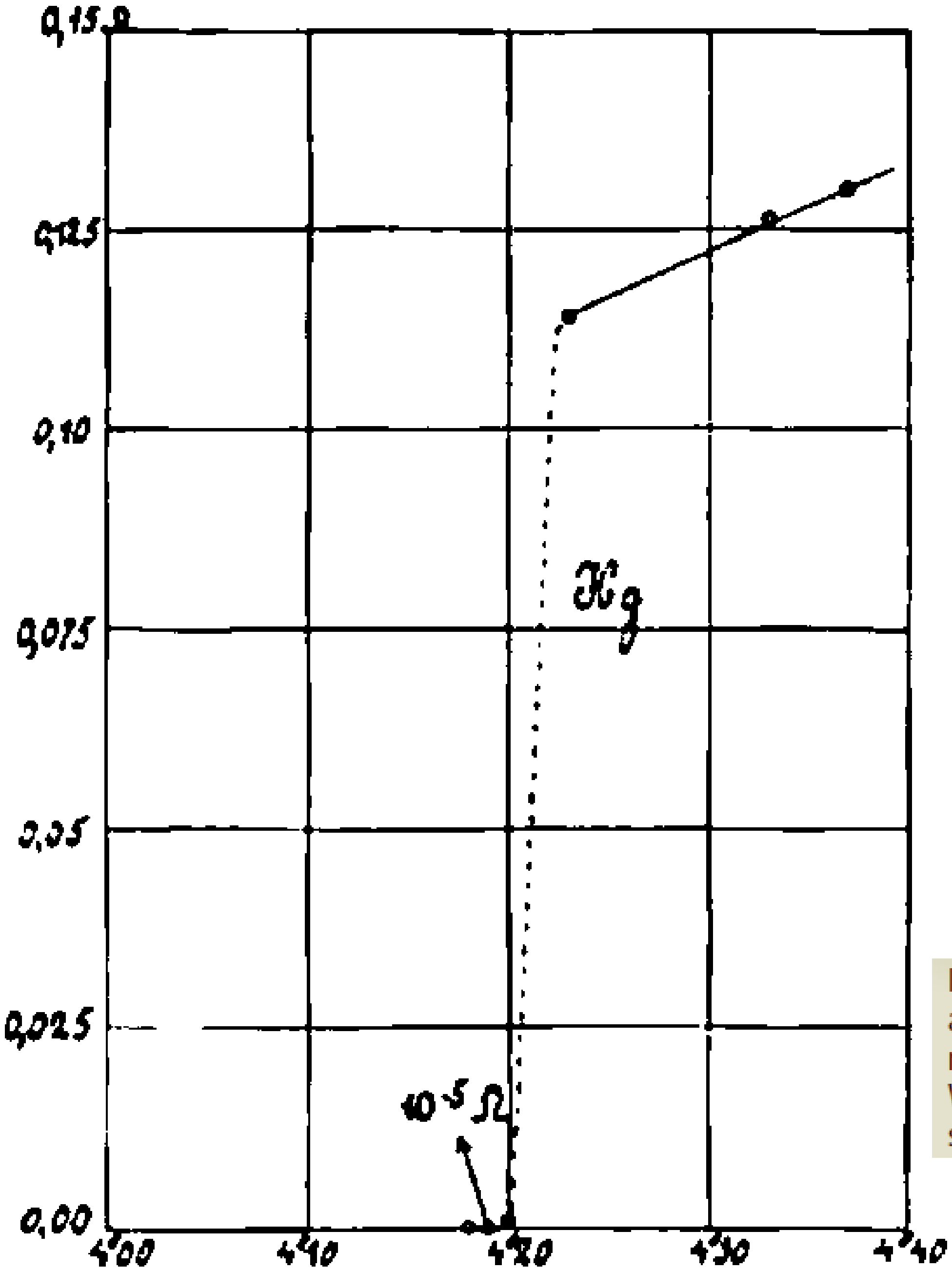


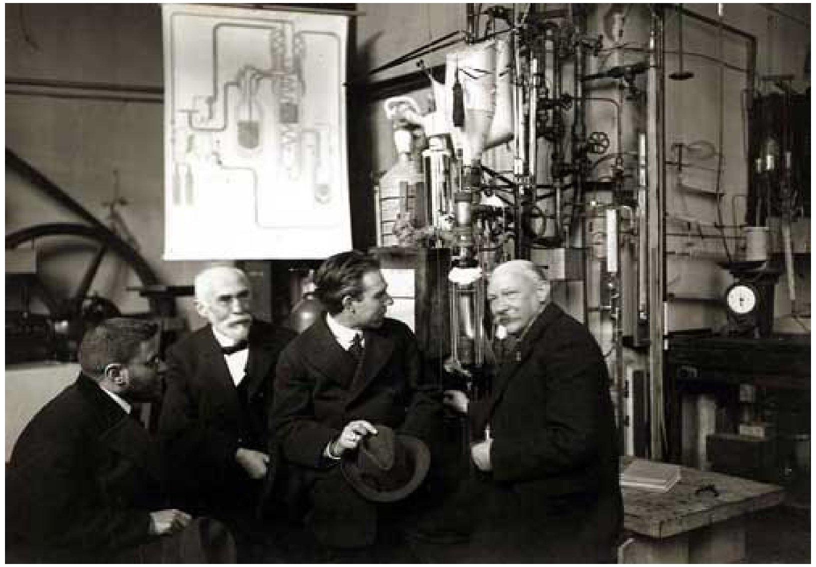
Macroscopic Quantum Effects



Flux quantization $\Phi = n\Phi_0$
Josephson Effects

The zero resistance transition of Hg measured in 1911 by Kamerlingh Onnes.

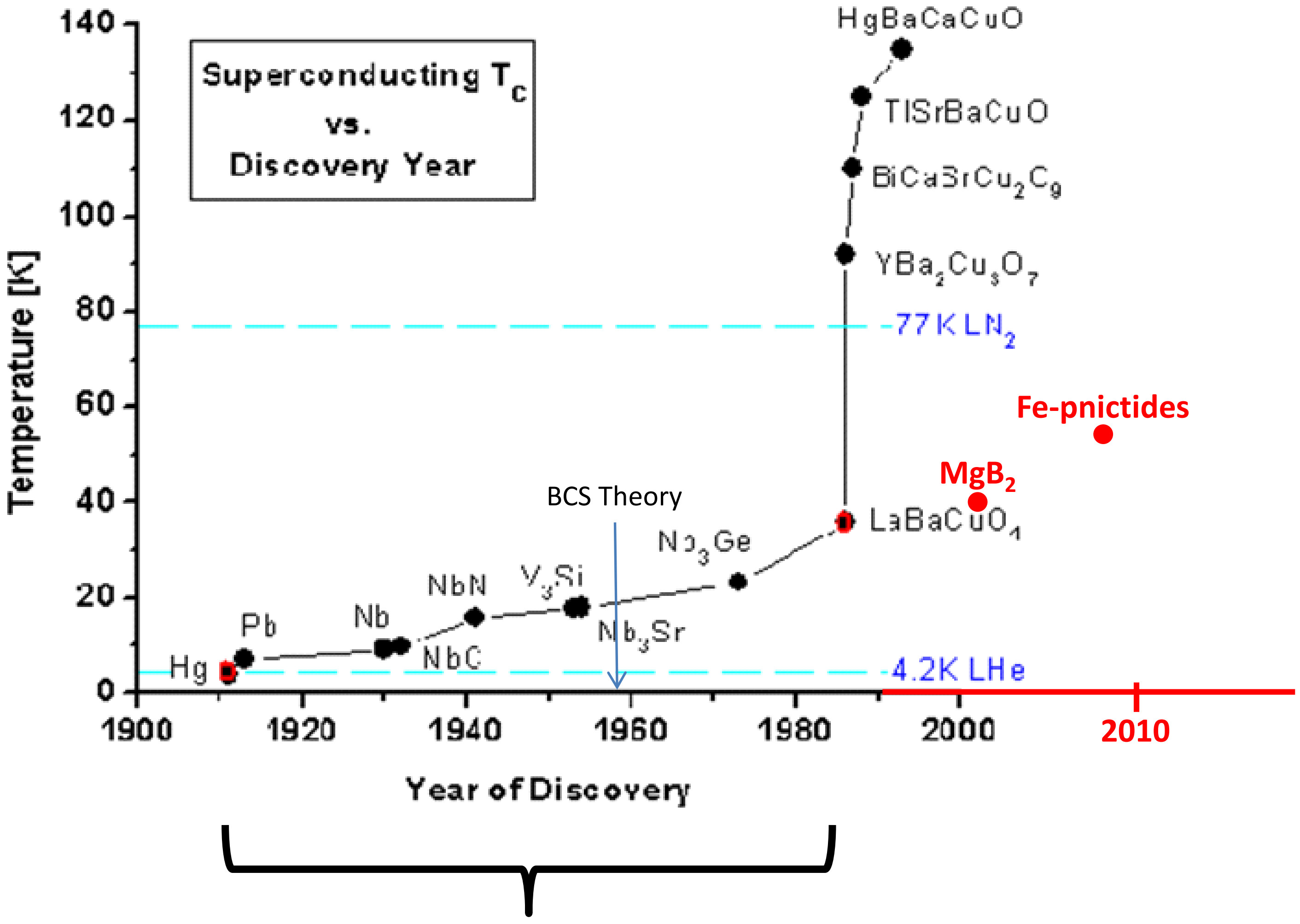




Heike Kamerlingh Onnes (right), the discoverer of superconductivity.
Paul Ehrenfest, Hendrik Lorentz, Niels Bohr stand to his left.

Figure 4. Historic plot of resistance (ohms) versus temperature (kelvin) for mercury from the 26 October 1911 experiment shows the superconducting transition at 4.20 K. Within 0.01 K, the resistance jumps from unmeasurably small (less than $10^{-6}\,\Omega$) to 0.1 Ω. (From ref. 9.)

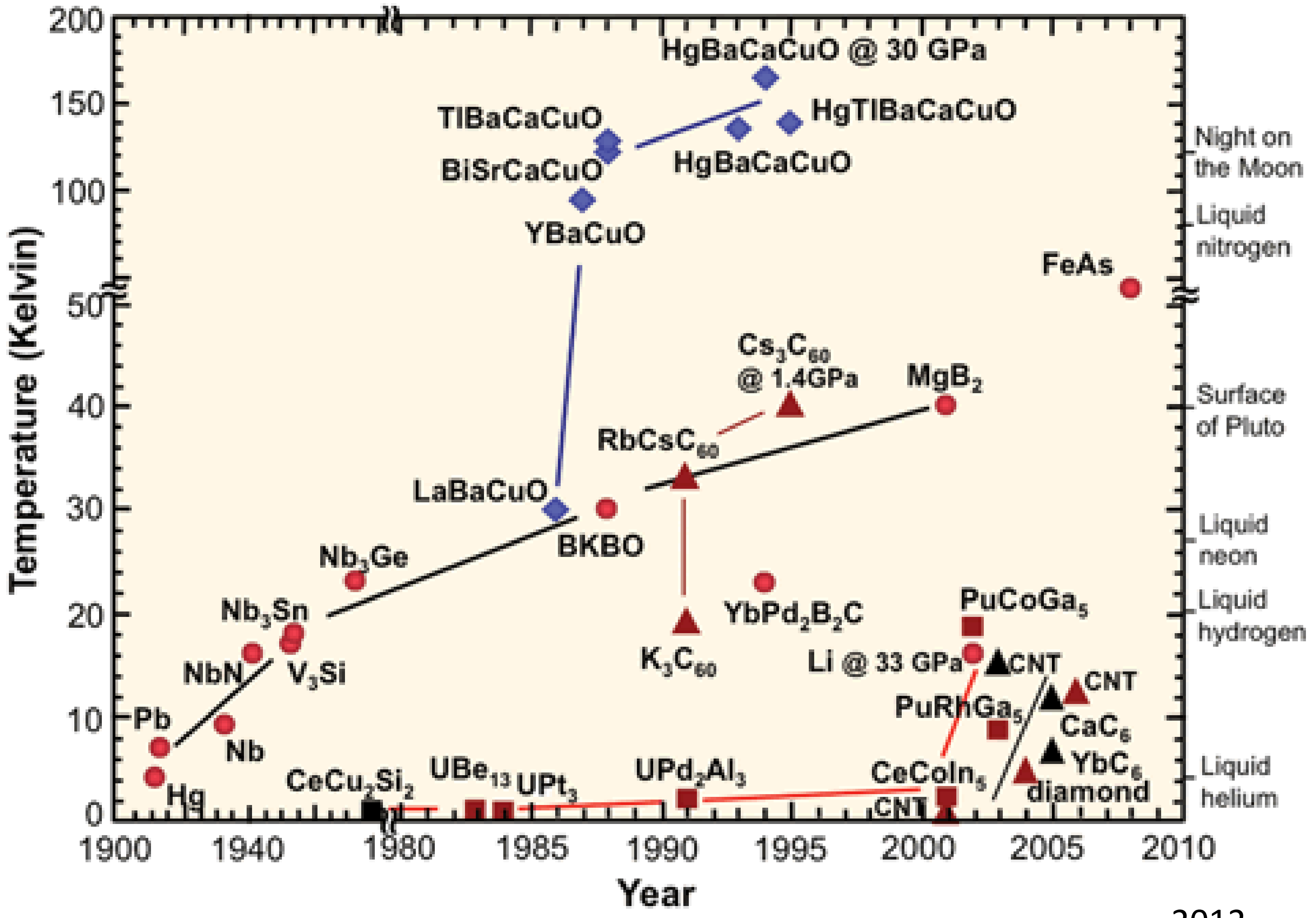
Look at the History of the "History of Superconductivity" ….



The increase of T_c over time was very modest:

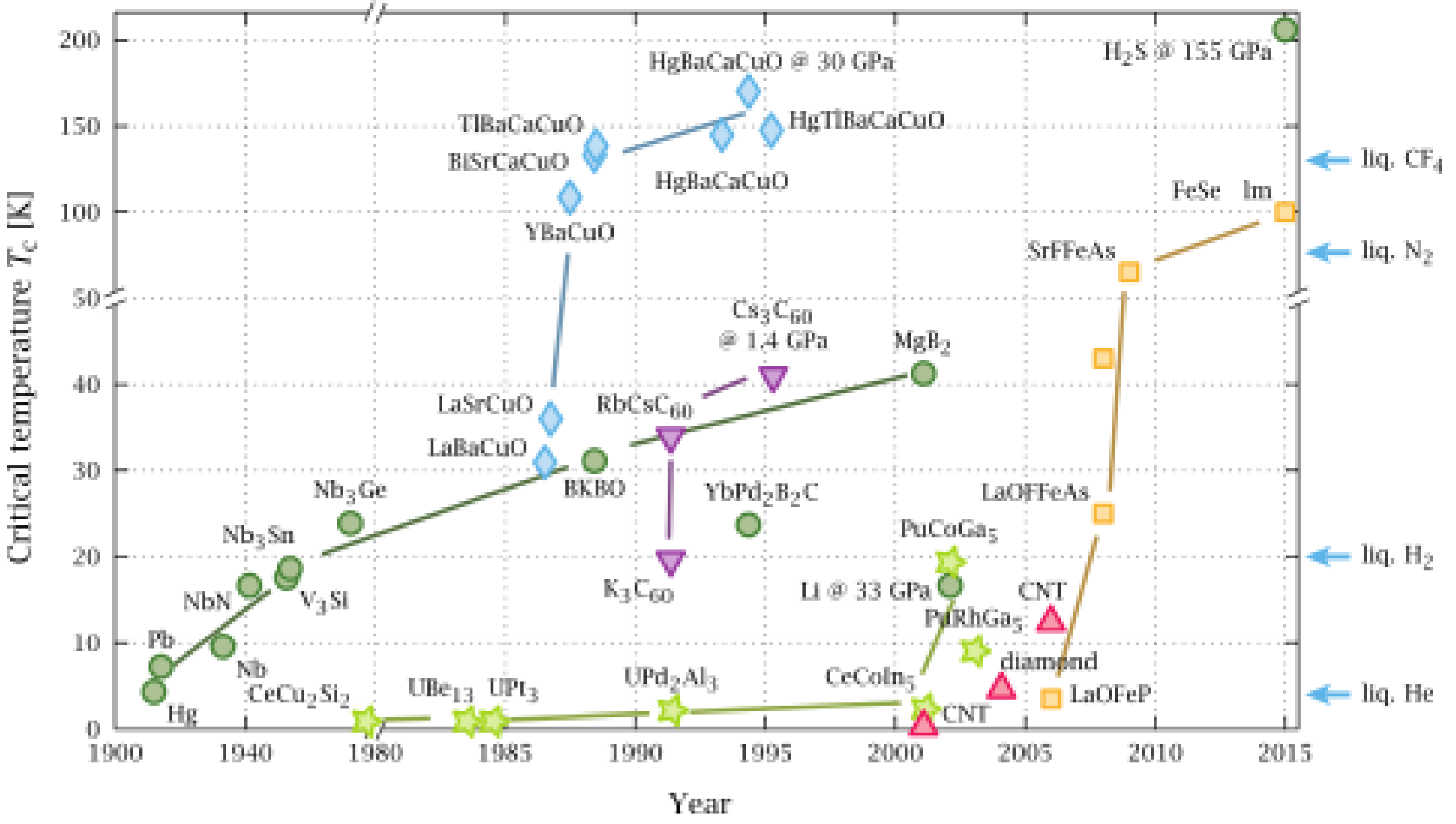
$$\frac{\Delta T_c}{\Delta t} \approx 0.4 \frac{\text{Kelvin}}{\text{year}}$$

2006



2012

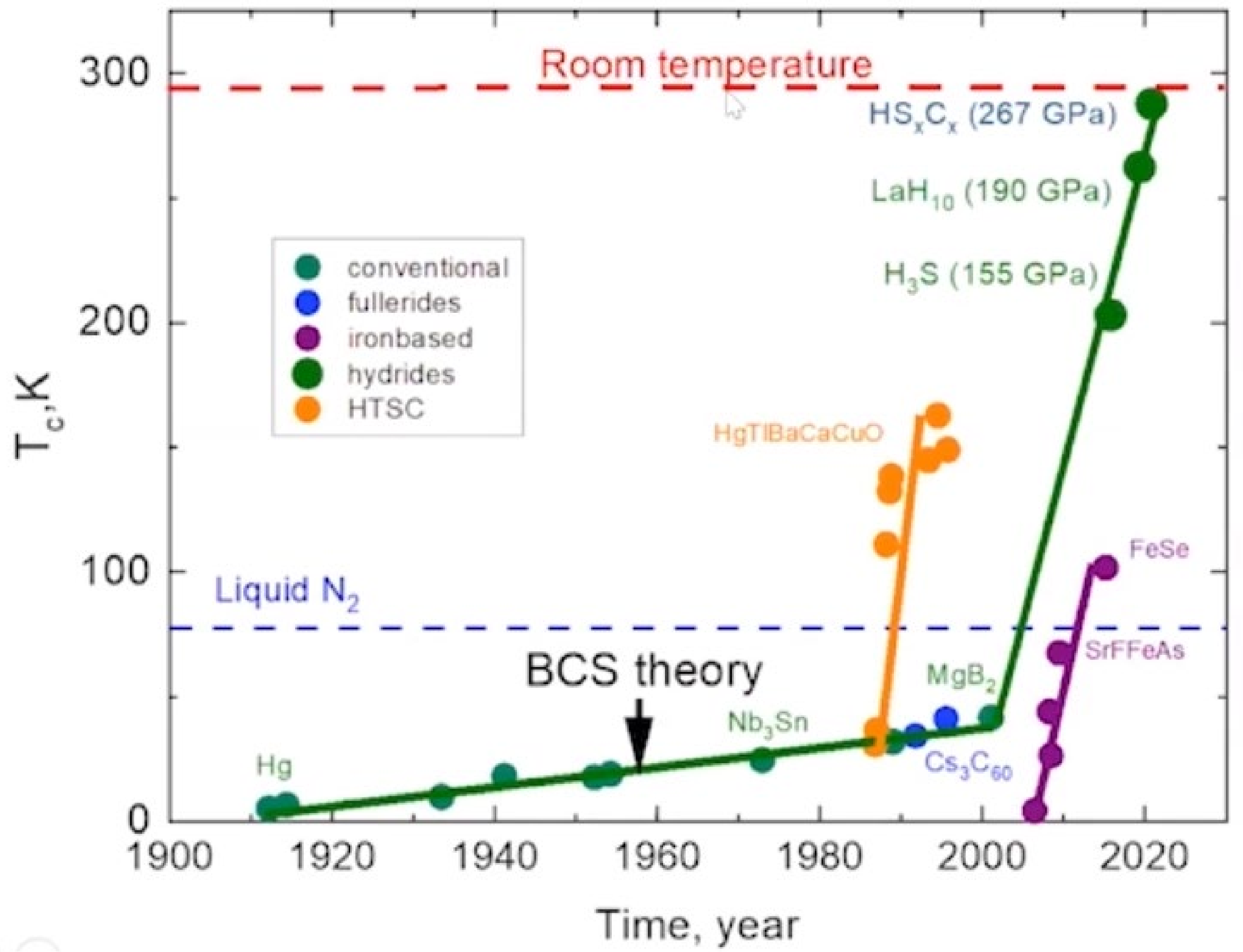
http://en.wikipedia.org/wiki/Superconductivity



2016

http://en.wikipedia.org/wiki/Superconductivity

Critical temperature of superconductivity with time



2020

Materials

Mikhail Eremets Plenary: A Path Towards Room Temperature Superconductivity

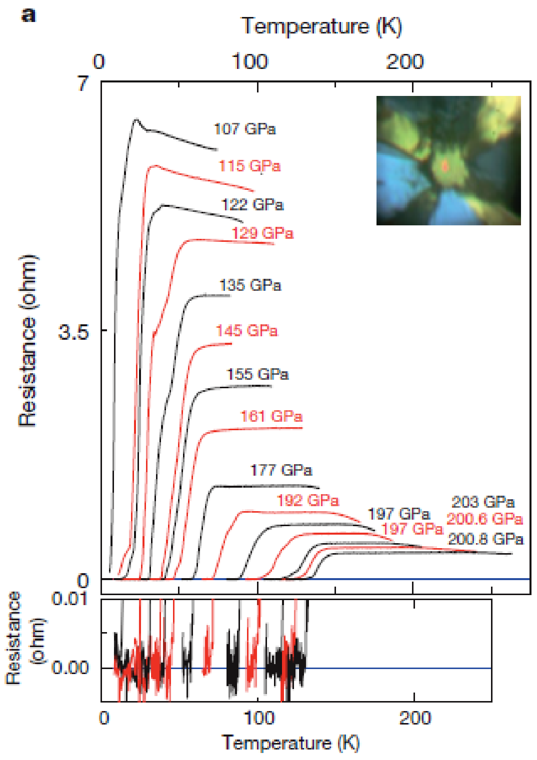
Mon. Oct 26, 2020 8:00 AM - 9:00 AM 757 Attending

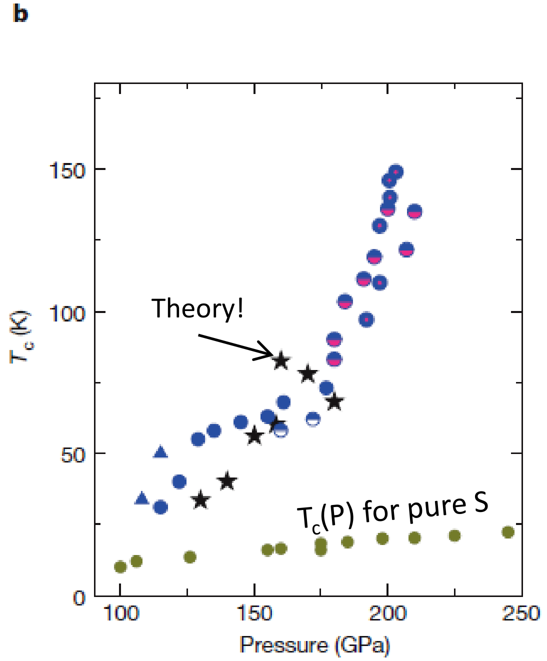
Conventional superconductivity at 203 kelvin at high pressures in the sulfur hydride system

A. P. Drozdov[1]*, M. I. Eremets[1]*, I. A. Troyan[1], V. Ksenofontov[2] & S. I. Shylin[2]

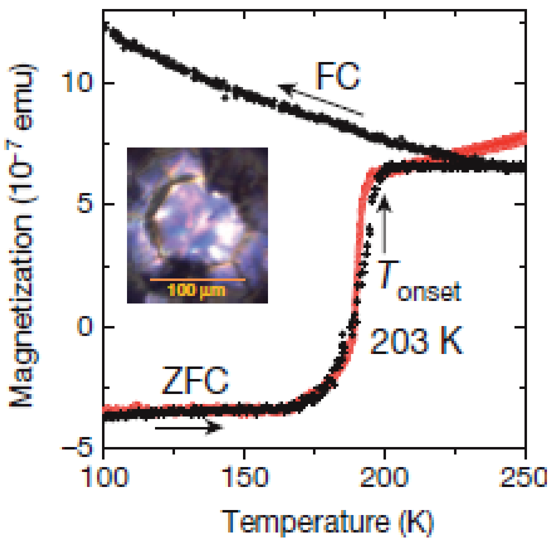
Nature 525, 73–76 (03 September 2015) doi:10.1038/nature14964

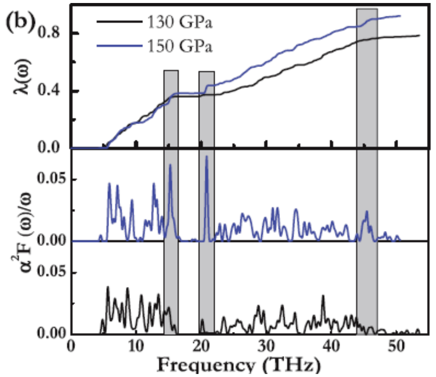
Zero Resistance





Meissner Screening





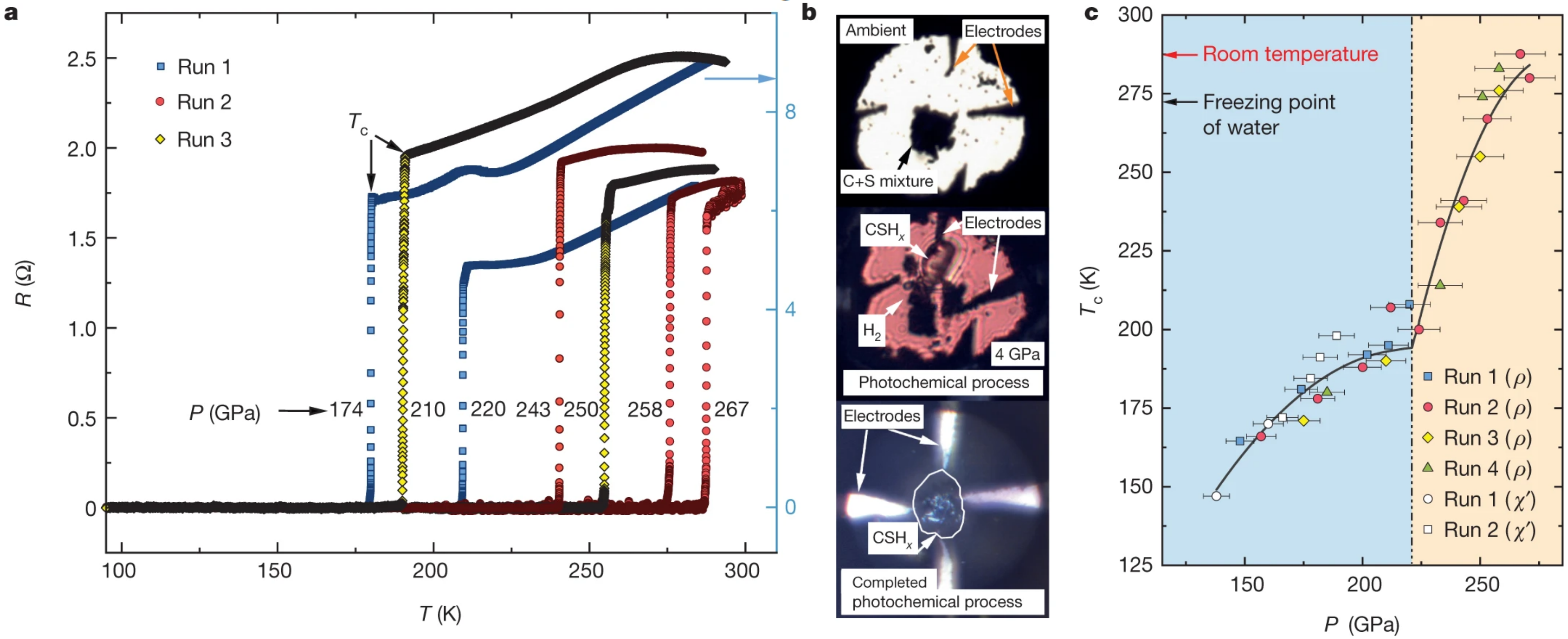
THE JOURNAL OF CHEMICAL PHYSICS 140, 174712 (2014)

The metallization and superconductivity of dense hydrogen sulfide

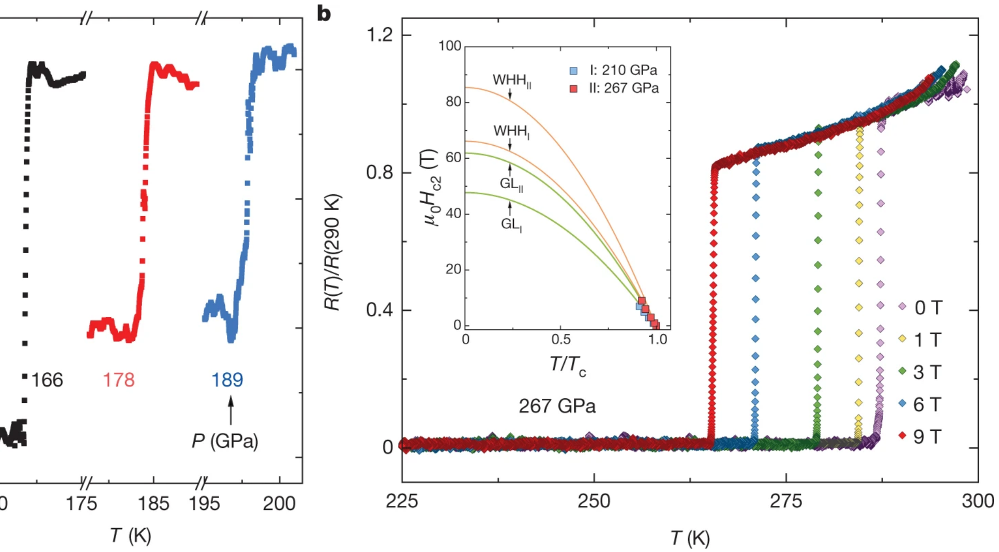
Yinwei Li,[1,a)] Jian Hao,[1] Hanyu Liu,[2] Yanling Li,[1] and Yanming Ma[3,b)]

Room-temperature superconductivity in a carbonaceous sulfur hydride

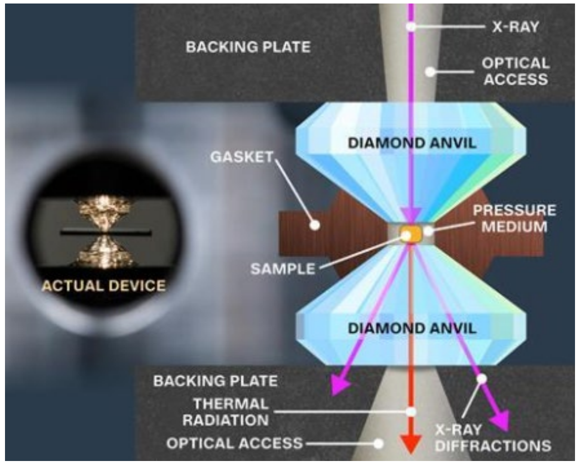
Nature | Vol 586 | 15 October 2020 | 373



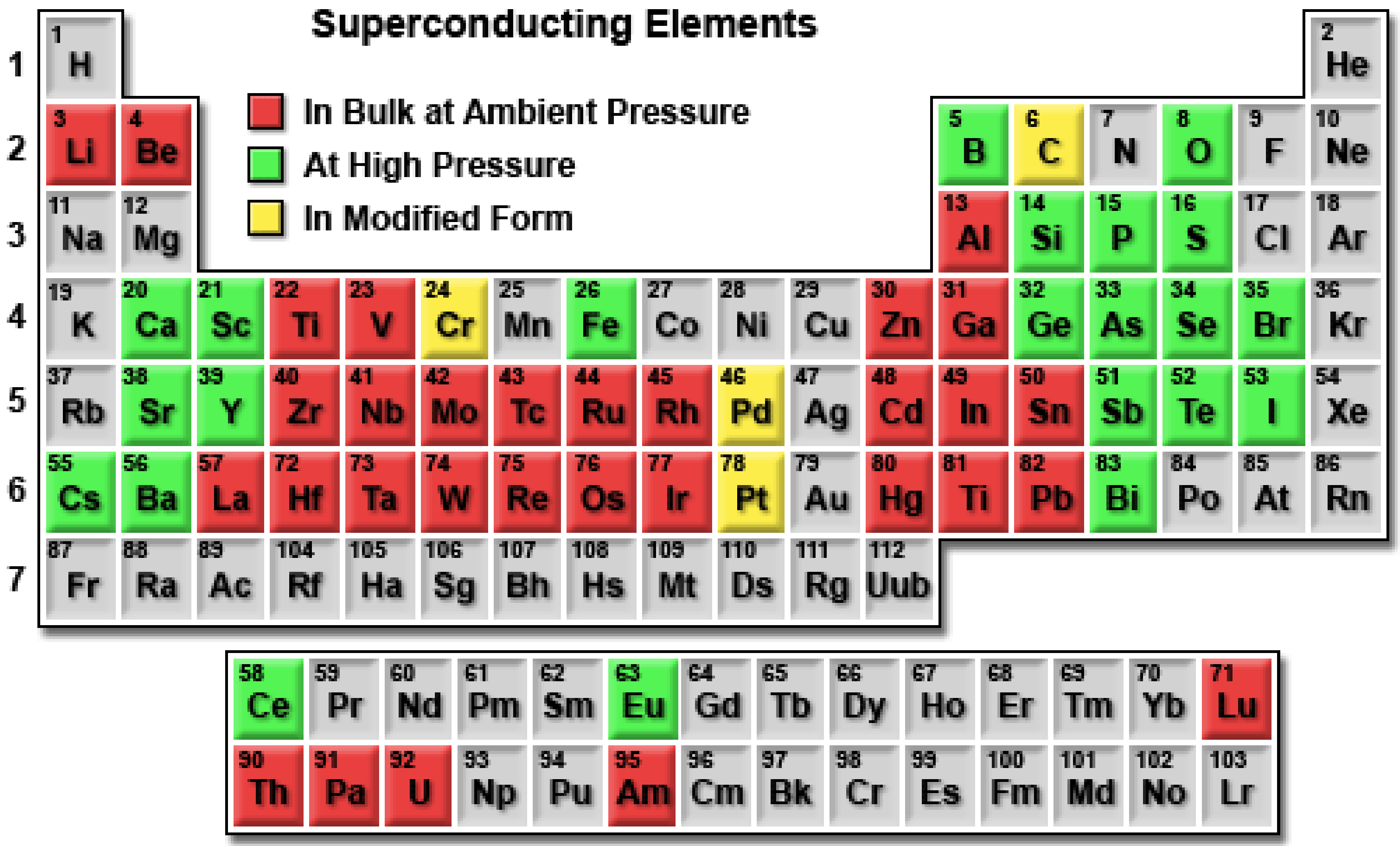
https://doi.org/10.1038/s41586-020-2801-z



the extremely narrow widths of the transitions in the absence of a magnetic field, and the fact that the widths do not change with the applied magnetic field, suggest that the observed phenomena are not associated with superconductivity.
J. Hirsch and F. Marsiglio, Nature, 596, pp. E9–E10 (2021)



https://www.chemistryworld.com/news/room-temperature-superconductivity-finally-claimed-by-mystery-material/4012591.article


Superconducting Elements
In Bulk at Ambient Pressure
At High Pressure
In Modified Form
1
2
3
4
5
6
7
1 H
2 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe
55 Cs
56 Ba
57 La
72 Hf
73 Ta
74 W
75 Re
76 Os
77 Ir
78 Pt
79 Au
80 Hg
81 Tl
82 Pb
83 Bi
84 Po
85 At
86 Rn
87 Fr
88 Ra
89 Ac
104 Rf
105 Ha
106 Sg
107 Bh
108 Hs
109 Mt
110 Ds
111 Rg
112 Uub
58 Ce
59 Pr
60 Nd
61 Pm
62 Sm
63 Eu
64 Gd
65 Tb
66 Dy
67 Ho
68 Er
69 Tm
70 Yb
71 Lu
90 Th
91 Pa
92 U
93 Np
94 Pu
95 Am
96 Cm
97 Bk
98 Cr
99 Es
100 Fm
101 Md
102 No
103 Lr

Classes of Superconductors

"Conventional" 3D BCS s-wave

Nb, Al, Pb, Sn, Nb_3Sn, Nb-Ti, etc. $T_c < 25$ K

A_3C_{60}, electronically-doped C_{60}, MgB_2 $T_c < 40$ K

"Organic" Quasi 1-D,2-D

$(TMTSF)_2X$, $(BEDT\text{-}TTF)_2X$ $T_c < 12$ K

"Oxide"

$Ba(Pb\text{-}Bi)_3O$, Ba-K-Bi-O $T_c < 30$ K

"Heavy Fermion" Anisotropic (p- or d-wave)

UPt_3, UBe_{13}, $CeCu_2Si_2$ $T_c < 2$ K

"Cuprates"

High-T_c:

- Hg-Ba-Ca-Cu-O $T_c < 135$ K ($T_c \to 154$ K (under pressure))
- Tl-Ba-Ca-Cu-O $T_c < 125$ K
- Bi-Sr-Ca-Cu-O $T_c < 108$ K
- ☆ Y-Ba-Cu-O $T_c < 93$ K

Low-T_c:

- La-Sr-Cu-O $T_c < 36$ K
- ☆ Nd-Ce-Cu-O $T_c < 25$ K

"Ruthenates" Sr-Ru-O (p-wave) $T_c < 1.5$ K

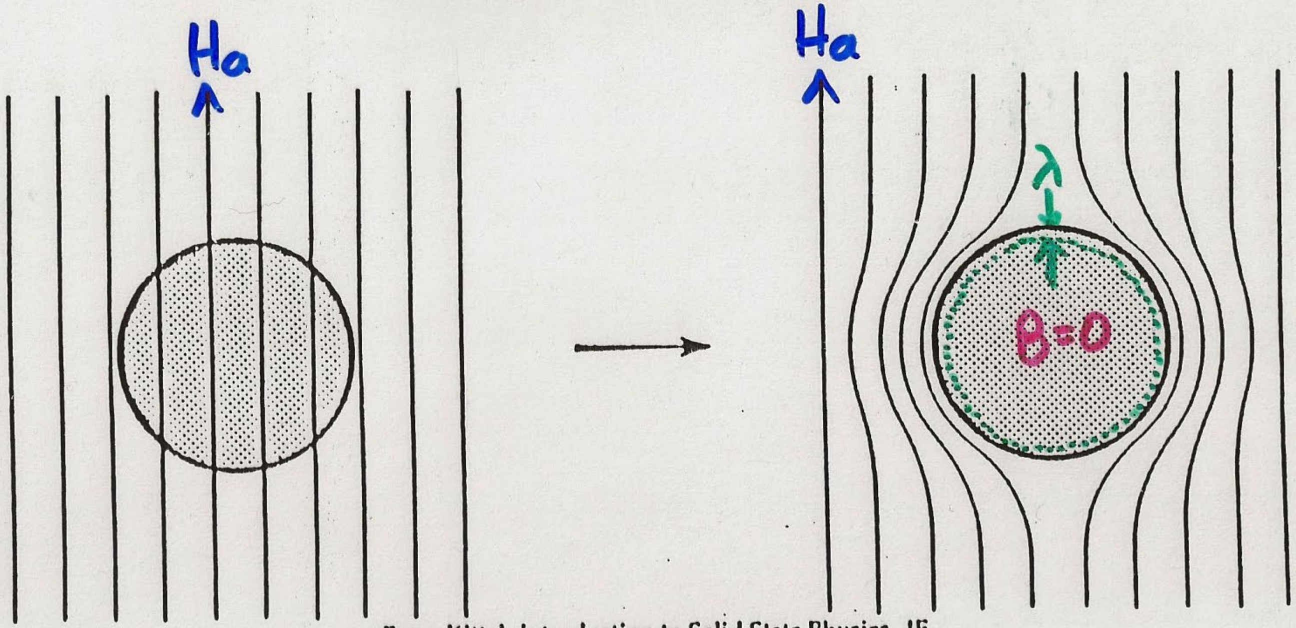
Superfluid ^4He -> Bose-Einstein condensate: $T_c \sim 2$ K

Superfluid ^3He -> S = 1 pairs, p-wave superfluid: $T_c \sim 10^{-3}$ K

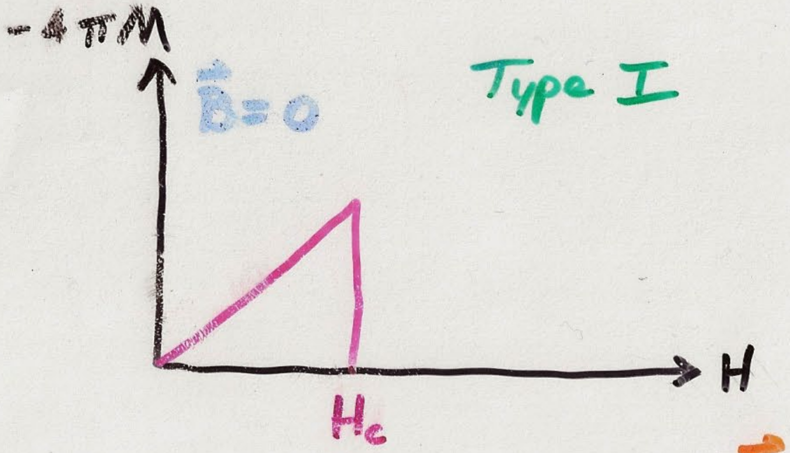
The Three Hallmarks of Superconductivity

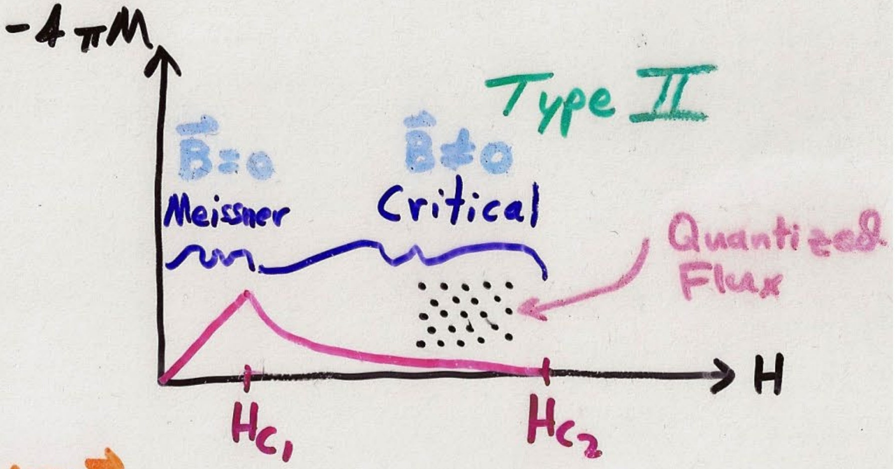
1) Zero Resistance
2) Meissner Effect
3) Macroscopic Quantum Effects

Meissner Effect



From Kittel: Introduction to Solid State Physics, 4E



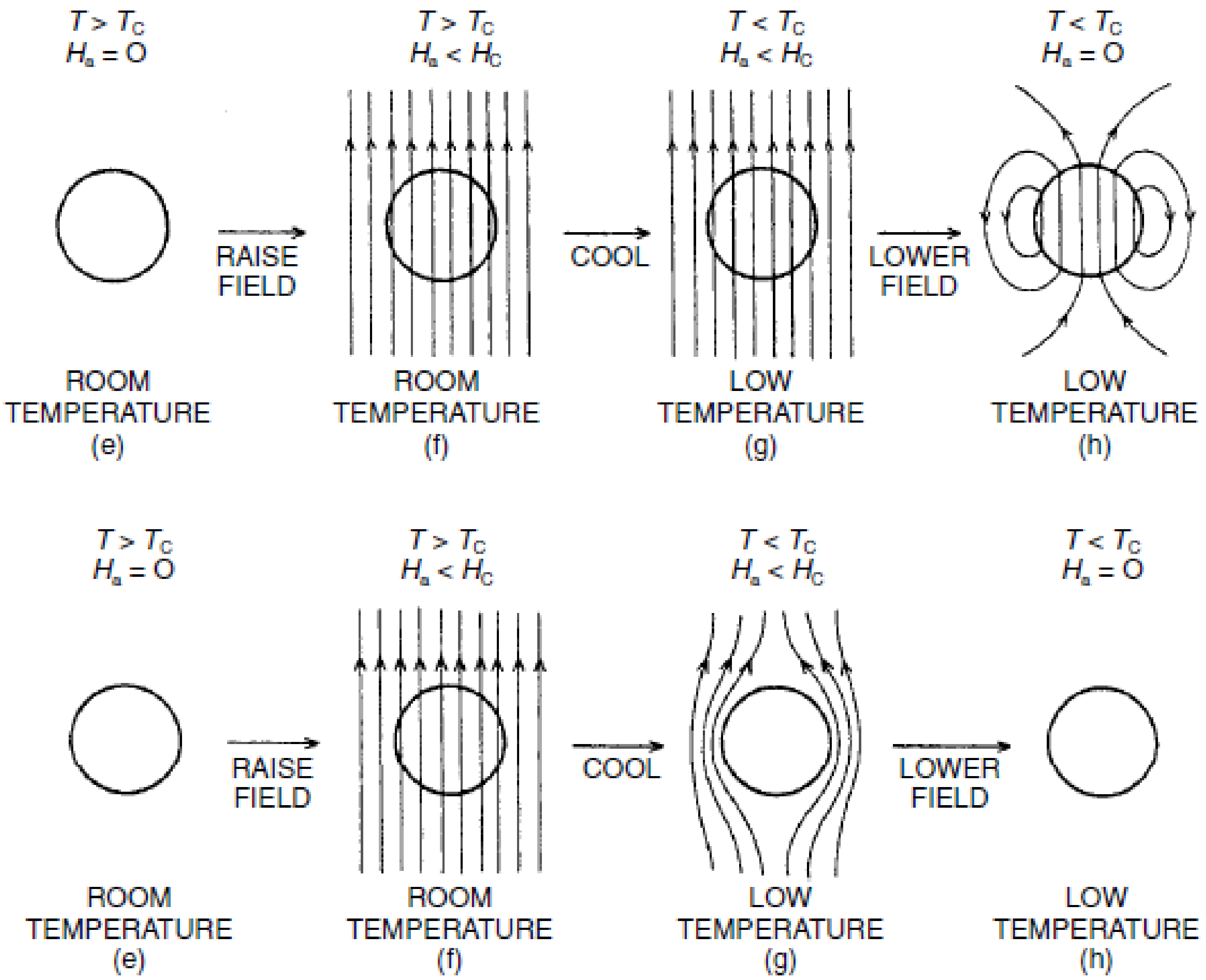


$$\vec{B} = \vec{H} + 4\pi\vec{M}$$

Perfect Conductor vs. Superconductor

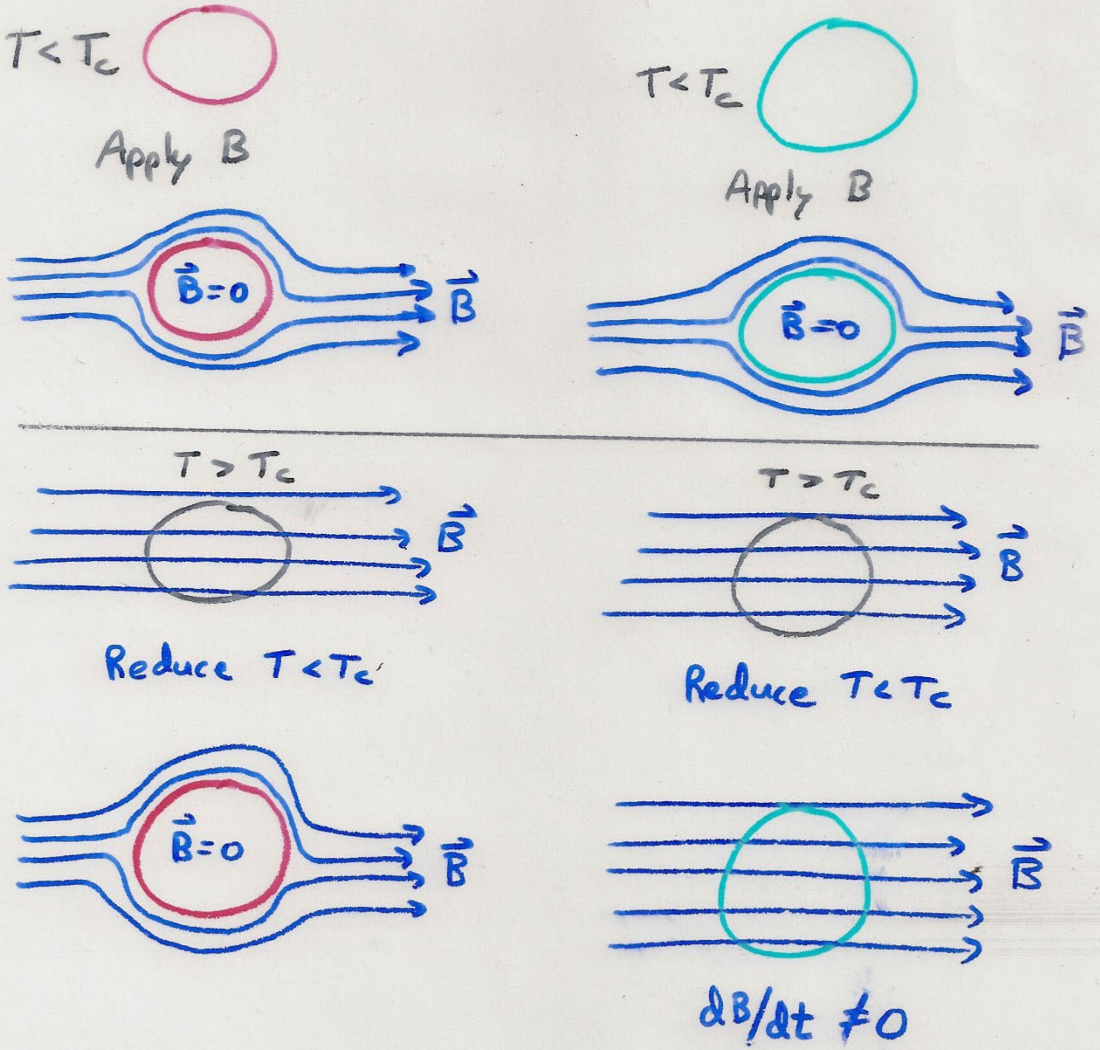
Perfect Conductor

Super-Conductor

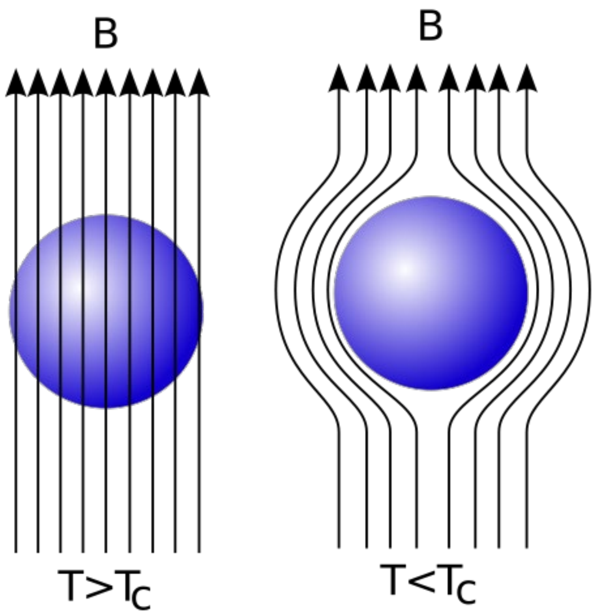


Zero Resistance and Perfect Diamagnetism

Superconductor vs Perfect Conductor



Meissner Effect (1934)

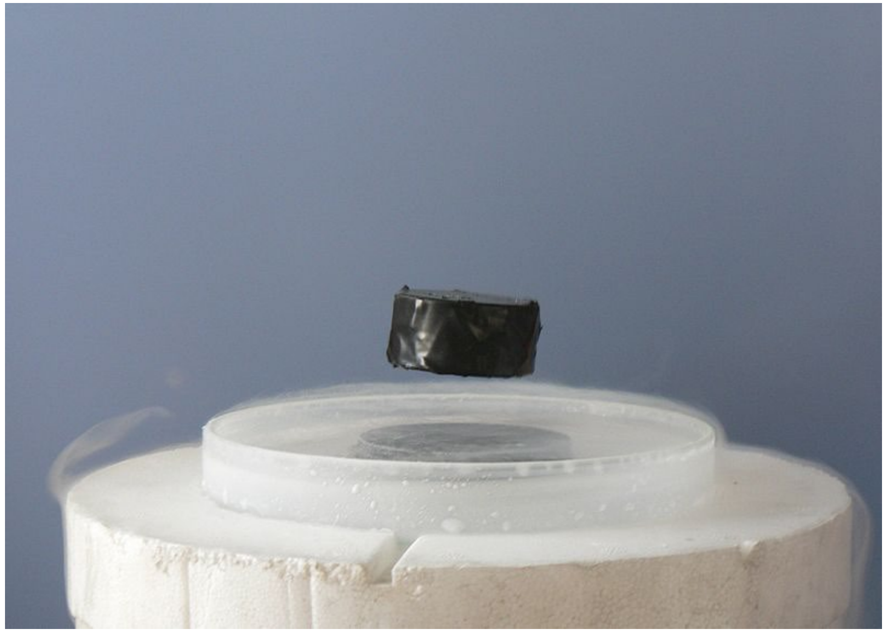


magnetic field
expelled from inside
a superconductor

"diamagnetism"

Superconductivity is more than just a state with zero resistance

$B = 0$



The Three Hallmarks of Superconductivity

1) Zero Resistance
2) Meissner Effect
3) Macroscopic Quantum Effects

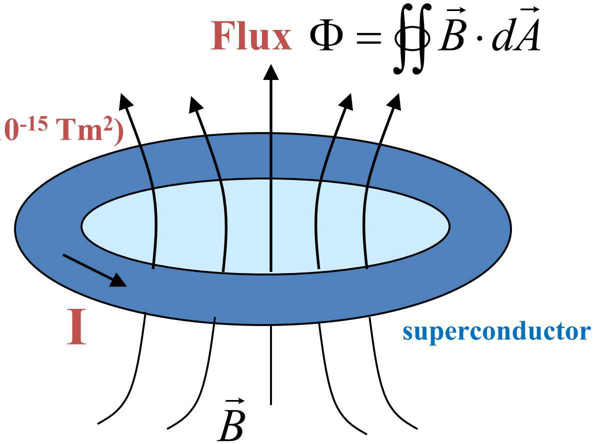
Macroscopic Quantum Effects

Superconductor is described by a single-valued Macroscopic Quantum Wavefunction $\Psi = |\Psi| e^{i\theta}$

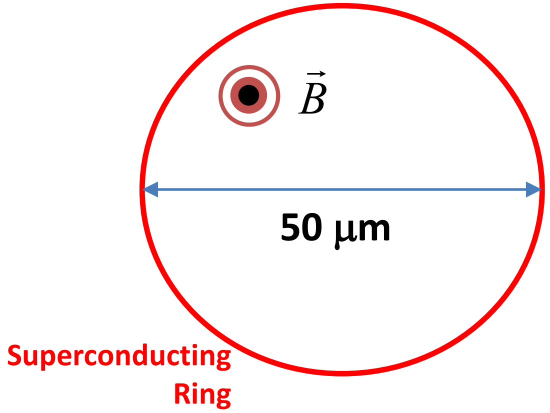
Consequence:

<u>Magnetic flux is quantized</u> in units of $\Phi_0 = h/2e$ (= 2.07 x 10^{-15} Tm^2)

$\Phi = n\,\Phi_0$, n = integer



Example of Flux Quantization

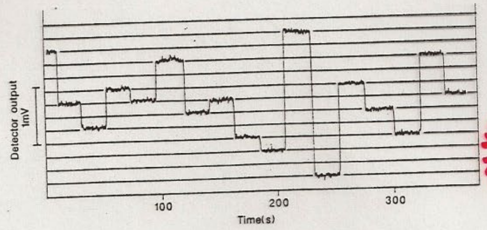


One flux quantum in this loop requires a field of B = Φ_0/Area = 1 μT

Earth's magnetic field B_{earth} ~ 50 μT

Flux Quantization in a High-T_c SC

C. E. Gough, et al. Nature <u>326</u>, 855 (1987).

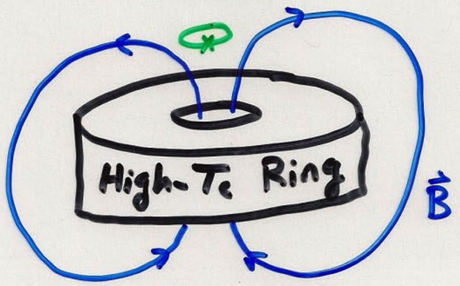


$$\updownarrow \Phi_0 = \frac{h}{2e}$$

Fig. 2 Output of the r.f.-SQUID magnetometer showing small integral numbers of flux quanta jumping in and out of the ring.

$YBa_2Cu_3O_7$
ceramic

4.2 K



Experimental value for the flux quantum

$$\Phi_0 = 0.97 \pm 0.04 \ \frac{h}{2e}$$

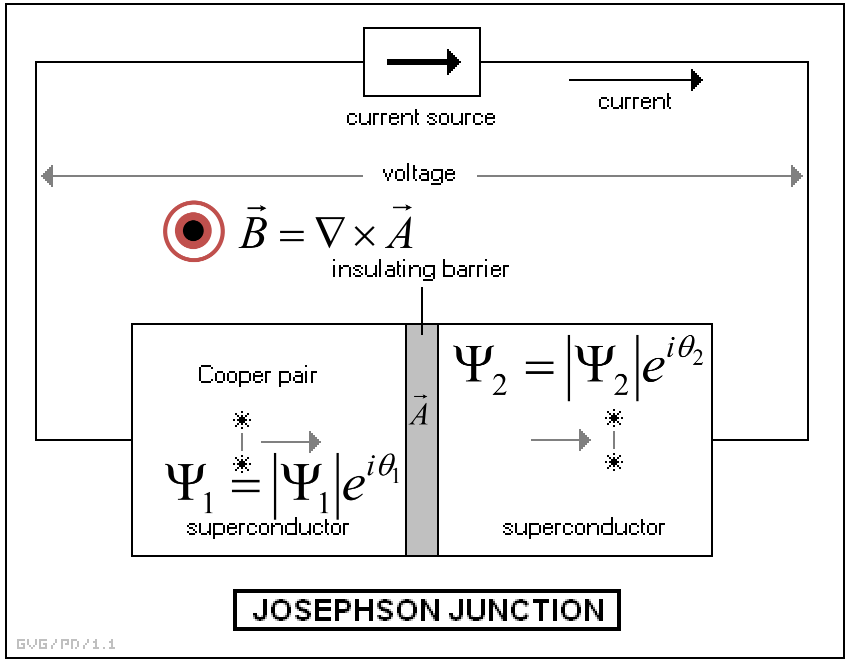
SQUID magnetometer output stable for 1000 s

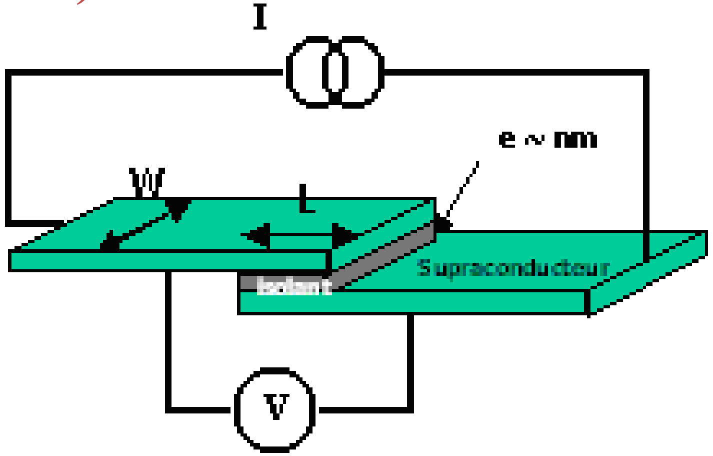
$$\Rightarrow R_{ring} < 10^{-13} \Omega$$

Macroscopic Quantum Effects

Continued

Josephson Effects (Tunneling of Cooper Pairs)





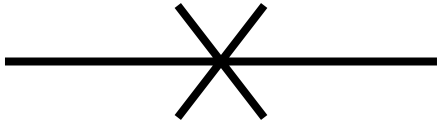
$$I = I_c \sin(\delta) \quad \textbf{DC}$$

$$\frac{d\delta}{dt} = \frac{2e}{\hbar} V \quad \textbf{AC}$$

$$\delta = \theta_1 - \theta_2 - \frac{2e}{\hbar} \int_1^2 \vec{A} \bullet d\vec{l}$$

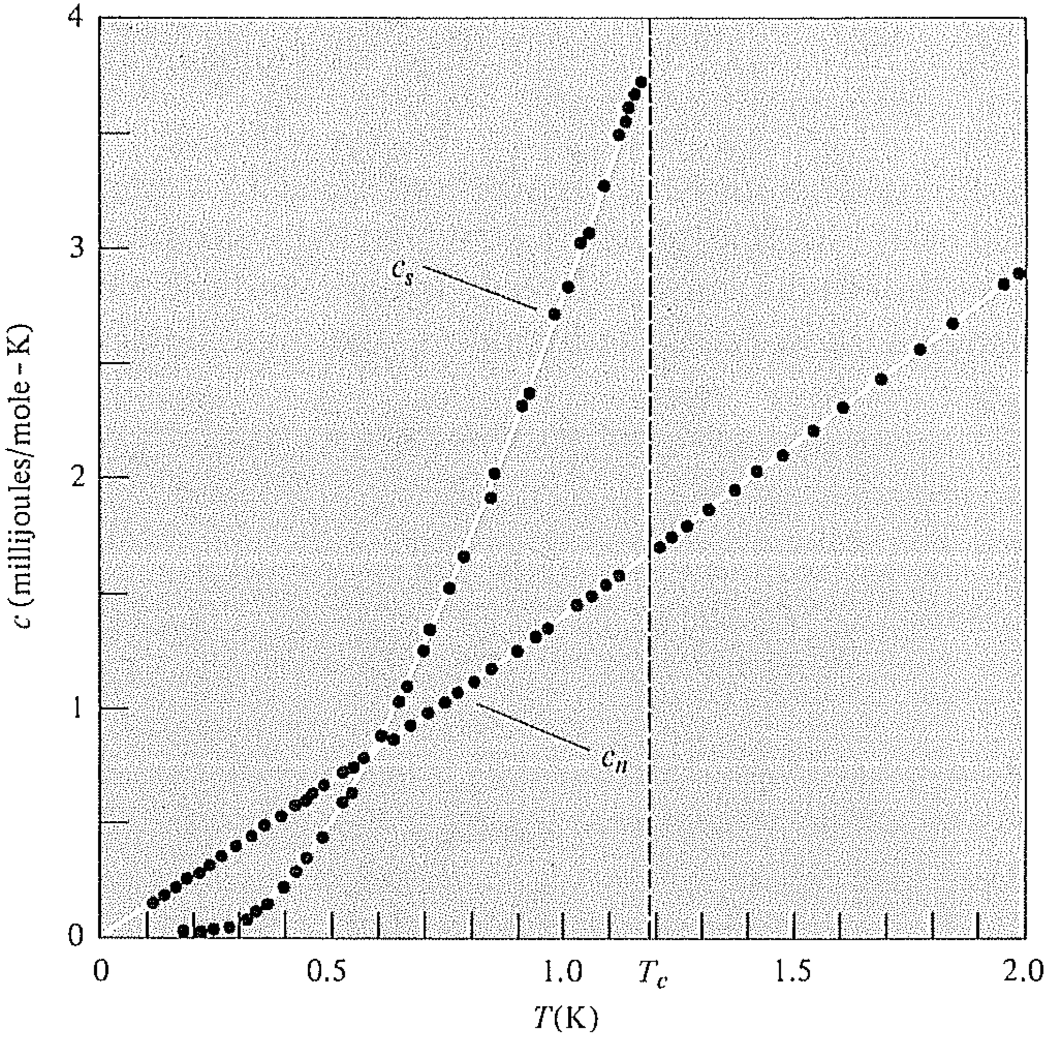
Gauge-invariant phase difference

$\delta(t)$ is the solution of a nonlinear diff. Eq.

Circuit representation of a JJ 

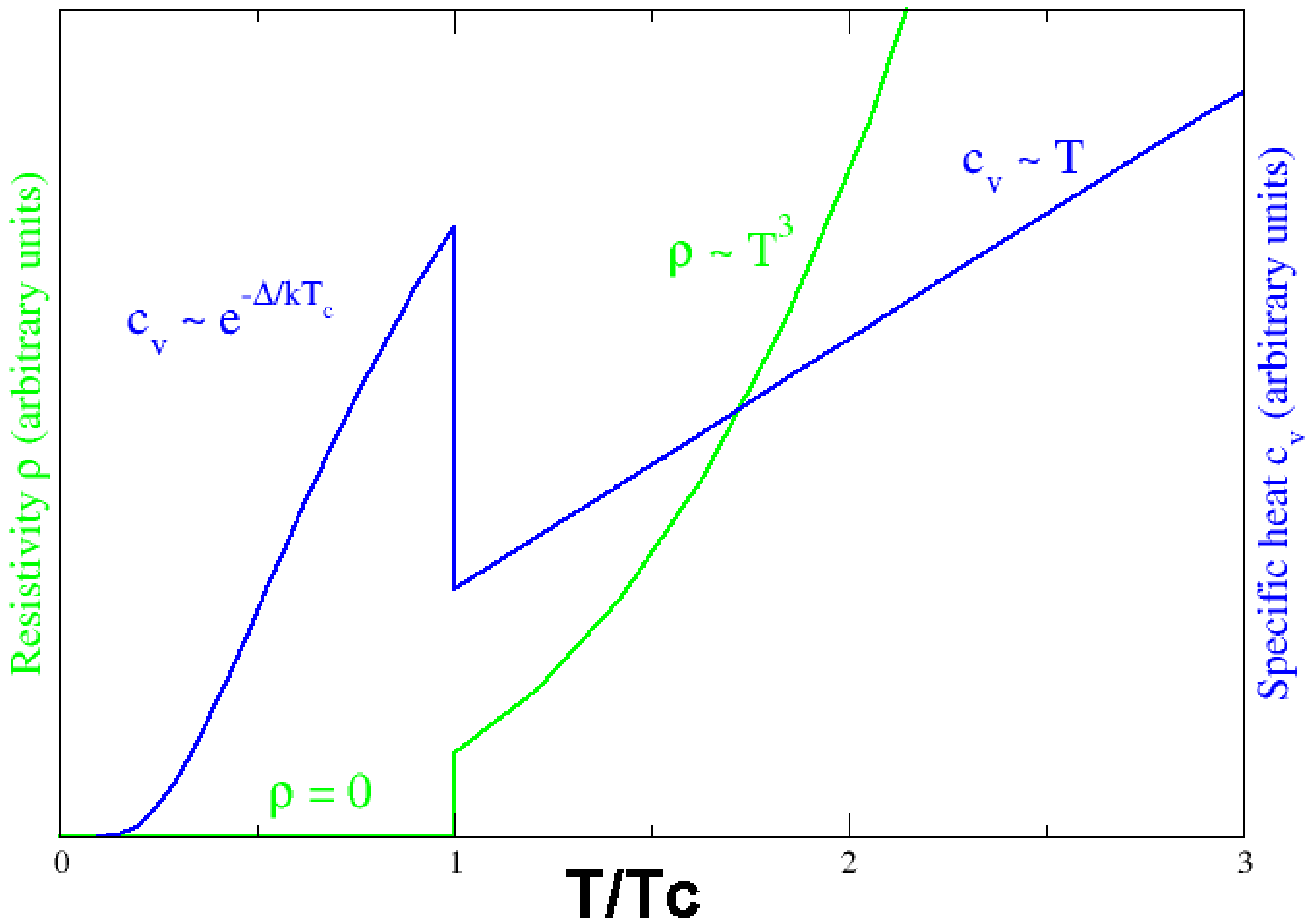
The Thermodynamics of Superconductors

Low Temperature Specific Heat of Aluminum



Low-temperature specific heat of normal and superconducting aluminum. The normal phase is produced below T_c by application of a weak (300-gauss) magnetic field, which destroys the superconducting ordering but has otherwise negligible effect on the specific heat. The Debye temperature is quite high in aluminum, so the specific heat is dominated by the electronic contribution throughout this temperature range (as can be seen from the fact that the normal-state curve is quite close to being linear). The discontinuity at T_c agrees well with the theoretical prediction (34.22) $[c_s - c_n]/c_n = 1.43$. Well below T_c, c_s drops far below c_n, suggesting the existence of an energy gap. (N. E. Phillips, *Phys. Rev.* **114**, 676 (1959).)

Ashcroft and Mermin, p. 734



http://en.wikipedia.org/wiki/Superconductivity

MEASURED VALUES OF THE RATIO[a] $[(c_s - c_n)/c_n]_{T_c}$

ELEMENT	$\left[\frac{c_s - c_n}{c_n}\right]_{T_c}$
Al	1.4
Cd	1.4
Ga	1.4
Hg	2.4
In	1.7
La (HCP)	1.5
Nb	1.9
Pb	2.7
Sn	1.6
Ta	1.6
Tl	1.5
V	1.5
Zn	1.3

[a] The simple BCS prediction is $[(c_s - c_n)/c_n]_{T_c} = 1.43$.

Source: R. Mersevey and B. B. Schwartz, *Superconductivity*, R. D. Parks, ed., Dekker, New York, 1969.

The 'Universal' Heat Capacity Jump at T_c

The prediction holds for weak-coupled SCs

Ashcroft and Mermin, p. 747

Electronic Entropy of Normal Metal and Superconductor

Obtain S from integrating C_V over T

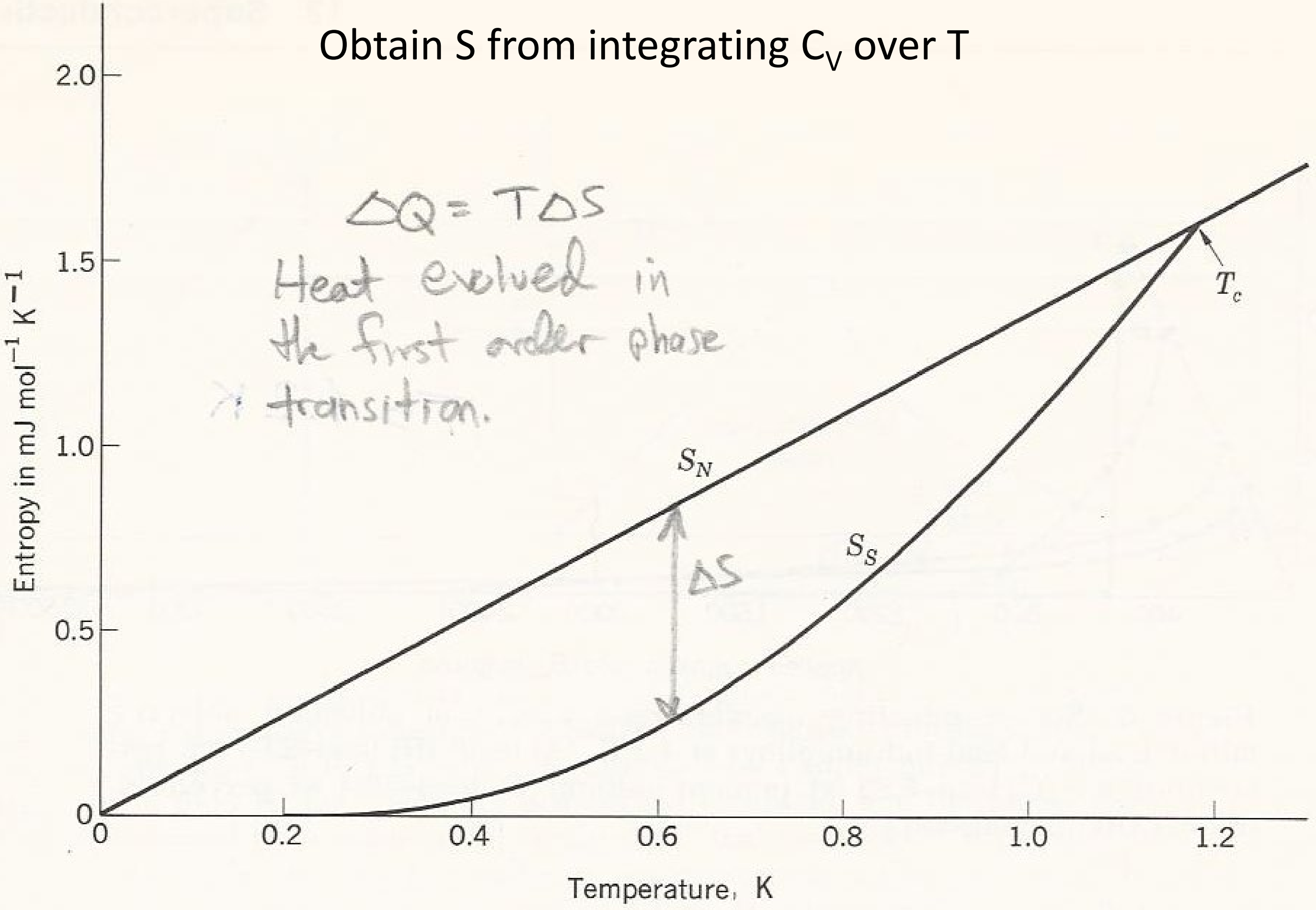


Figure 7a Entropy S of aluminum in the normal and superconducting states as a function of the temperature. The entropy is lower in the superconducting state because the electrons are more ordered here than in the normal state. At any temperature below the critical temperature T_c the specimen can be put in the normal state by application of a magnetic field stronger than the critical field.

C. Kittel, Solid Introduction to State Physics, 5th Edition, page 364.

Free Energy of Normal Metal and Superconductor

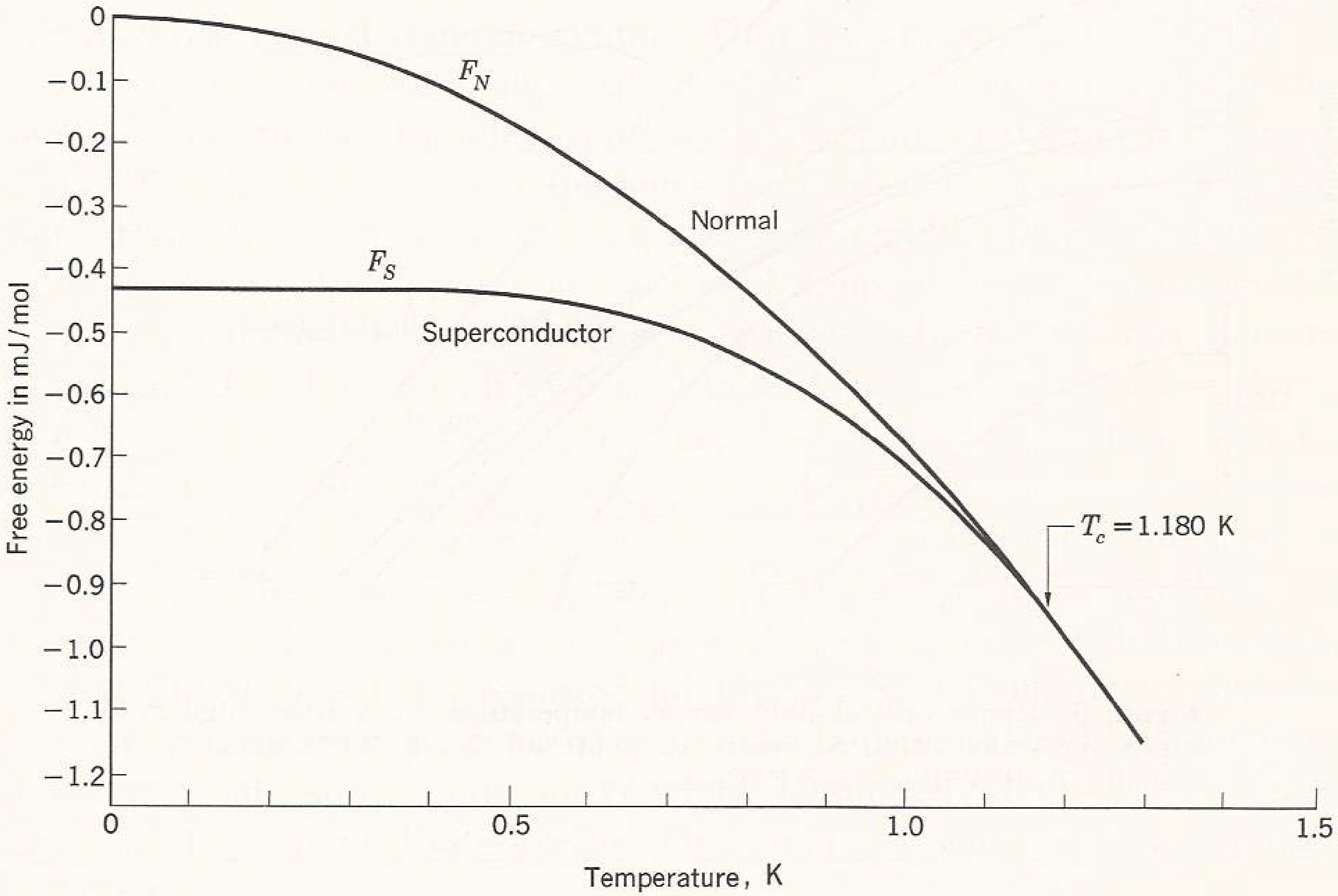
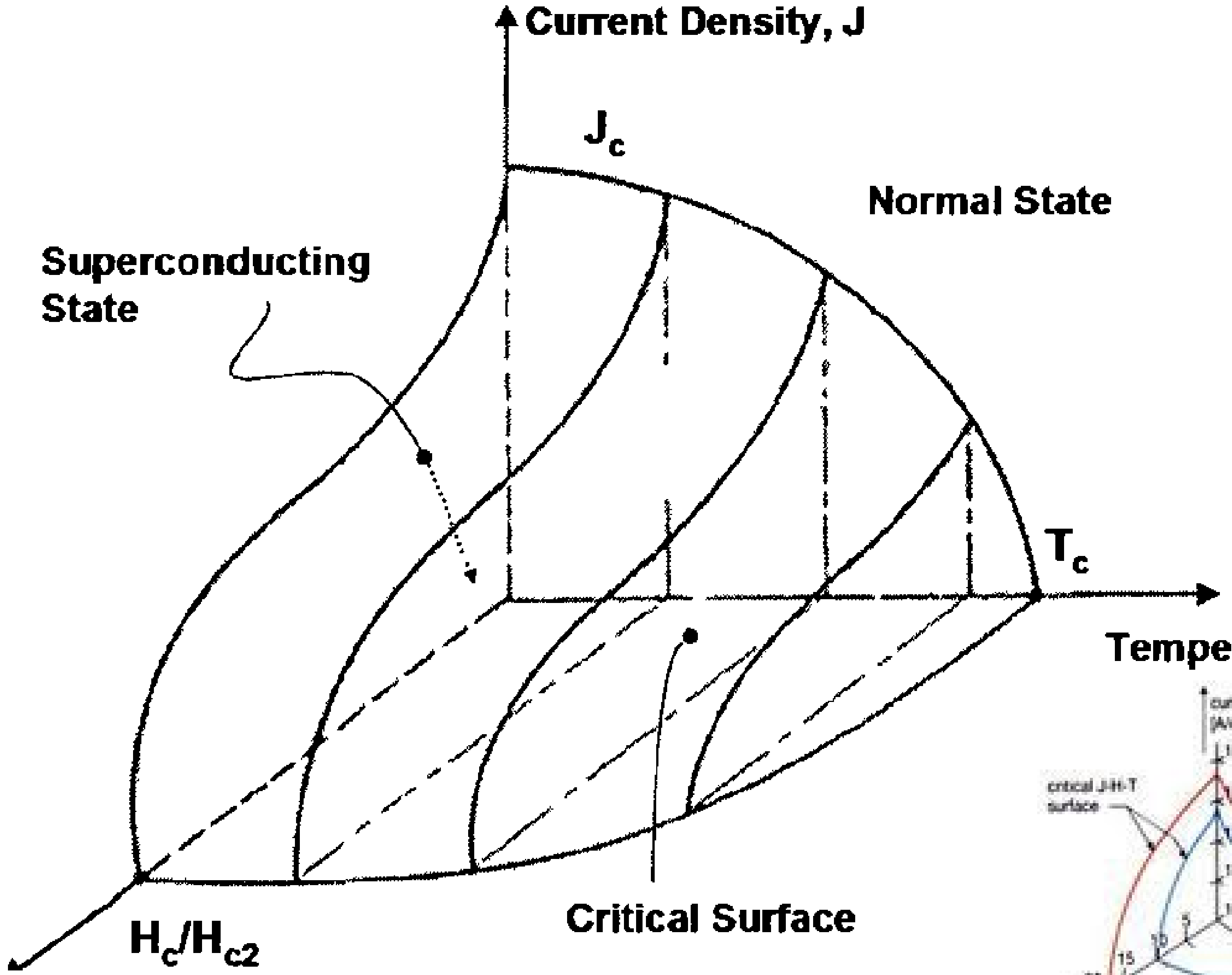
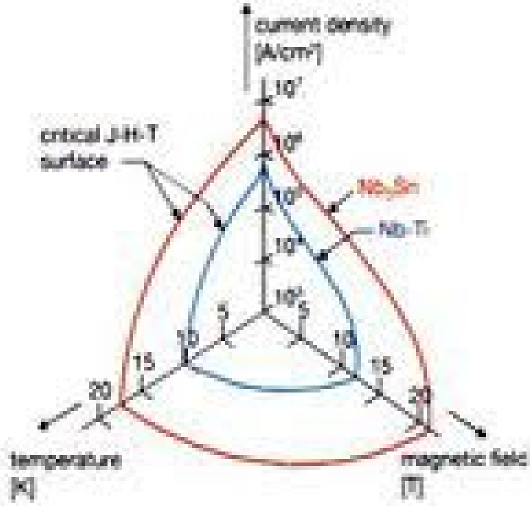


Figure 7b Experimental values of the free energy as a function of temperature for aluminum in the superconducting state and in the normal state. Below the transition temperature $T_c = 1.180$ K the free energy is lower in the superconducting state. The two curves merge at the transition temperature, so that the phase transition is second order (there is no latent heat of transition at T_c). The curve F_S is measured in zero magnetic field, and F_N is measured in a magnetic field sufficient to put the specimen in the normal state. (Courtesy of N. E. Phillips.)

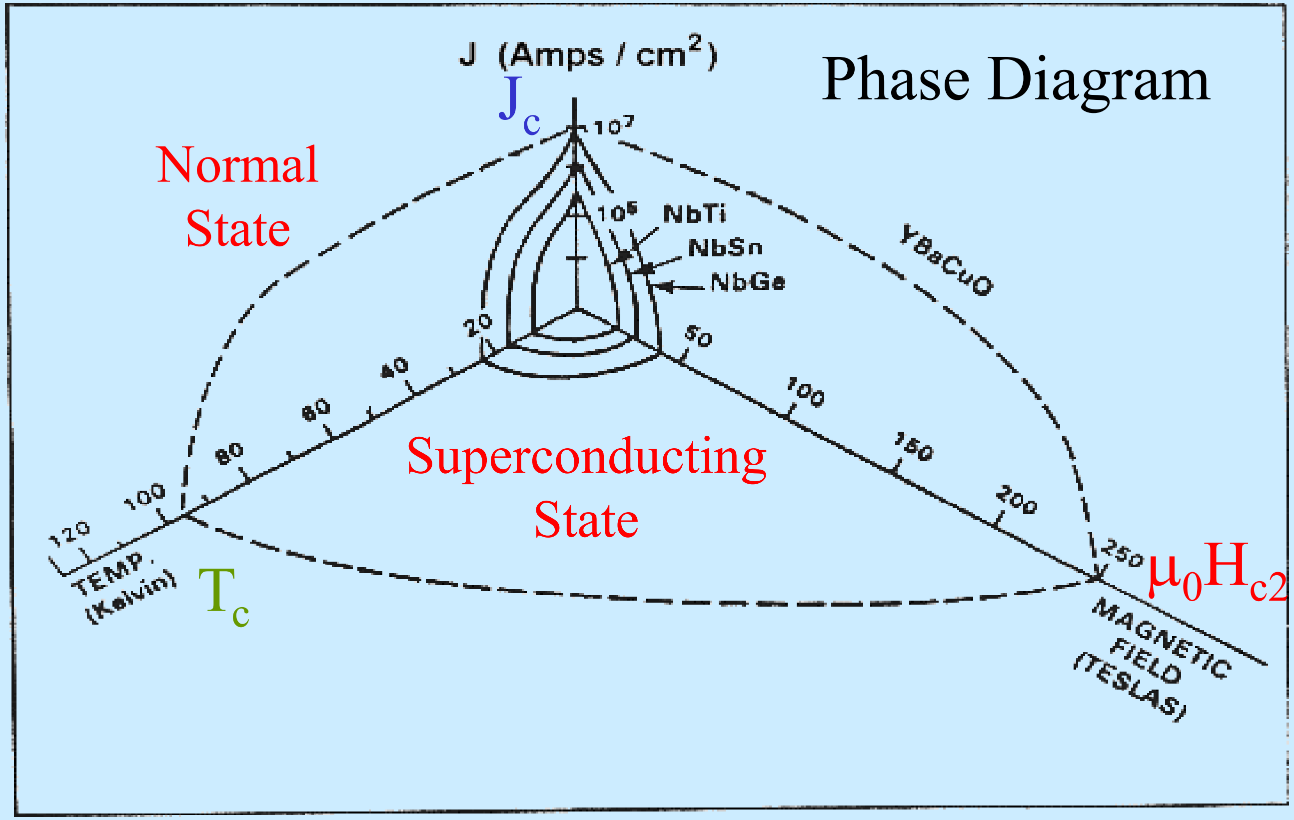
C. Kittel, Solid Introduction to State Physics, 5th Edition, page 364.

The Limits
of Superconductivity


Current Density, J
J_c
Normal State
Superconducting State
T_c
Temperature, T
Critical Surface
H_c/H_{c2}


current density [A/cm²]
critical J-H-T surface
Nb_3Sn
Nb-Ti
temperature [K]
magnetic field [T]

What are the Limits of Superconductivity?



UNIVERSITY OF MARYLAND

History of Superconductivity and Superconductor Devices

1911	Discovery H. Kamerlingh Onnes (Leiden)	$R = 0$	ERA of discovery
1933	Meissner effect (Ochsenfeld)	$B = 0$	
1950	Ginzburg-Landau theory		
1957	BCS theory (UIUC)		
1960's	Push for higher Tc (failed)		ERA of devices
1960	Giaever tunneling (GE)		
1962	Josephson effect	"Superconductivity is a solved problem"	
1964	dc SQUID (Mercereau)		
1970	rf SQUID (Zimmerman)		
1970's	Applications of SQUID's		
1980's	New materials		ERA of new materials and unconventional superconductivity
1985	Heavy Fermion SC's		
1986	HTSC (Bednorz and Müller – IBM Zürich)		
1990's	Symmetry/Mechanism/Applications of HTSC		
2000's	Superconducting qubits		ERA of quantum information
2010's	Topological materials and devices		
2020's	Quantum Information Science and Quantum Computing?		

The HISTORY of SUPERCONDUCTIVITY and SUPERCONDUCTOR DEVICES (1911-1940)

1900-1910

The Birth of Cryogenics

The field of low temperature physics was initiated with the development of equipment and techniques that enabled the liquefaction of hydrogen and helium.

1898 Liquefaction of Hydrogen

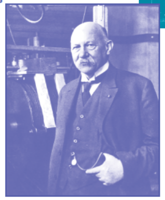
James Dewar at the Royal Institute in London produced liquid hydrogen by Joule-Thomson expansion and measured its temperature to be 20K. A year later he formed solid hydrogen at 12K.

1. James Dewar. Photo courtesy of the AIP Niels Bohr Library and the W. F. Meggers Collection.

1908 Liquefaction of Helium

Heike Kamerlingh-Onnes at Leiden first liquefied helium on July 10, 1908, and determined its temperature to be 4.2K. This achievement marked the onset of cryogenic research. Kamerlingh-Onnes was disappointed that he was unable to solidify helium by pumping on the vapor, but he was able to reduce its temperature to close to 1K.

2. The first helium liquefier in Kamerlingh-Onnes' laboratory in Leiden. Heike Kamerlingh-Onnes (left) and Master Technician G. J. Flim (right), who built the apparatus. Photo courtesy Deutsches Museum, Munich.



3. Heike Kamerlingh-Onnes and the first helium liquefier. Photo courtesy of the AIP Niels Bohr Library and the Burndy Library.

10

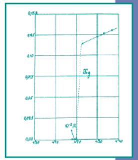
1910-1920

The Discovery of Superconductivity

The age of superconductivity began with the observation of a precipitous drop to zero in the electrical resistance of mercury metal at low temperatures. Within the first decade, many of the most important distinguishing characteristics of the superconducting state were identified.

1911 Discovery of Superconductivity

While measuring the temperature dependence of pure metals at low temperatures, Heike Kamerlingh-Onnes and Gilles Holst observed a sharp reduction in the resistance of Hg at 4.2K. This phenomenon was first reported to the Amsterdam Academy on April 28, 1911, and published in a communication in which it is stated that "a pure metal can be brought to such a condition that its electrical resistivity becomes zero, or at least differs inappreciably from that value" [Akademie der Wetenschappen 13, 1274 (1911)]. This marked the discovery of superconductivity and established the single most important property of a superconducting material, the critical temperature.



4. The resistivity of mercury vanishes at the superconducting transition temperature of 4.2 K (Kamerlingh-Onnes, 1912).

1911 First of Many Superconductivity Conferences

Kamerlingh-Onnes first presented his results on superconductivity in Hg at the First Solvay Congress in the Hotel Metropole in Brussels on November, 2, 1911. The report attracted little attention at the time.

5. Participants in the first Solvay conference, 1911. Standing(left to right) Goldschmidt, Planck, Rubens, Sommerfeld, Lindemann, de Broglie, Knudsen, Hasenoehrl, Hostelet, Herzen, Jeans, Rutherford, Kamerlingh-Onnes, Einstein, Langevin. Seated (left to right): Nernst, Brillioun, Solvay, Lorentz, Warburg, Perrin, Wien, Mme Curie, Poincare. Photo courtesy of the Niels Bohr Photo Archives.

1913 Nobel Prize in Physics

Awarded to Heike Kamerlingh-Onnes "for his investigations on the properties of matter at low temperatures which led, *inter alia* to the production of liquid helium."

1913 Observation of the Critical Current and Critical Magnetic Field

Superconductivity was found to be destroyed by electrical currents or magnetic fields exceeding a threshold value (Kamerlingh-Onnes).

1914 Observation of the Persistent Current in a Superconducting Coil

First observation of stable circulating supercurrents in a closed superconducting loop (Kamerlingh-Onnes).

20

1920-1930

More Materials, More Phenomena

The second decade of superconductivity saw the observation of superconductivity in new materials, including the first alloys, and the first indications of unusual magnetic behavior.

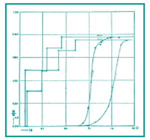
1920 First Test of the Isotope Effect

Heike Kamerlingh-Onnes found no resolvable difference in the superconducting transition temperature of Pb^{207} compared to Pb^{206}. A null result, but significant in light of the eventual importance of the isotope effect in the determination of the mechanism.

1925 Concept of the Penetration Depth

By balancing the kinetic energy of the screening currents and magnetic field energy of a superconductor in an applied field, G. L. de Haas-Lorentz, the wife of Wander J. de Haas and daughter of Hendrik Antoon Lorentz, proposed that the currents flow within a surface layer that later became known as the London penetration depth. This idea went relatively unnoticed because it was published in the then obscure Dutch journal *Physica*, which later evolved into one of the preeminent journals for superconductivity research.

1925 Observation of Magnetic Hysteresis



Wander J. de Haas found that the resistive transition in an applied field was observed to be irreversible and demonstrate sharp jumps. Experiments eliminated magnetic impurities and crystal structure changes as the origin of this effect, but the observation remained unexplained for many years.

6. Hysteresis and discontinuities in magnetic transition curves for mercury. (de Haas, Sizoo, and Kamerlingh-Onnes, 1926).

1928 Superconductivity in Binary Compounds

Superconductivity was initially studied only in elements, except for some preliminary observations in Hg-Sn alloys. The late twenties showed a burst of discoveries and studies of binary alloy superconductors at Leiden, including Ag_3Sn, Cu_3Sn, Bi_5Tl_3, and SbSn.

1928 Superconductivity in Tantalum (T_c = 4.4K)

The discovery of superconductivity in Ta at 4.4 K was significant because it marked the first superconductor discovered outside Leiden in the labs of Walther Meissner at the PTB in Berlin. It was also the first refractory superconducting material. This lab would go on the discover superconductivity in many transition metal compounds.

1930 Superconductivity in Niobium (T_c = 9.2K)

Walther Meissner found that niobium is superconducting, with the highest transition temperature of any element at 9.2 K. It remains the most important superconductor for device applications.

30

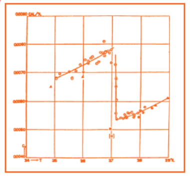
1930-1940

The Discovery of the Meissner Effect

The phenomenon of superconductivity was found to be even more remarkable with the discovery of the Meissner effect, the exclusion of magnetic field from the bulk of a superconducting sample. Following this discovery, the decade was dominated by the formulation and testing of electrodynamic models for superconductivity.

1932 Observation of Specific Heat Jump

A jump in the specific heat of Sn at the superconducting transition was observed by Wilhelm Keesom and Johannes Kok (Leiden). These investigators showed that a latent heat is only present in finite magnetic field.

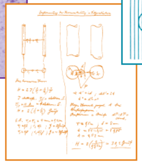


7. Specific heat discontinuity of tin at the superconducting transition. The measurements are for zero background field, except for the point marked with a square, which was accidentally obtained with a field larger than H_c. (Keesom and Kok 1932).

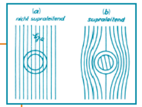
1933 Discovery of the Meissner Effect

Walther Meissner and Robert Ochsenfeld (Berlin) demonstrated that superconductivity is a state of perfect diamagnetism in which the magnetic field is zero inside a superconductor. They suggested that the field was expelled from the bulk by spontaneous supercurrents on the surface. This work indicated that the superconducting state is distinctly different from simply a state of perfect conductivity.

8. Walther Meissner. Photo courtesy of the Emilio Segre Visual Archives.



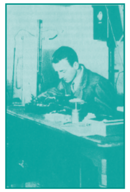
9. Notebook sketches in Meissner's hand. Courtesy of the Deutsches Museum, Munich.



10. Magnetic field lines penetrate the non-superconducting, hollow lead tube (left) and are excluded by the superconducting tube (right). (Meissner, Ochsenfeld, and Heidenreich, 1934)

1933 Two-Fluid Model

Cornelius Gorter and Hendrik B. G. Casimir (Leiden) proposed a two-fluid model that describes the superconductor as a temperature-dependent mixture of normal electrons and superelectrons. This picture was remarkably successful at characterizing thermodynamic properties and has similarities to the microscopic BCS state that would only emerge over 20 years later. It also predated the two-fluid model of superfluid helium.

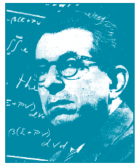


11. Cornelius Gorter. Photo courtesy of Physica.

12. Hendrik B. G. Casimir. Photo courtesy of Physica.

1934 London Electrodynamic Theory

A comprehensive model for the electrodynamics of the superconducting state, still in wide use today, was developed by brothers Fritz and Heinz London (Oxford). The pair of London equations proposed describe the temporal and spatial variation of the supercurrent. This model introduced the concept of the rigidity of the superconducting wavefunction and defined the London penetration depth characterizing the screening of magnetic fields at the surface of a superconductor.

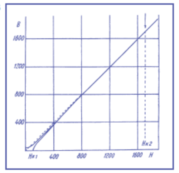


13. Fritz London, c. 1954. Courtesy Niels Bohr Photo Archive.

14. Heinz London. Courtesy Niels Bohr Photo Archive.

1935 Observation of Two Magnetic Fields

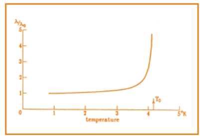
Magnetic moment measurements in $PbTl_2$ alloys by Rjabinin and Schubnikov showed evidence for two critical magnetic fields.



15. Magnetization curve for $PbTl_2$, showing two critical fields (Rjabinin and Schubnikov, 1935).

1940 Measurement of Penetration Depth

The first measurements of the temperature dependence of the penetration depth were made by David Shoenberg (Cambridge). These results demonstrated the divergence of the penetration depth at T_c, corresponding to the vanishing of the superfluid density.



16. The variation of the penetration depth with temperature (Shoenberg 1940).

40

The HISTORY of SUPERCONDUCTIVITY and SUPERCONDUCTOR DEVICES (1940-1970)

1940-1950

Clues to the Mechanism

While activity was greatly slowed during the war years, this decade saw the recognition of a few key experimental clues that would ultimately point the way to a theoretical understanding of the mechanism for superconductivity.

1941 Superconductivity in NbN (T_c =16 K)

This discovery, which came out of a program to study transition metal carbides and nitrides headed by Eduard Justi (Berlin), jumped the transition temperature to above 12K, accessible in pumped liquid hydrogen.

1946 Evidence for a Superconducting Energy Gap From Thermodynamic Measurements

John Daunt and Felix Mendelssohn (Oxford) showed that there is no Thomson heat in the superconducting state. They suggested that this implied the existence of an energy gap between the superconducting electrons and the normal electrons of approximately 10^{-4} eV.

1950 Discovery of the Isotope Effect

The observation that the transition temperature scales as the inverse square root of the nuclear mass in superconducting isotopes, first made by Charles Reynolds and Bernard Serin (Rutgers), and by Emmanuel Maxwell (NBS), gave a strong clue that phonons were involved in the mechanism for superconductivity.

1950 Prediction of Flux Quantization

Fritz London first pointed out that the magnetic flux in multiply-connected superconductor loops should be quantized, a significant phenomenon important for device applications of superconductivity. It would be over a decade before this would be verified. At about the same time, his famous book *Superfluids* appeared, elucidating the now familiar analogies between superconductivity and superfluidity.

1950 Attractive Phonon-Mediated Electron-Electron Interaction

The fundamental interaction responsible for superconductivity was identified with the proposal by Herbert Fröhlich (Liverpool) and John Bardeen (Illinois) that an indirect attractive interaction could arise between electrons. The attraction relies on the polarization of the ionic lattice by electrons, creating a positively charged region.

1950 Ginzburg-Landau Theory

A phenomenological theory of the superconducting state was developed by Vitaly Ginzburg and Lev Landau (Moscow). This model presented a series of equations based on minimizing the free energy of a superconductor that describe the spatial variation of the superconducting order parameter and the supercurrent density.

17

17. Lev Davidovich Landau (1908-1968). Photo courtesy Niels Bohr Library.

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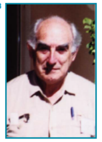
18. Vitaly Ginzburg in 1999. Photo courtesy D. van Harlingen.

40

1950-1960

Development of the Theory of Classical Superconductors

The major theoretical breakthroughs of classic superconductivity were made in this decade, beginning with the phenomenological Ginzburg-Landau theory in 1950 and culminating in the microscopic BCS theory in 1957. Important progress was also made in advancing the transition temperature and critical field of superconductors.

1952 Non-Local Electrodynamic Theory

To fit penetration depth measurements obtained from microwave resonance experiments, Brian Pippard (Cambridge) introduced a non-local relationship between the supercurrent density and the magnetic vector potential. This expression introduced the concept of the electromagnetic coherence length and correctly anticipated the result that would emerge from the microscopic theory later in the decade.

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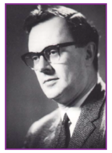
19. Brian Pippard.

1954 Superconductivity in the A-15s

In the early 50s, Bernd Matthias, J. Eugene Kunzler and John Hulm (Chicago) initiated a materials approach for the production of new superconductors based on a set of chemical rules. This would ultimately result in the discovery of many new superconductors, in particular the A-15s such as V_3Ge (T_c = 16 K), Nb_3Ge (T_c = 16 K), V_3Si (T_c=17.5 K), and the important magnet material Nb_3Sn (T_c = 18 K).

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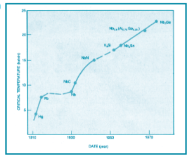
20. Superconducting critical temperatures as a function of time. The earliest materials were pure metals, found primarily in Kamerlingh-Onnes' laboratory. The materials of the next group are alloys with the B1 structure, and the most recently discovered have the A15 structure (Hulm, Kunzler, and Matthias 1981).

1956 Concept of Electron Pairing

The fundamental nature of the superconducting ground state was established by Leon Cooper (Illinois), who showed that the normal Fermi liquid is unstable to the formation of bound electron pairs in the presence of any attractive interaction.

1957 Microscopic Theory of Superconductivity

The landmark paper of John Bardeen, Leon Cooper, and John Schrieffer (Illinois) presented a comprehensive microscopic theory for superconductivity based on a pair wavefunction. This theory has been impressively successful at describing the thermodynamic, electrodynamic, and magnetic properties of classic superconductors. The BCS theory was quickly confirmed by observations of the Hebel-Slichter peak in the NMR relaxation rate and infrared absorption measurements by Michael Tinkham (Harvard) and Rolfe Glover (Stanford).

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21. John Bardeen, Leon Cooper, and Robert Schrieffer, who received the Nobel Prize in Physics in 1972 for their theory of superconducting pairing. Photo courtesy of Emilio Segre Visual Archives.

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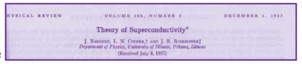
PHYSICAL REVIEW VOLUME 108, NUMBER 5 DECEMBER 1, 1957

Theory of Superconductivity*

J. Bardeen, L. N. Cooper,† and J. R. Schrieffer‡

Department of Physics, University of Illinois, Urbana, Illinois

(Received July 8, 1957)

22. The paper in which the BCS theory of superconductivity was first presented.

50

1957 Theory of the Mixed State

The field of vortex physics was launched with the predictions by Alexei Abrikosov of the mixed state characterized by the penetration of magnetic field in a periodic lattice of localized flux-quantized vortices. This phenomenon, caused by a negative normal state-superconducting state surface energy, distinguished Type I and Type II superconductors.

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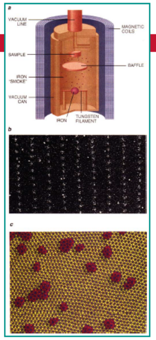

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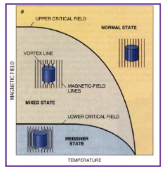

24. This magnetic phase diagram shows what happens when a Type II superconductor is immersed in a magnetic field. A conventional superconductor has three phases. In the Meissner state, the applied field is expelled. In the mixed or vortex state, the field penetrates in discrete bundles. In the normal state, the field destroys superconductivity and penetrates the material uniformly (from Bishop, Gammel, and Huse 1993).

23. a) Apparatus for Bitter decoration experiments. A "smoke" of magnetized iron particles is created at the bottom of the apparatus, and is deposited on the superconducting sample, preferentially near the vortices. van der Waals forces keep the iron particles in place after the sample has been warmed to room temperature for inspection. b) Flux chains imaged by the Bitter technique. Here the magnetic flux lines pass through the sample at an angle to the crystallographic axis. c) In a perfect triangular flux lattice, each flux line has six nearest neighbors. As shown in this computer digitized image, defects in the lattice appear as flux lines with different numbers of nearest neighbors. Here, the defects have been shaded red. (Bishop, Gammel, and Huse, Scientific American, 1993).

25

25. Alexei Abrikosov. Photo courtesy of Physica.

1958 Proximity Effect

The spreading of the pair condensate at the interface between a superconductor and a normal metal was discovered by Hans Meissner (Johns Hopkins) and studied in detail by Pierre-Gilles de Gennes and others.

1959 Unification of the Ginzburg-Landau and BCS Theories

Lev Gor'kov demonstrated that the phenomenological Ginzburg-Landau equations could be derived from a Green's function treatment of the microscopic BCS theory.

26

26. Lev Gor'kov in 1999.

1960-1970

Tunneling and the Josephson Effect

Two surprising discoveries, quasiparticle tunneling and the Josephson effect, marked the decade of the Sixties. These phenomena substantially broadened the scientific understanding and technological applicability of superconductors.

1960 Extending the BCS Theory

Important extensions to the BCS formulation of superconductivity were contributed by several Russian theorists, most notably the Eliashberg strong-coupling theory, the Bogoliubov self-consistent field method, and the Abrikosov-Gor'kov picture of pair-breaking by magnetic impurities.

1960 Quasiparticle Tunneling

The powerful tool of quasiparticle tunneling spectroscopy was born with the experiments of Ivar Giaever (General Electric), who demonstrated tunneling into superconductors. This technique allows probing of the quasiparticle density of states and the energy gap of superconductors.

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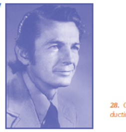
27. Ivar Giaever. Photo courtesy of the Nobel foundation.

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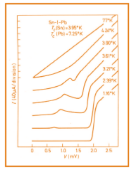

28. Current-voltage characteristic of a superconducting-insulator-superconducting tunnel junction.

1961 Experimental Verification of Flux Quantization

Quantization of the magnetic flux in a closed superconducting ring was verified by magnetization measurements by Bascom Deaver and William Fairbanks (Stanford).

1962 First Commercial NbTi Superconducting Wire

29


Improved methods for enhancing the pinning of vortices enables the production of multifilamentary NbTi, extending the range of superconducting magnets to above 10T. This technology revolutionized the high field magnet industry and impacted diverse fields, providing magnets for particle accelerators, NMR spectroscopy of biochemical structures, and magnetic resonance imaging (MRI) for medical diagnosis.

29. Martin Wood, founder of Oxford Instruments, tests a superconducting magnet. Photo courtesy of Oxford Instruments.

30

30. A high critical current density microstructure in a conventionally processed Nb-Ti superconducting wire. Figure courtesy of the Applied Superconductivity Center, University of Wisconsin.

1962 The Josephson Effect

The remarkable phenomenon of dissipationless pair tunneling was predicted by Brian Josephson, then a graduate student at Cambridge. Although Josephson supercurrents may have been previously seen in tunneling measurements and dismissed as shorts, the definitive confirmation of the dc effect was made by John Rowell and Philip W. Anderson at Bell Labs, who observed the magnetic field modulation of the supercurrent. The ac Josephson effect was confirmed by Sidney Shapiro, who observed steps in the current-voltage characteristics of a tunnel junction irradiated with microwaves. The phase-dependent Josephson supercurrent is the basis for many superconductor electronic devices.

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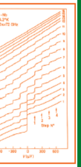
31. Steps in the current-voltage curves of a Josephson junction induced by applied microwave radiation.

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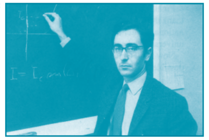
32. Brian Josephson, one of the recipients of the 1973 Novel Prize in Physics for his theoretical predictions of the properties of a supercurrent through a tunnel barrier. Photo courtesy of Physica.

60

1962 Observation of Quantum Interference

The interference of the phases of two Josephson junctions interrupting a superconducting loop was first demonstrated by Robert Jaklevic, John Lambe, Arnold Silver, and James Mercereau (Ford). This ultimately led to the development of the dc SQUID (Superconducting QUantum Interference Device), the most sensitive detector of magnetic fields and currents.

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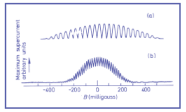

33. First observation of the critical current modulation of a two-junction interferometer in an applied magnetic field.

1962 Bean Critical State Model

Charles P. Bean introduced a description of the profiles of magnetic flux penetrating a superconducting sample in an applied magnetic field. This was followed by a theory for thermally-activated flux creep in such systems by P. W. Anderson and Y.P. Kim.

1964 Andreev Reflection

A. F. Andreev first described the process in which an electron excitation is retroreflected as a hole excitation with the creation of a Cooper pair. This phenomena plays a significant role in charge transport in Josephson tunnel junctions and mesoscopic superconductor devices.

1965 Direct Evidence for the BCS Phonon Mechanism

The most definitive proof that the attractive phonon-mediated electron-electron interaction is responsible for classic BCS superconductivity was extracted from the electron-phonon coupling parameter $\alpha^2F(\omega)$ from tunneling data using the inversion procedure of Bill McMiillan and John Rowell (Bell Labs).

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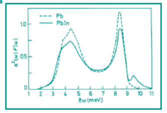


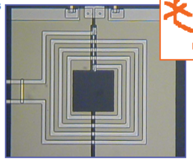
34. Phonon spectra obtained from tunneling data by the McMillan-Rowell inversion technique.

1965 Invention of the SQUID Voltmeter

The first practical superconducting device was the SQUID voltmeter developed by John Clarke (Cambridge). This instrument used a SLUG (Superconducting Low-inductance Undulating Galvanometer) in a potentiometric circuit to measure voltages as small as 10^{-14} volts, five orders of magnitude better than the semiconducting devices of the time.

36

36. Schematic of dc SQUID, showing two weak links. Figure courtesy of John Clarke.

35

35. Planar SQUID. Figure courtesy of John Clarke.

1967 Measurement of e/h using the ac Josephson Effect

Barry Taylor, William Parker, and Donald Langenberg (University of Pennsylvania) used voltage steps in a microwave-irradiated Josephson junction to determine the ratio of e/h to high precision. This phenomena would ultimately become the basis for the standard volt.

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The HISTORY of SUPERCONDUCTIVITY and SUPERCONDUCTOR DEVICES (1940-1970)

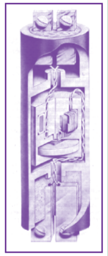
The Development of Superconductor Devices

The seventies saw the development of the most important applications of superconductivity, including superconductor electronic devices and high-field superconductor wires. During this decade, several new classes of materials were discovered that were precursors of breakthroughs on the horizon of superconductivity.

1970-1980

1970 Invention of the rf SQUID

The response of a superconducting loop containing a single Josephson junction, known (somewhat inappropriately) as an rf SQUID, was first used as a sensitive magnetic field detector by James Zimmerman and Arnold Silver (Ford).

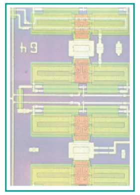


37. Toroidal rf SQUID developed by Biomagnetic Technology, Inc.

1970s Nonequilibrium Superconductivity

Throughout the decade, there was a concentrated effort to understand the behavior of superconductors driven out-of-equilibrium by fields or currents. Key phenomena studied included gap relaxation and enhancement, first observed by F. G. Wyatt and A. H. Dayem; charge imbalance, first observed by Michael Tinkham (Harvard) and John Clarke (Berkeley); and phase-slip centers, first observed by William Skocpol, Malcolm Beasley, and Michael Tinkham.

1970s Josephson Computer Program



IBM carried out extensive research to build a computer based on Josephson current-injection logic. Though moderately successful scientifically, the project was ultimately cancelled due to marketing issues and competition with silicon technology.

38. Josephson junctions serve as the basic circuit elements in a superconducting computer, and are shown here. A Josephson junction consists of two superconductors separated by a thin insulating layer; here the junctions lie under the four small circles visible in each brown region. (Matisoo 1980).

1972 Nobel Prize in Physics

Awarded to John Bardeen, Leon Cooper, and Robert Schrieffer "for their jointly developed theory of superconductivity, usually called the BCS-theory."

1973 Nobel Prize in Physics

Awarded to Leo Esaki and Ivar Giaever "for his experimental discoveries regarding tunneling phenomena in semiconductors and superconductors, respectively" and Brian Josephson "for his theoretical predictions of the properties of a supercurrent through a tunnel barrier, in particular those phenomena which are generally known as the Josephson effects."

1973 Superconductivity in Nb_3Ge (T_c = 23K)

This discovery by John Gavaler at Westinghouse marked the end of a period in which the superconducting transition temperature had been steadily pushed upwards. The superconducting transition temperature was to go no higher for over a decade.

1975 Superconductivity in BaPbBiO (T_c = 14K)

The first observation of superconductivity in an oxide by Arthur Sleight at Dupont. This interesting material did not have extraordinary properties or technological potential, but is a notable precursor to the high T_c copper oxide materials found one decade later.

1975 Use of SQUIDs for Neuromagnetism

The pioneering work of Samuel Williamson (NYU) began a still continuing quest to utilize SQUID detectors for the non-invasive imaging of magnetic signals from the brain. Clinical applications are emerging as detector arrays incorporating over 120 SQUIDs and sophisticated image analysis techniques are developed.

39. Array of SQUID magnetometers for neuromagnetic imaging (Neuromag, Ltd., Helsinki)

1979 SIS Quasiparticle Mixer

Advances in microfabrication and the development of a quantum theory by John Tucker (Aerospace) motivated the use of the sharp rise in the quasiparticle conduction as a mixer, an approach refined by Paul Richards and coworkers (Berkeley). SIS mixers remain the most sensitive detectors for submillimeter-wave radio astronomy.

40. Submillimeter radio telescope array of the Berkeley-Illinois-Stanford Association (BIMA) located at Hat Creek, California. This telescope utilizes Josephson junction SIS mixer detector elements. Photo courtesy of BIMA.

1979 Superconductivity in $CeCu_2Si_2$ (T_c = 0.6 K)

Several years after the discovery of the heavy fermion compounds, superconductivity was first observed in $CeCu_2Si_2$ by Frank Steglich (Darmstadt). This discovery was the first indication that superconductivity could arise from mechanisms other than the conventional BCS phonon-mediated interaction.

1979 Superconductivity in Charge Transfer Salts

The first organic superconductor was the one-dimensional conductor $(TMTSF)_2PF_6$, discovered by Denis Jerome (Orsay) and Klaus Bechgaard (Copenhagen).

The Discovery of High Temperature Superconductors

Superconductivity's most dramatic decade started with a lull in scientific activity engendered by the feeling that the field was mature and largely understood. At the same time, technological applications of superconducting materials and devices were expanding with notable advances in high field magnets for medical diagnosis and the development of Josephson junction and SQUID-based electronics. Halfway through this decade, the field exploded with the discovery of high temperature superconductors. Overshadowed but also significant have been the discoveries of other superconductor families, including the heavy fermion and organic superconductors.

1980-1990

1981 Observation of Macroscopic Quantum Tunneling in Josephson Junctions and SQUIDs

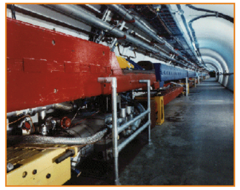
Driven by theoretical progress by Anthony Leggett (Illinois) and others, and by advances in the microfabrication of superconductor structures, Josephson effect devices emerged as the preeminent test system for observing macroscopic quantum phenomena (MQT). Experiments verified the existence of MQT and nucleated work toward the observation of macroscopic quantum coherence, a realization of the Schrodinger's cat paradox. This effort continues today.

1982 Magnetic Monopole Detection

The report of a possible observation of a magnetic monopole passing through a superconducting coil by Blas Cabrera (Stanford) nucleated a world-wide effort to search for monopoles with large and sophisticated SQUID detectors. This effort faded away by the end of the decade as no further events were detected.

1983 Design of the Superconducting Super Collider

Planning began for the design and construction of a particle accelerator that would utilize superconducting magnets on a scale never before envisaged.



41. Superconducting magnets in the main accelerator ring at Fermilab.

1983-1986 Superconductivity in Heavy Fermion Materials

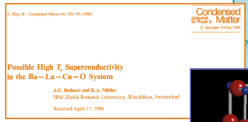
The family of heavy fermion superconductors grew with the discovery of superconductivity in UBe_{13} (T_c = 0.95 K), UPt_3 (T_c = 0.5 K), and URu_2Si_2 (T_c = 1.2 K). Evidence mounted for gaps with point and line nodes, and for a pairing mechanism of magnetic origin.

1984 -1990 Superconductivity in Organic Materials

The critical temperature of organic superconducting materials continued to rise with the synthesis of two-dimensional layered materials with the κ-$(ET)_2X$ structure, reaching a maximum of 13 K in κ-$(ET)_2Cu[N(CN)_2]Cl$.

1986 Discovery of Superconductivity in $La_{1.85}Ba_{0.15}CuO_4$ (T_c = 35 K)

Alex Müller and Georg Bednorz (IBM Zurich) observed superconductivity at 35K in a perovskite compound of La, Ba, and Cu in January 1986, although the results were not widely known until their publication in Zeitschrift der Physik in September. The phenomena was quickly confirmed in many laboratories. This discovery started the field of high temperature superconductivity and began the intense rush to find even higher transition temperature materials and to understand their properties that still continues today.



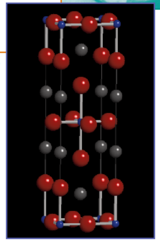
Condensed Matter

Possible High T_c Superconductivity in the Ba–La–Cu–O System

J.G. Bednorz and K.A. Müller

IBM Zürich Research Laboratory, Rüschlikon, Switzerland

Received April 17, 1986

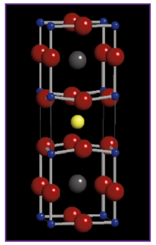


42. Alex Müller and Georg Bednorz on the day they learned they would share the 1987 Nobel Prize in Physics. Figure courtesy of Physica.

43. The paper in which the discovery of superconductivity in $La_{1.85}Ba_{0.15}CuO_4$ at 35 K was first announced.

44. Layered structure of $LaBaCuO_4$. Figure courtesy of C. Jones and J. McDevitt.

1987 Superconductivity in YBaCuO (T_c = 92 K)



Superconductivity was first observed at temperatures above 77K in a compound of Y, Ba, and Cu in January of this year. The structure was quickly determined to be the famous oxygen-deficient 1-2-3 compound $YBa_2Cu_3O_{7-x}$ which has become the most studied superconductor of all time.

45. Crystal structure of YBaCuO. Figure courtesy of C. Jones and J. McDevitt.

1987 Nobel Prize in Physics

Awarded to Johannes Georg Bednorz and Karl Alexander Müller "for their important breakthrough in the discovery of superconductivity in ceramic materials."

1987 Woodstock of Physics

A special session at the American Physical Society March Meeting in the New York Hilton was held on March 17, 1987. This event, which lasted through the night, attracted over 2000 scientists eager to hear the latest news on the high temperature superconductors.

46. Speakers at the special session on superconductivity. Photo courtesy of Physics Today.

47. Scientists pouring into the session. Photo courtesy of Physics Today.

1986 Superconductivity in BiSrCaCuO (T_c= 110 K)

The transition temperature was pushed into triple digits with the discovery of the Bi-based superconductors . The strong anisotropy of BSCCO has made it an attractive system for studying cuprate properties and vortex physics. BSSCO has also emerged as the choice for making superconducting wires, using powder in tube methods.

1988 Superconductivity in TlBaCaCuO (T_c=120 K)

The transition temperature continued to rise rapidly with the discovery of the thallium-based family of superconductors. The toxicity of Tl has somewhat limited the study of this material.

1989 Observation of Two Superconducting Phase Transitions in UPt_3

The widely suspected unconventional nature of the superconductivity of the heavy fermion compounds became apparent with the observation of two distinct peaks in the temperature dependent specific heat of UPt_3, indicating two different bulk superconducting phases.

1989 Singlet Pairing in the Cuprates

Definitive evidence that the superconducting state of the high temperature cuprates involved singlet pairing was provided by NMR Knight shift measurements. This limited the possible candidates for the search for pairing symmetry which was soon to begin.

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The HISTORY of SUPERCONDUCTIVITY and SUPERCONDUCTOR DEVICES (1990-2000)

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temperature super-

ession. Photo courtesy of

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was soon to begin.

1990-2000

Understanding High Temperature Superconductivity

The Nineties has focussed on mapping the properties of the high temperature superconductors, in particular on the unconventional d-wave symmetry in the superconducting state and the unusual behavior of the normal state. The proposal of a wide range of theoretical models and the emergence of experimental tests to distinguish them characterizes much of the current activity in this field. High T_c superconductor applications have developed much more slowly than was originally anticipated, but promising technologies begin to emerge by the end of the decade.

1990 Theories on the Table

The decade opened with intense debate over the possible mechanisms for superconductivity, with major candidates incorporating the t-J model, antiferromagnetic spin fluctuations, resonant valence bonds, spin bags, interlayer tunneling, excitonic superconductivity, and even phonons. Some of these, in particular the spin fluctuation mechanism, predicted d-wave symmetry in the cuprates, motivating experimental tests of the order parameter symmetry.

1991 Observation of Anisotropy and Nodes in the Energy Gap

Early work in the cuprates suggested that the energy gap was not fully formed. This has been demonstrated by a wide variety of thermodynamic, transport, and tunneling measurements. Of particular note are NMR measurements which first ruled out isotropic s-wave pairing; angle resolved photoemission measurements which map out the anisotropic magnitude of the energy gap; and low temperature penetration depth measurements, which showed a linear temperature dependence down to nearly 1 K in high quality single crystals of YBCO. These experiments were all strong evidence for nodes in the superconducting gap.

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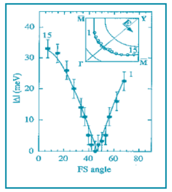

48. Angle resolved photoemission data showing nodes in the energy gap of the high temperature superconductor BiSrCaCuO. Figure courtesy of J. C. Campuzano.

1991 Superconductivity in Alkali-Doped Fullerenes

Superconductivity was discovered in K_3C_{60} at about 20 K, an fcc crystal composed of carbon buckyballs intercalated with alkali atoms. The maximum known T_c in these materials occurs at about 30K in the Rb-doped compound.

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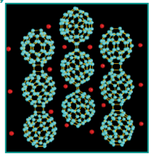

49. Polymeric fullerene chains in RbC_{60}. (Stephens, 1994.)

1993 Superconductivity in HgBaCaCuO (T_c = 133K)

The highest transition temperature material known to date is a compound containing Hg. Under pressure, the highest T_c observed is 165 K. It is ironic that Hg again plays a key role in the history of superconductivity.

52

52. A 1.5 T whole body MRI magnet being lowered through the roof of a hospital. Photo courtesy of Oxford Instruments.

1993 Verification of d-Wave Symmetry in Cuprates by Phase-Sensitive Tests

Motivated by theoretical predictions of d-wave symmetry, corner SQUID interferometer experiments show direct evidence for a phase shift of π between orthogonal directions in YBCO crystals. This result, now confirmed by many experiments and in many cuprates, has established their unconventional d-wave symmetry.

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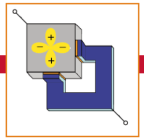


50. SQUID spanning corner of YBCO crystal, showing nodal structure of superconducting wave function deduced in experiment. Figure courtesy of Dale van Harlingen.

1994 Superconductivity in Sr_2RuO_4 (T_c = 1.3K)

Although synthesized since the 1950s, this material has only recently been found to be superconducting, and remains the only known superconducting layered perovskite which does not contain Cu. It has been suggested that the strong ferromagnetic fluctuations in this material could produce odd-symmetry p-wave pairing, and experimental results seem to support this scenario.

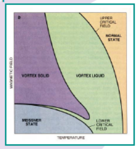
1995 Characterizing the Pseudogap

A wide variety of experiments have shown evidence for a reduction of the single-particle density of states in underdoped cuprates. NMR, ARPES, specific heat, transport, and tunneling measurements all indicate unusual normal state properties extending far above the superconducting transition. Theories attributing this phenomenon to such mechanisms as phase fluctuations, preformed pairs, and antiferromagnetic spin correlations have been proposed.

1996 Observation of Vortex Lattice Melting

Highlighting a decade of studying the vortex properties of the high temperature cuprates, researchers present the first definitive proof of a thermodynamic first-order transition from a solid-like vortex lattice to a vortex liquid. This work and that of many investigators has helped to elucidate the complex magnetic field vs. temperature phase diagram of the cuprates.

51



51. High temperature superconductors have all the phases found in the magnetic field-temperature phase diagram of normal superconductors (see 1957 entry on the mixed state), as well as a vortex liquid regime. This state exists because thermal fluctuations melt the vortex solid, which is a lattice in clean superconductors or a glass in dirty superconductors (from Bishop, Gammel, and Huse 1993).

1996 Observation of Striped Phases

Neutron scattering experiments indicate the presence of incommensurate spin and charge dynamic stripe ordering in HTSC compounds. Known to occur in other doped antiferromagnetic insulators such as the manganites, it is unclear yet what role if any these stripe phases play in the mechanism for superconductivity of the cuprates.

1999 Applications of High Temperature Superconductivity Expand

During this decade, encouraging progress has been made in the implementation of high temperature superconductors in passive microwave circuits such as cellular phone filters, SQUID detectors for geophysical surveying, medical imaging, and non-destructive testing, superconducting wires and tapes for power transmission, and high field magnets.

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53. High field magnets are required for magnetic levitation, proposed for used in high speed transit. Photo courtesy of the Japanese National Shinkansen Association.

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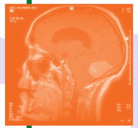

54. A magnetic resonance imaging (MRI) scan through the head showing a developing meningicoma. Figure courtesy of Siemens Medical.

90

2000

The Future of Superconductivity

As the millenium approaches, many major challenges exist that will make superconductivity a vibrant field well into the next century. Understanding the mechanism and developing a microscopic theory for the high temperature superconductors remains the highest priority. The real excitement, however, is the prospect of discovering new superconducting materials with even higher transition temperatures and more exotic symmetries. Primary unsolved problems include:

The Future

- Determining the mechanism and establishing a microscopic theory of high temperature superconductivity.
- Reconciling the interplay of magnetism and superconductivity in the cuprates, ruthenates, and heavy fermion superconductors.
- Assessing the impact of unconventional gap symmetry on the properties and technological applications of superconductors with strong magnitude and phase anisotropies.
- Understanding the anomalous normal state of the cuprates, encompassing such mysteries as the pseudogap, stripe phases, doping dependences, and in particular, the relationship between the normal state properties and the onset of superconductivity.
- Exploring the fragility of the d-wave order parameter at interfaces, vortices, and defects, arising from the scattering of quasiparticles from the sign change in the order parameter.
- Elucidating the role of c-axis coupling in determining the superconducting transition temperature of the cuprates.
- Developing a viable technology for producing high current wires and tapes made of high temperature superconductors.
- Developing a viable tunnel junction technology for fabricating active high temperature superconducting analog and digital electronic circuits.
- Finding routes to raising the transition temperature and answering the provocative question of whether it will be possible to achieve room temperature superconductivity.

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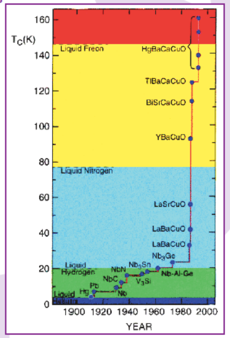
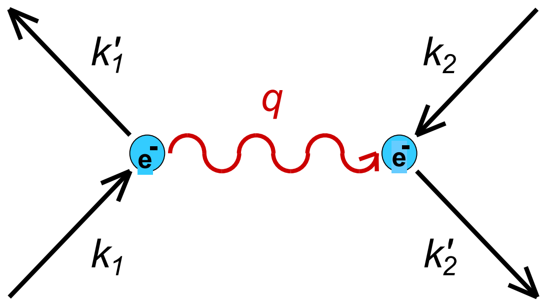


55. A century of climbing transition temperatures. The biggest jumps are associated with the discovery of new families of compounds. Figure courtesy of Bertram Batlogg.

Conventional ("classic") superconductivity

BCS theory:

Bardeen, Cooper, Schrieffer (1957)



John Bardeen | Leon Cooper | Bob Schrieffer

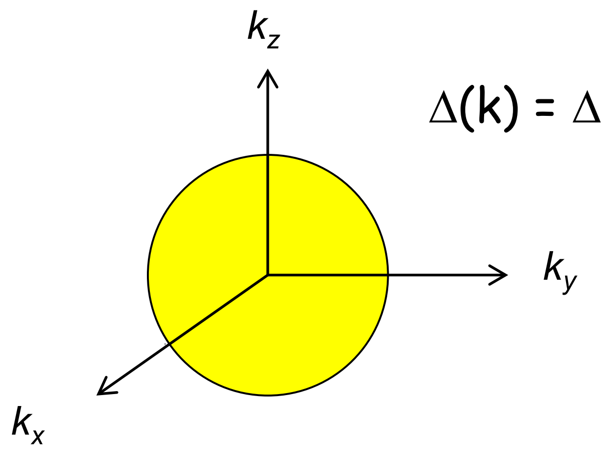
- **MECHANISM** = attractive phonon-mediated electron-electron interaction → Cooper pairing

- **GROUND STATE** = superfluid pair condensate

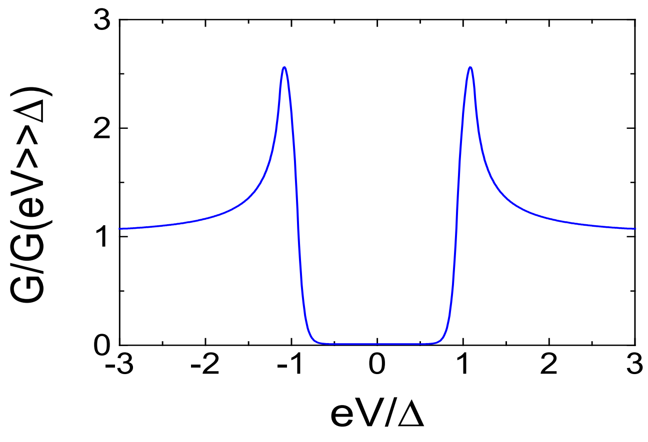
$$\psi = n_s e^{i\varphi}$$ ← *phase*

macroscopic phase coherence

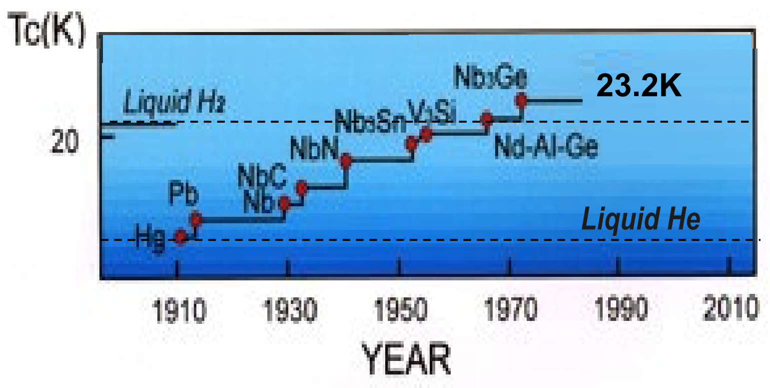
- **EXCITATIONS** = normal "quasiparticles" with an isotropic energy gap



"s-wave"



quasiparticle tunneling spectroscopy reveals the fully-formed energy gap

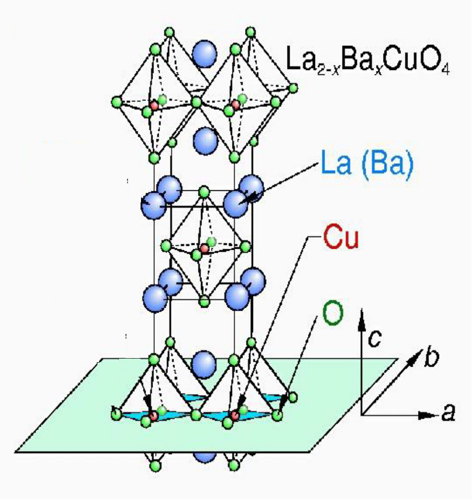


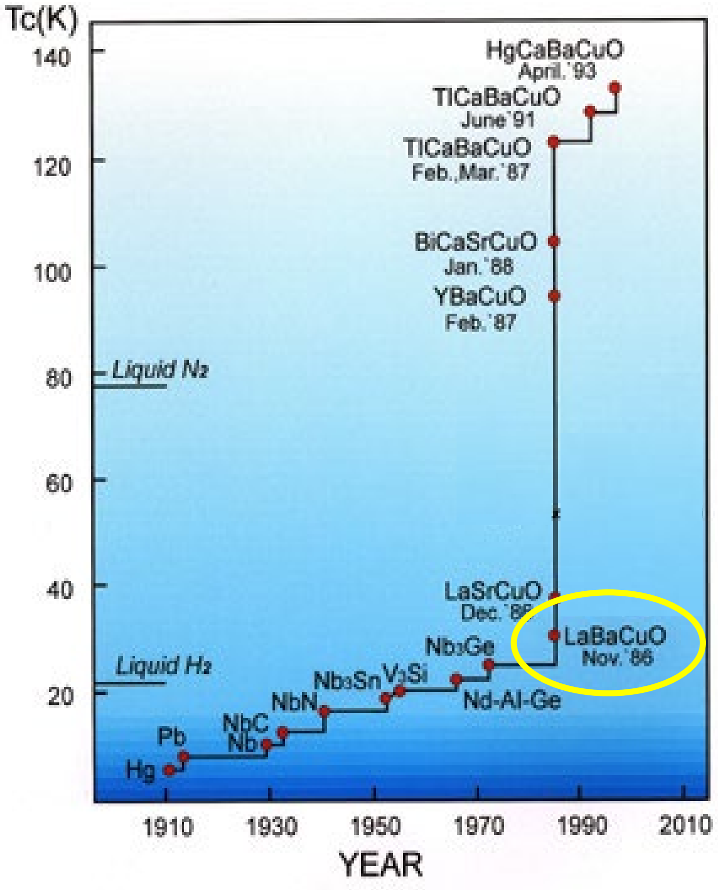
T_c increased slowly from 4K to 23K over 75 years from 1911 to 1986

High Temperature Superconductivity (1986)


Alex Müller   Georg Bednorz

IBM Zurich Research Laboratory





Woodstock of Music (1969)

3 days / 33 acts / 500,000 hippies

Woodstock of Physics (1987)

Mac Beasley!

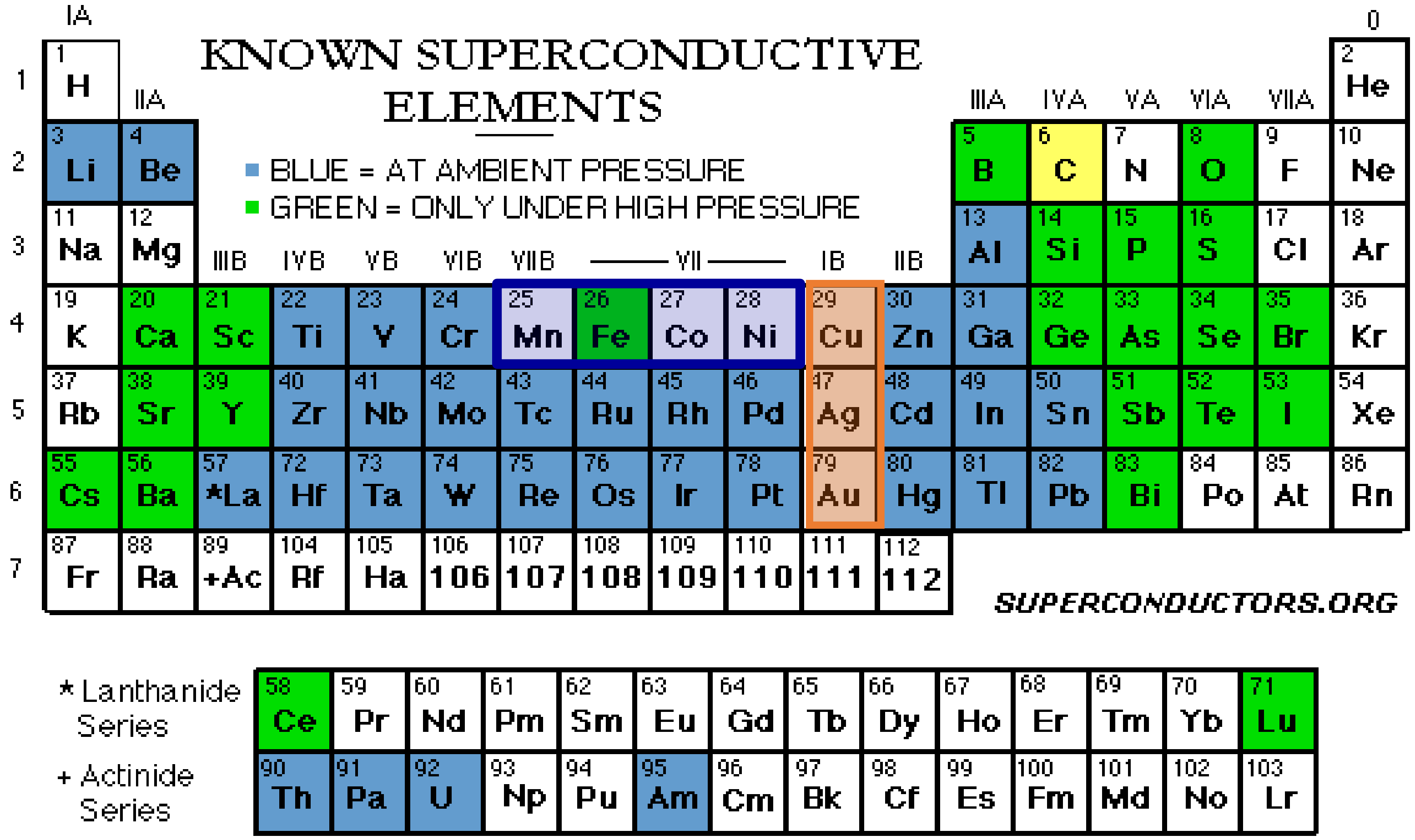
8 hours / 50 talks / 2500 physicists

"Our lives will be changed" … this did not turn out at expected but is rather true for physicists

challenged our understanding of condensed matter physics

opened new opportunities for superconductor research

Extent of Superconductivity



+ <u>thousands</u> of metallic compounds and alloys

More illuminating: what materials are NOT superconducting?

Magnetic materials (Mn, Fe, Co, Ni)

Good metals (Cu, Ag, Au)

Most important for fundamental research:

Al	$1.2K$
In	$3.4K$
Sn	$3.7K$
Pb	$7K$
YBCO	$90K$

Most important for applications:

Al	$1.2K$
Nb	$9K$
NbN	$16K$
Nb_3Sn	$18K$

Most important for qubits:

Al	$1.2K$
Ta	$4.2K$
Nb	$9K$

Reasons to Study Superconductivity in 2025

Superconductivity is a remarkably robust and widespread ground state for metals. Many different pairing states and pairing mechanisms have been identified. What new pairing states and mechanisms remain to be discovered? What remarkable electronic states of matter remain for us to find? How high can the superconducting T_c, critical fields H_c, and critical current densities J_c go?

Superconductivity also competes with many other ordered states of matter, such as ferro- and anti-ferromagnetism, charge density waves, topological insulating states, ferroelectricity, etc. This competition often gives rise to materials with surprising new properties and behavior as a function of temperature, magnetic field, pressure, strain, etc.

Quantum mechanics is 100 years old now, and superconductivity is fundamentally a quantum mechanical phenomenon. Superconductivity is a prime enabler for quantum information science and quantum computing. Understanding the basic physics of superconductivity is essential for bringing about successful applications in quantum technology.

What new quantum phenomena can be discovered based on superconductivity?

What new applications will superconductors have in quantum technology? Can we build single-photon detectors, the ultimate in sensitivity, that span the electromagnetic spectrum from the infrared to the radio frequencies?