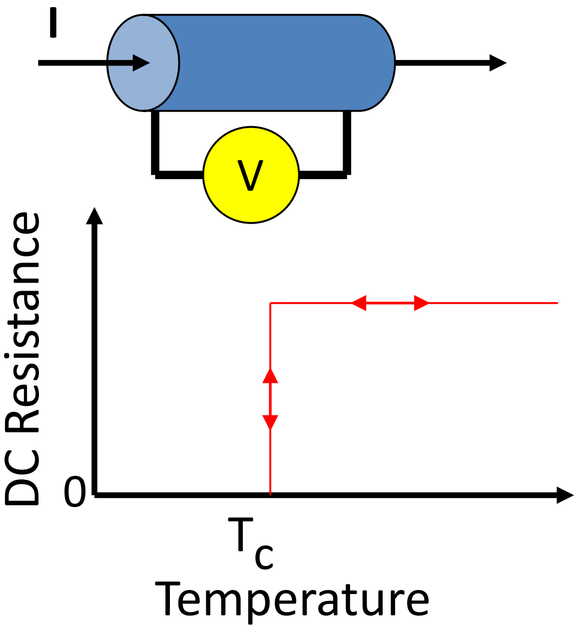
The Three Hallmarks of Superconductivity

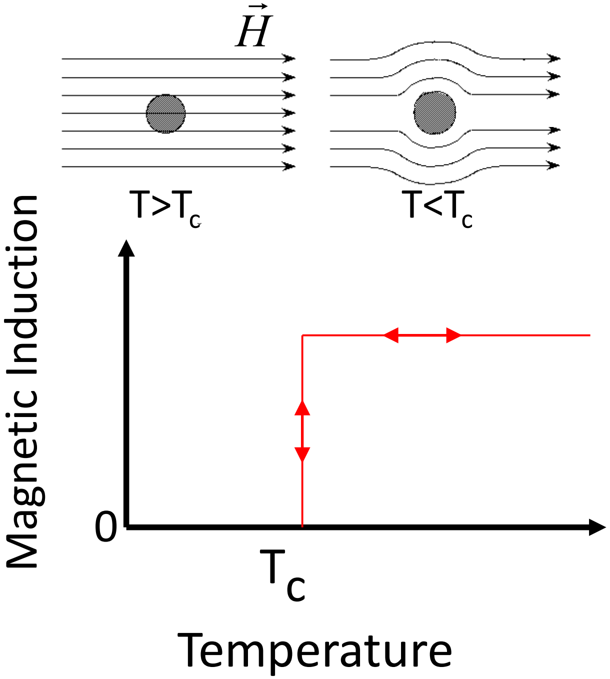
1) Zero Resistance
2) Meissner Effect
3) Macroscopic Quantum Effects

The Three Hallmarks of Superconductivity

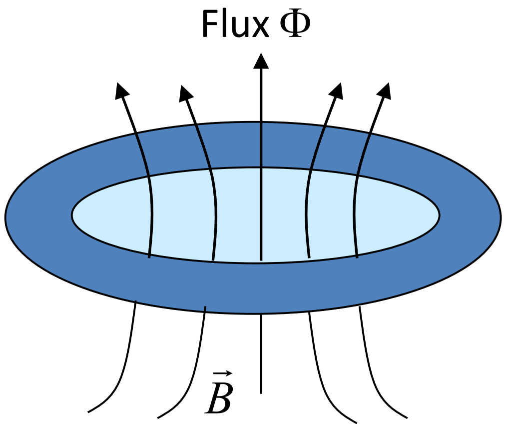
Zero Resistance



Complete Diamagnetism

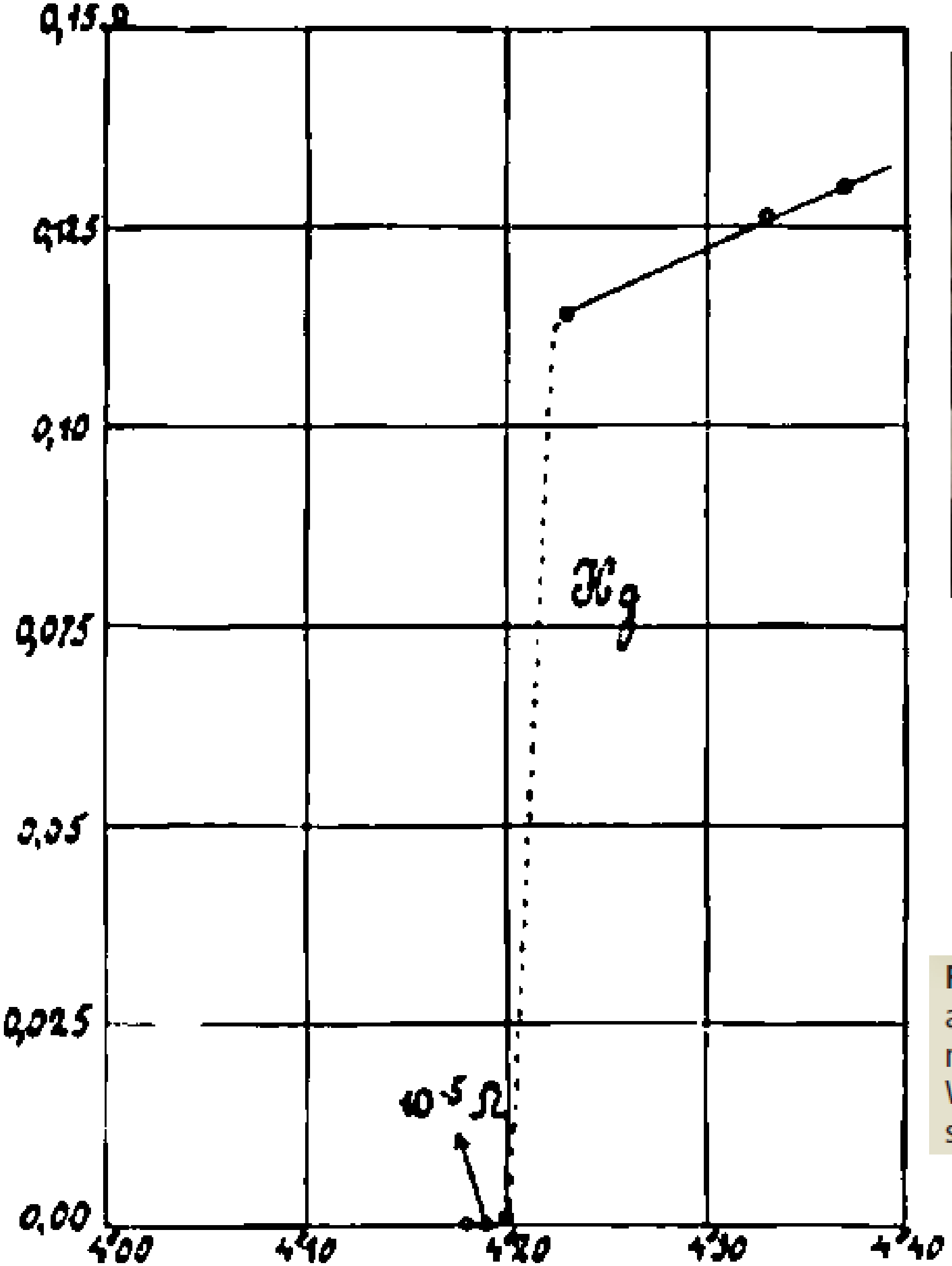


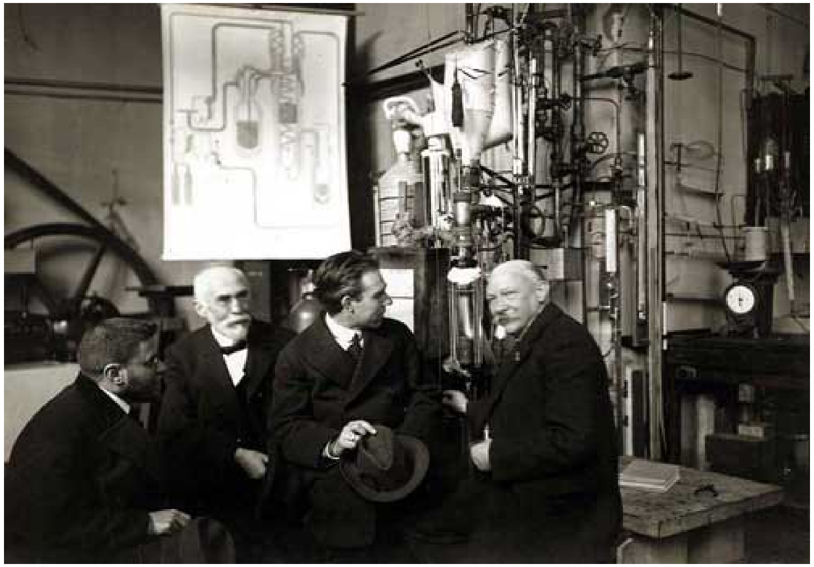
Macroscopic Quantum Effects



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

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

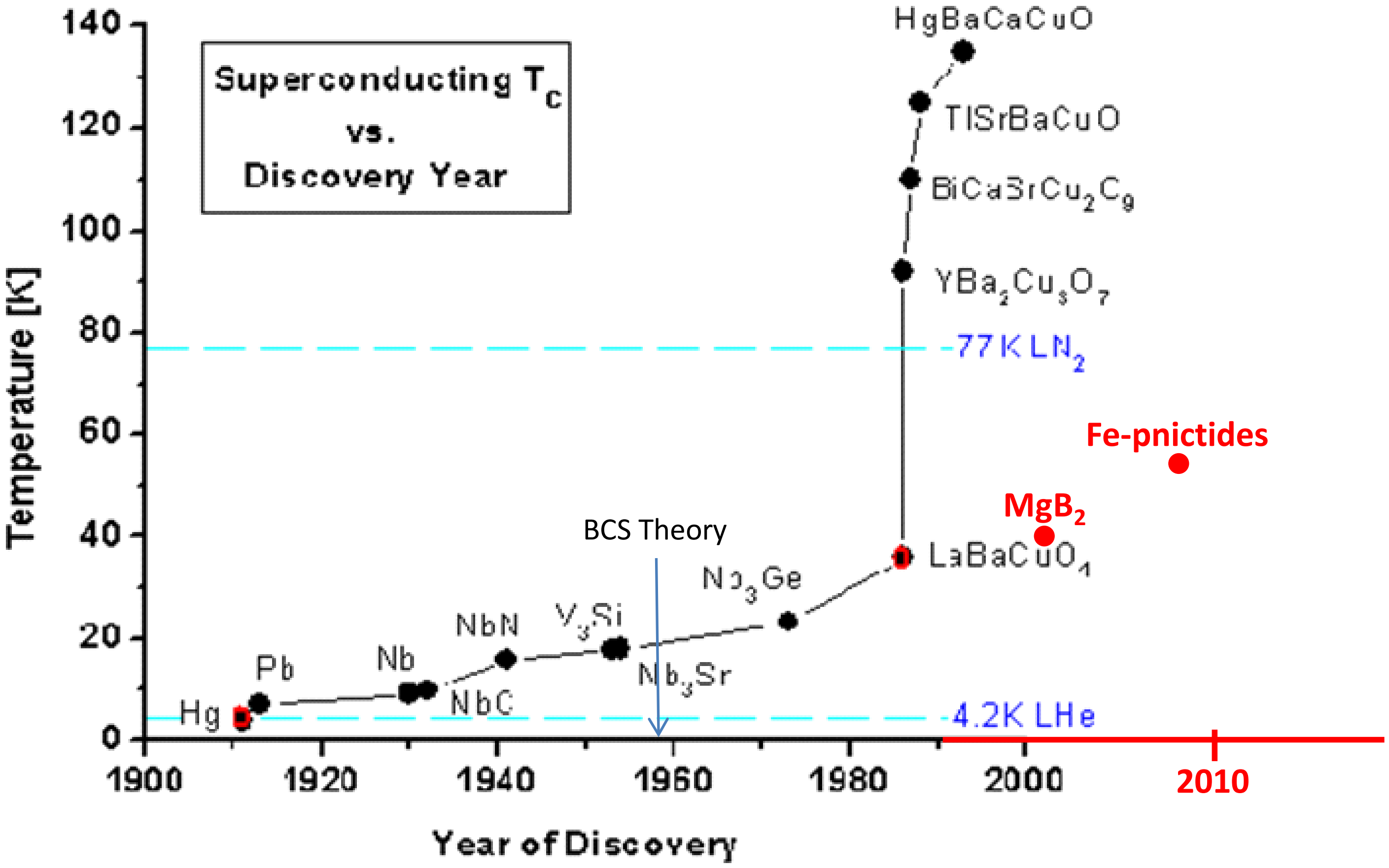




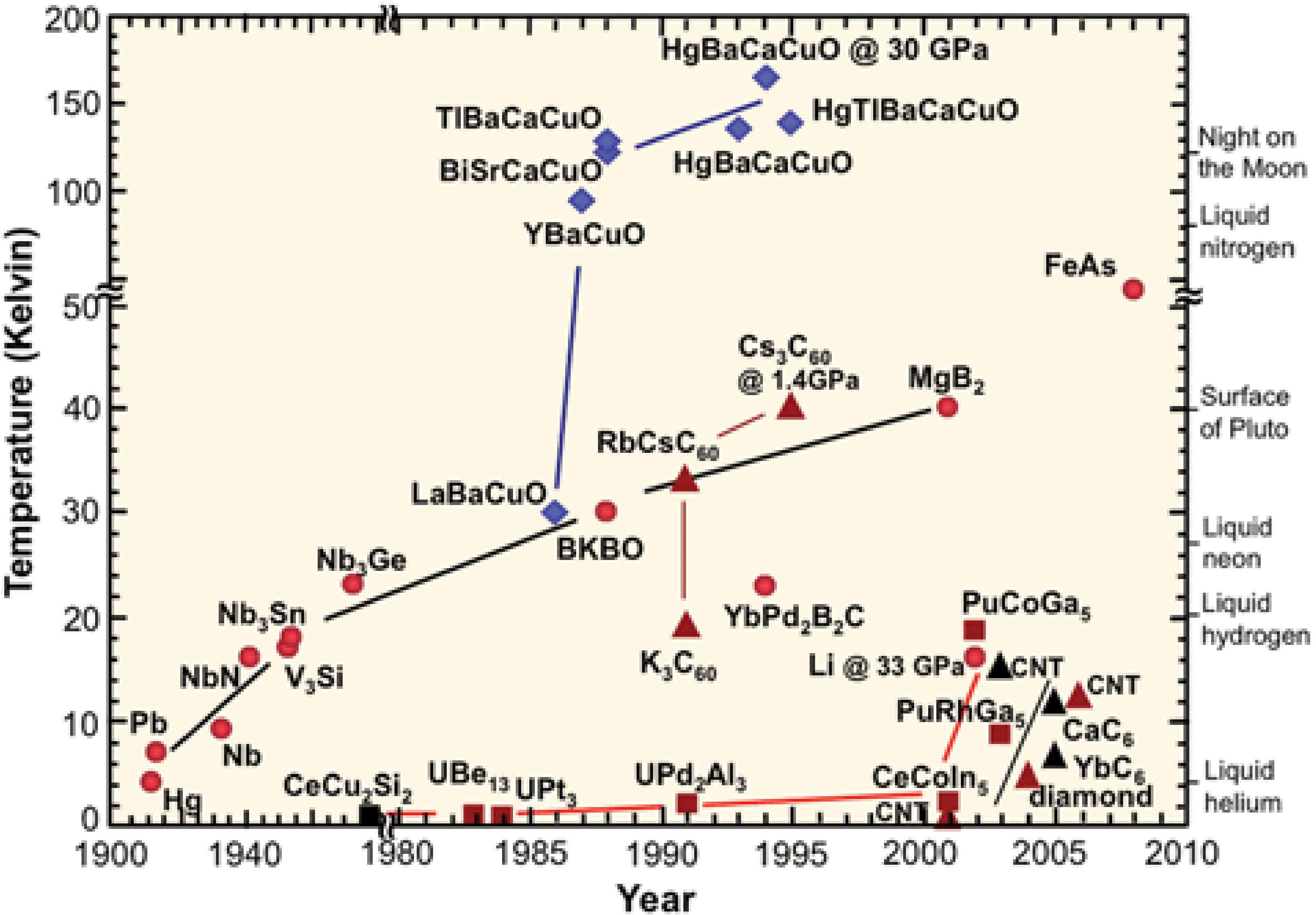
Heike Kamerlingh Onnes (right), the discoverer of superconductivity. Paul Ehrenfest, Hendrik Lorentz, Niels Bohr stand to his left.

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} Ω) to 0.1 Ω. (From ref. 9.)

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

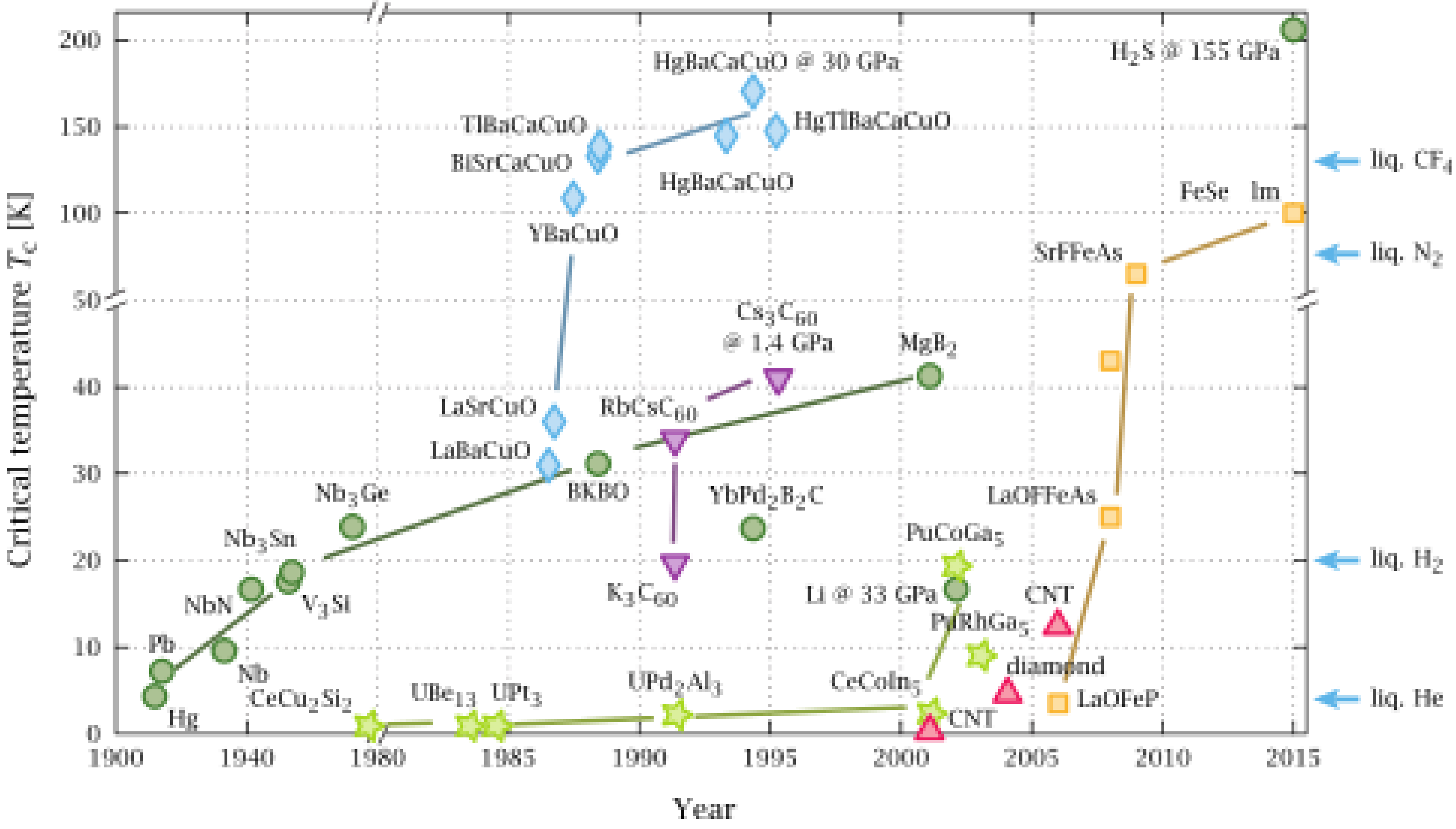


2006



2012

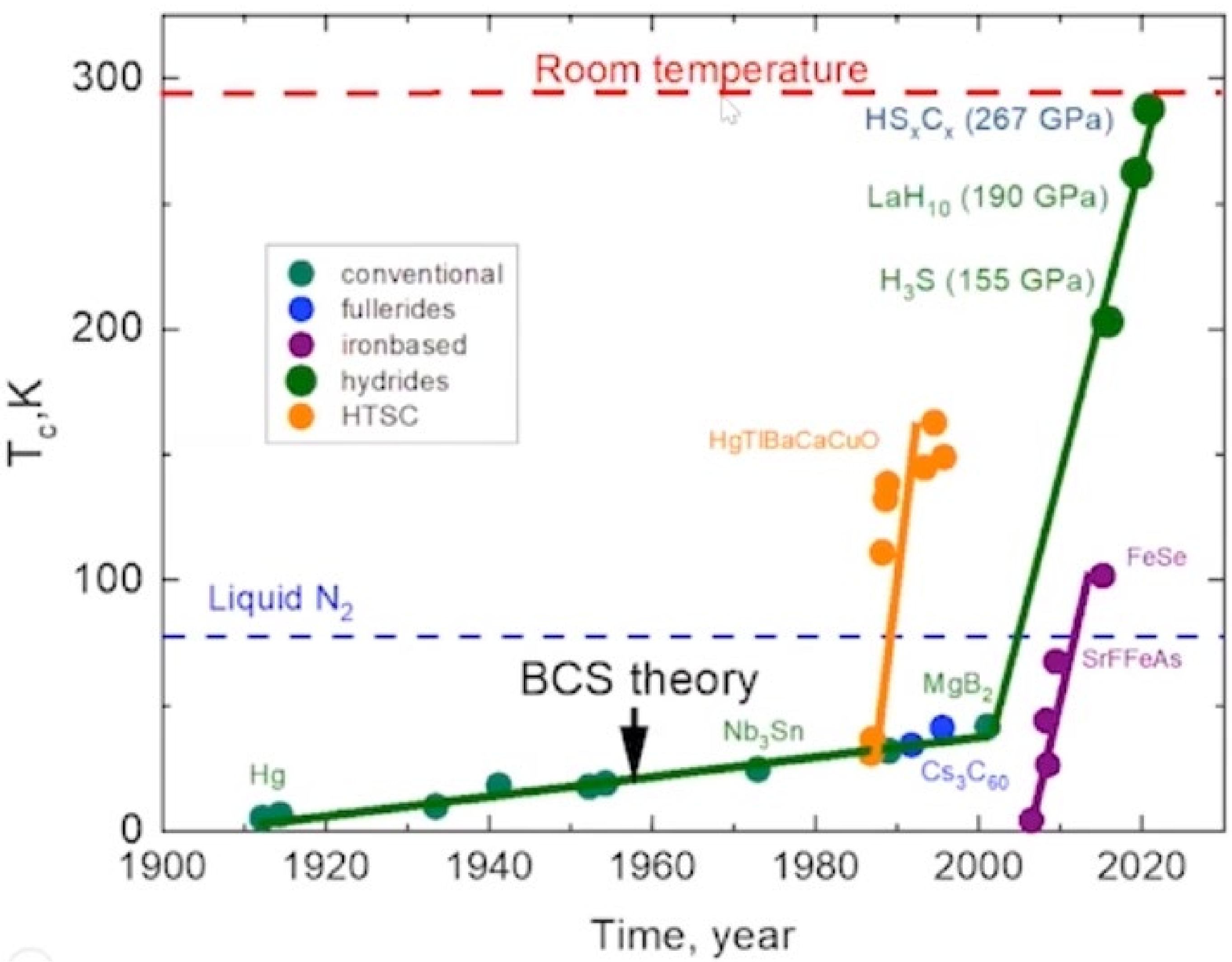
http://en.wikipedia.org/wiki/Superconductivity



2016

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

Critical temperature of superconductivity with time



ASC 2020
VIRTUAL CONFERENCE
Oct 24 – Nov 7 2020

2020

Materials

Mikhail Eremets Plenary: A Path Towards Room Temperature Superconductivity

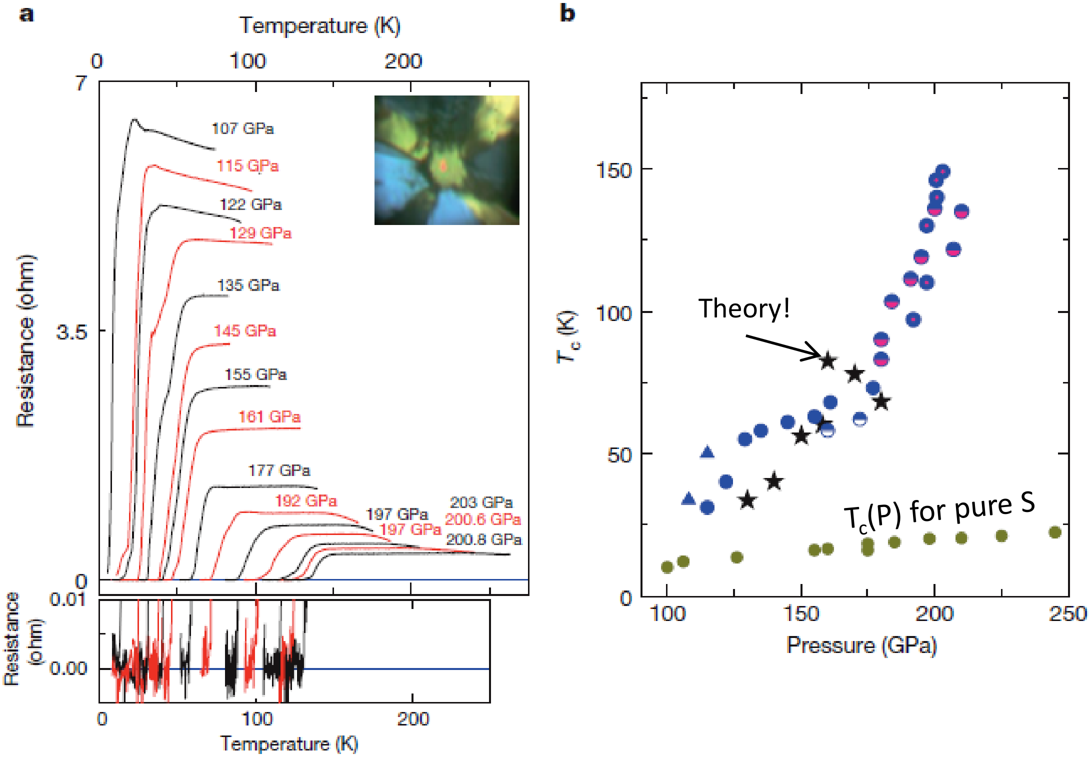
Mon. Oct 26, 2020 8:00 AM - 9:00 AM 757 Attending

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

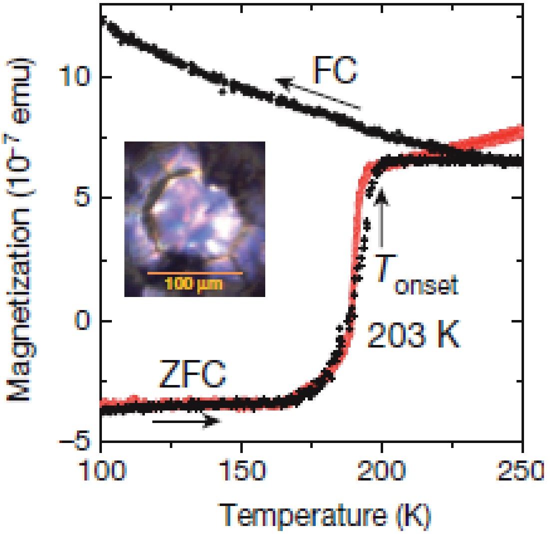
A. P. Drozdov[1]*, M. I. Eremets[1]*, I. A. Troyan[1], V. Ksenofontov[2] & S. I. Shylin[2]

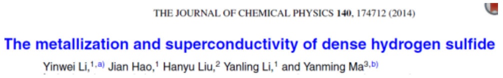
Nature 525, 73–76 (03 September 2015) doi:10.1038/nature14964

Zero Resistance



Meissner Screening

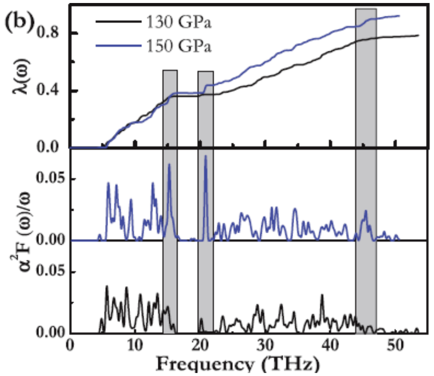




THE JOURNAL OF CHEMICAL PHYSICS **140**, 174712 (2014)

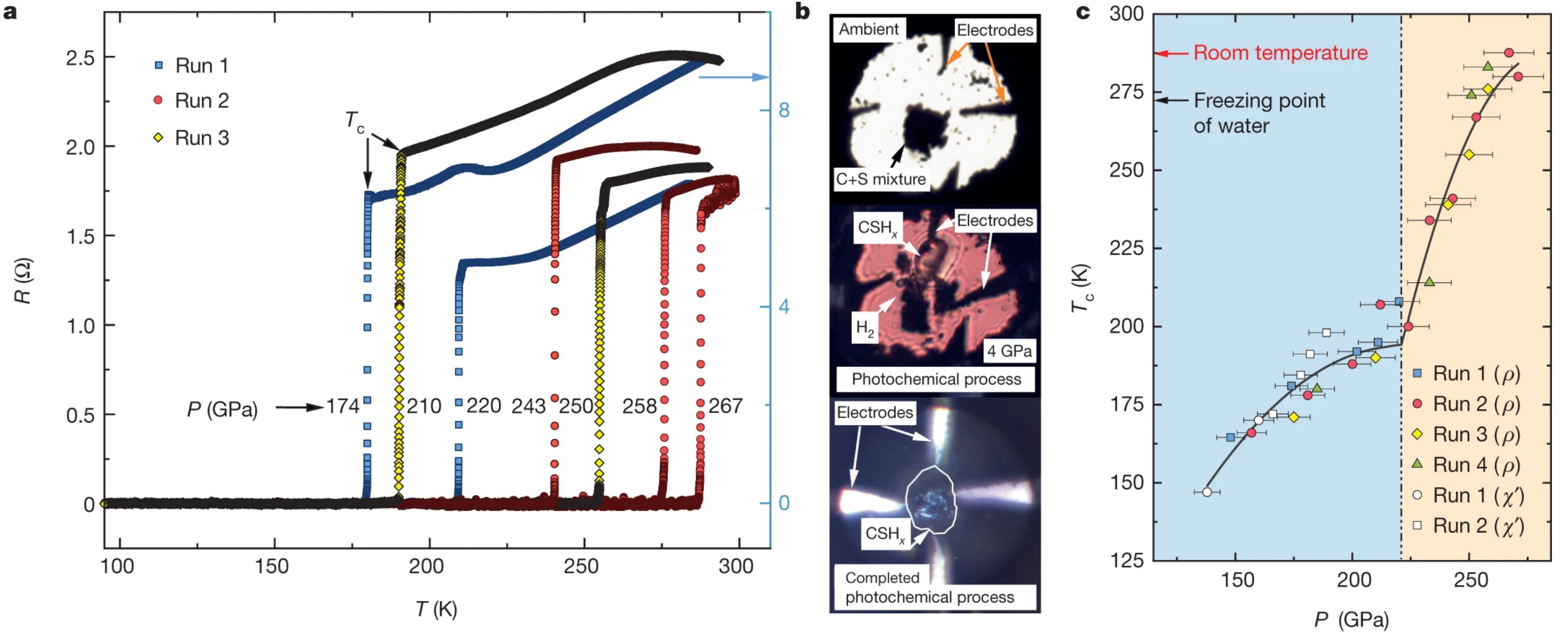
The metallization and superconductivity of dense hydrogen sulfide

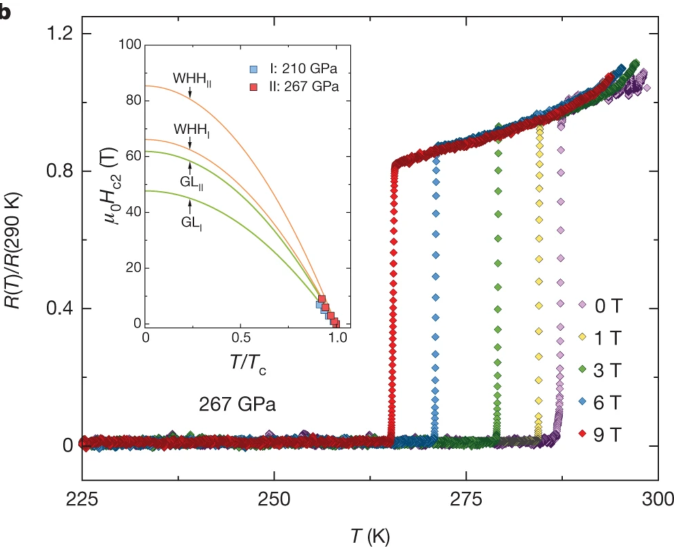
Yinwei Li,[1,a)] Jian Hao,[1] Hanyu Liu,[2] Yanling Li,[1] and Yanming Ma[3,b)]



Room-temperature superconductivity in a carbonaceous sulfur hydride

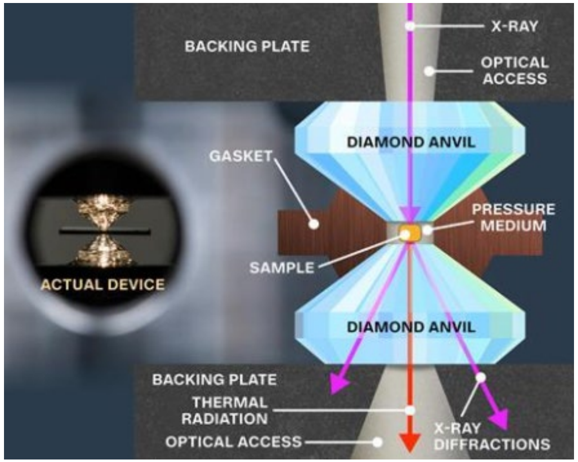
Nature | Vol 586 | 15 October 2020 | **373**





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

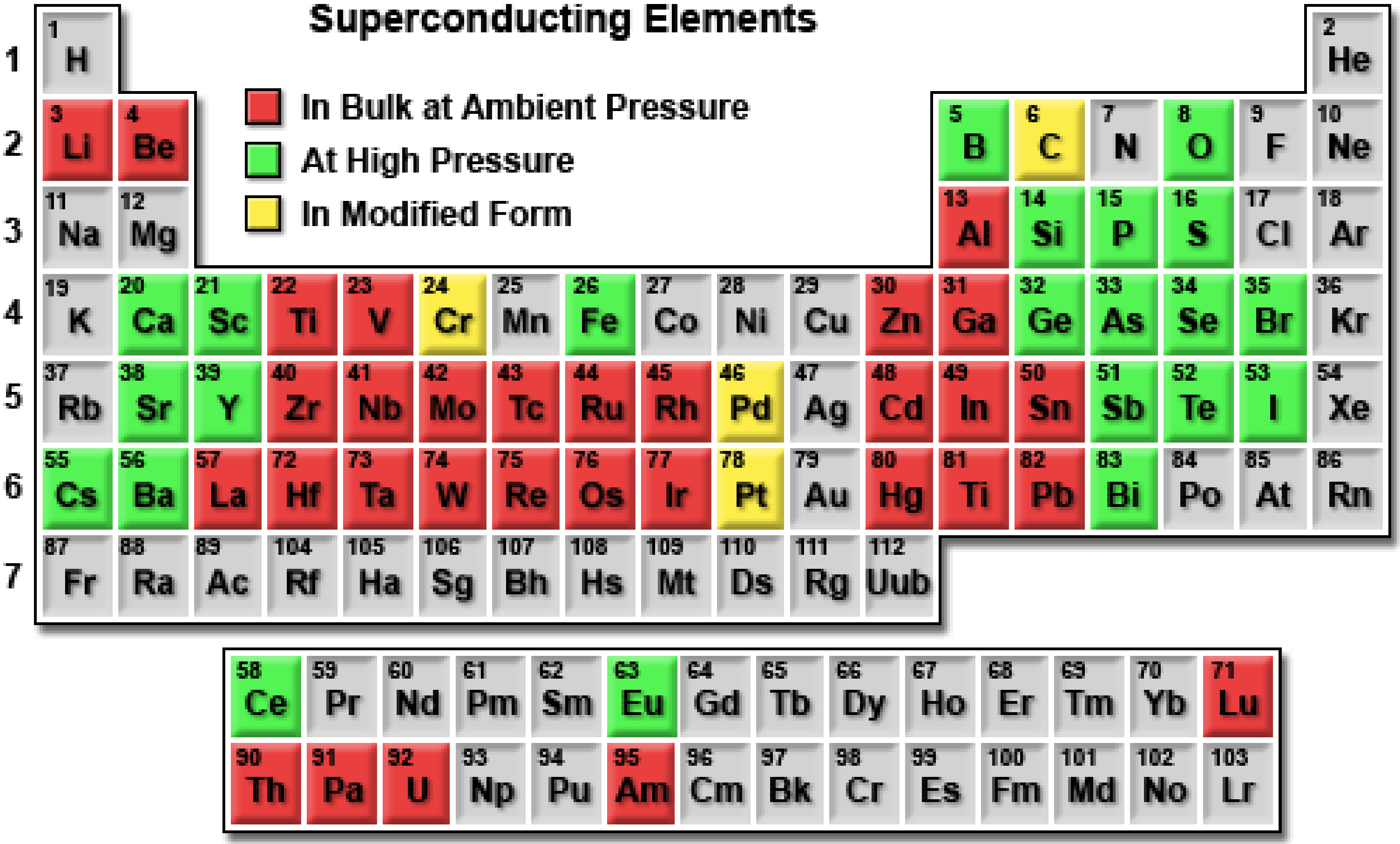
the extremely narrow widths of the transitions in the absence of a magnetic field, and the fact that the widths do not change with the applied magnetic field, suggest that the observed phenomena are not associated with superconductivity. J. Hirsch and F. Marsiglio, Nature, 596, pp. E9–E10 (2021)



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	1 H																	2 He
2	🟥 3 Li	🟥 4 Be											🟩 5 B	🟨 6 C	7 N	🟩 8 O	9 F	10 Ne
3	11 Na	12 Mg											🟥 13 Al	🟩 14 Si	🟩 15 P	🟩 16 S	17 Cl	18 Ar
4	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
5	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
6	🟩 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 Ti	🟥 82 Pb	🟩 83 Bi	84 Po	85 At	86 Rn
7	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"

$T_c \to 154$ K (under pressure)

High-T_c:

Hg-Ba-Ca-Cu-O $T_c < 135$ K

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

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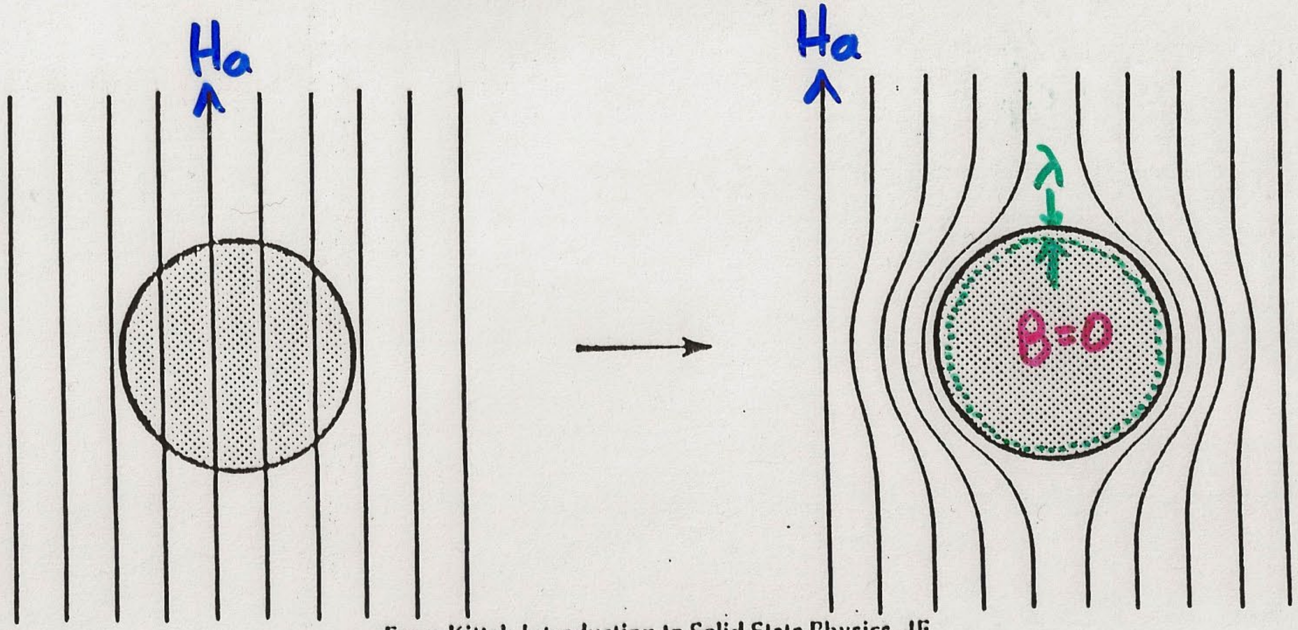
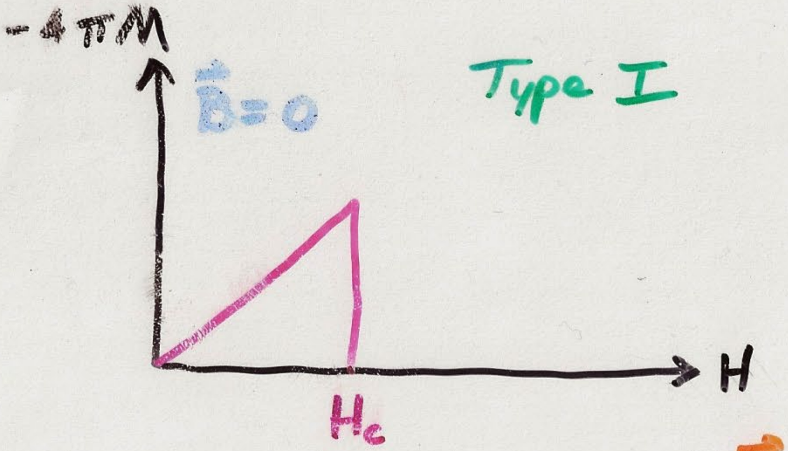
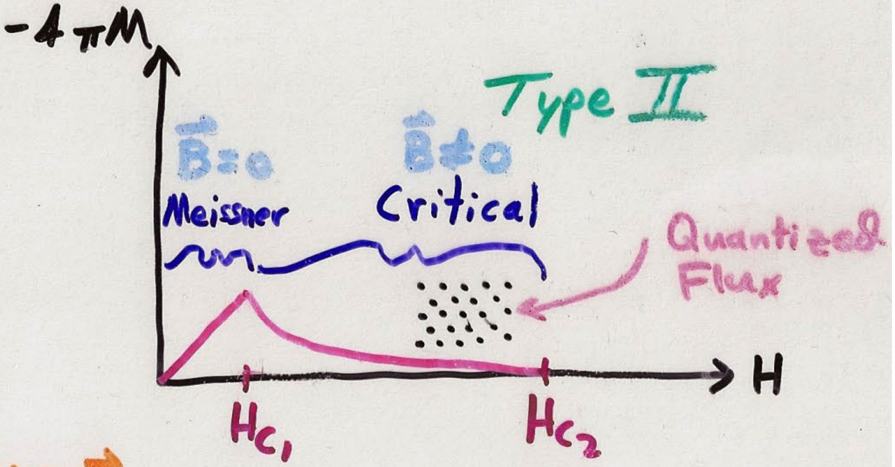
3) Macroscopic Quantum Effects

Meissner Effect



From Kittel: Introduction to Solid State Physics, 4E

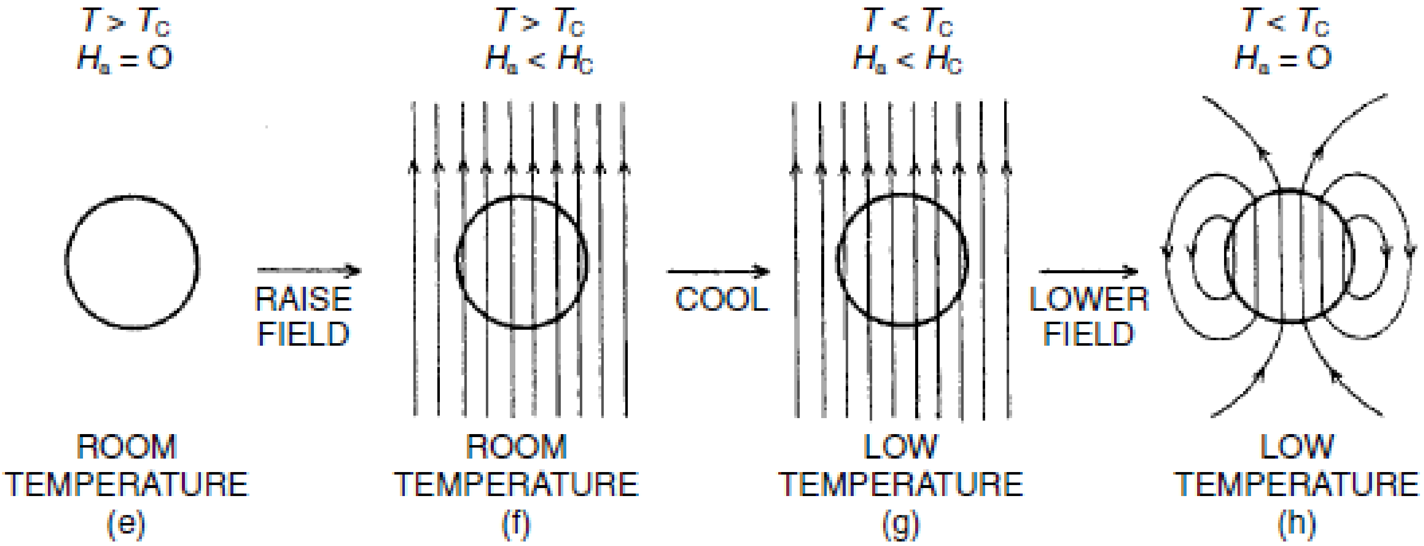




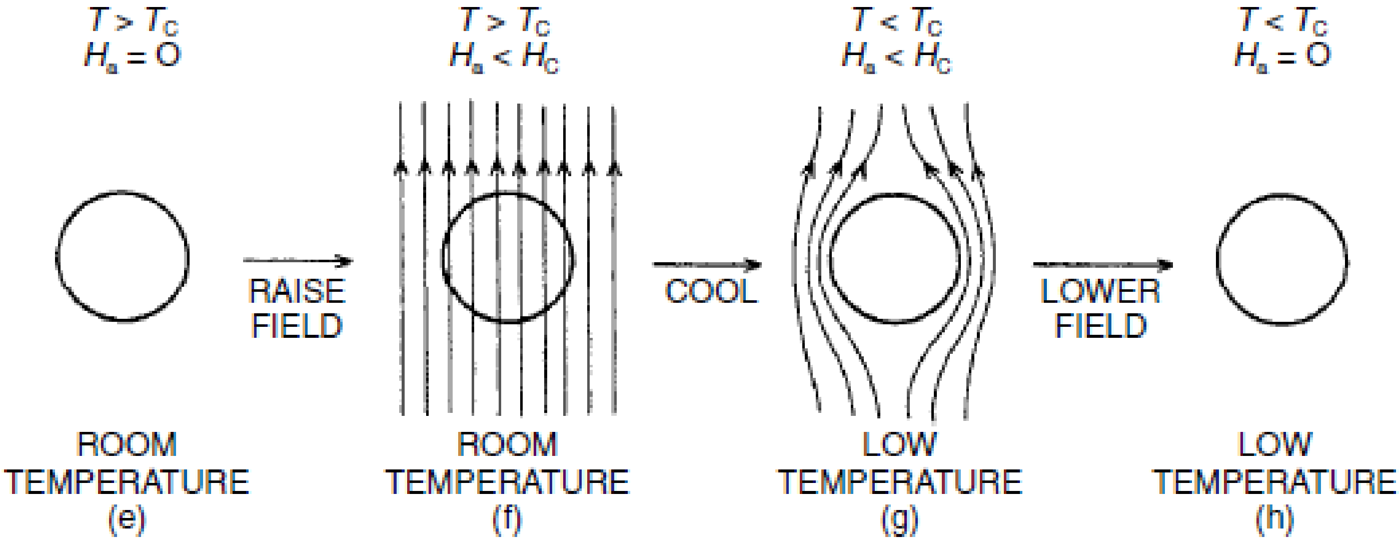
$$\vec{B} = \vec{H} + 4\pi\vec{M}$$

Perfect Conductor vs. Superconductor

Perfect Conductor

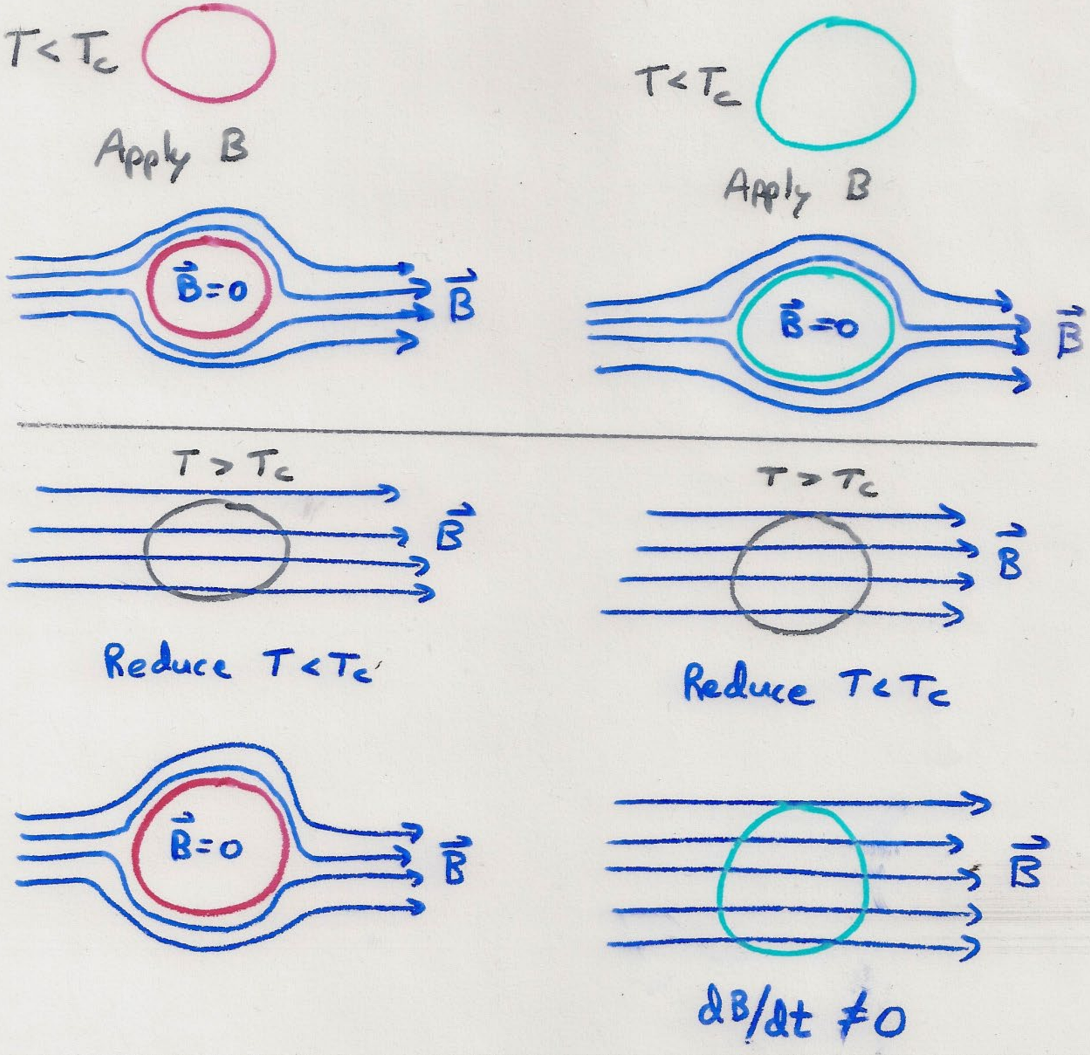


Super-Conductor



Zero Resistance and Perfect Diamagnetism

Superconductor vs **Perfect Conductor**



The Three Hallmarks of Superconductivity

1) Zero Resistance
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3) Macroscopic Quantum Effects

Macroscopic Quantum Effects

Superconductor is described by a single-valued Macroscopic Quantum Wavefunction

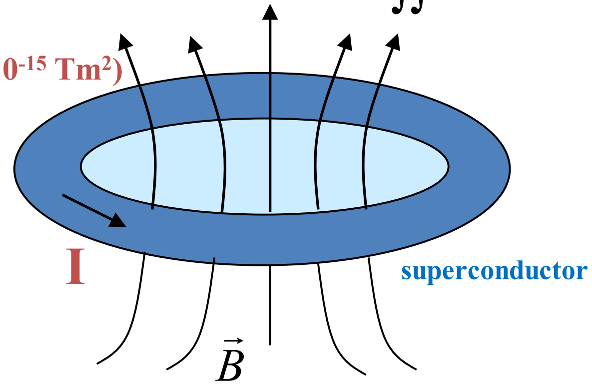
$$\Psi = |\Psi| e^{i\theta}$$

Consequence:

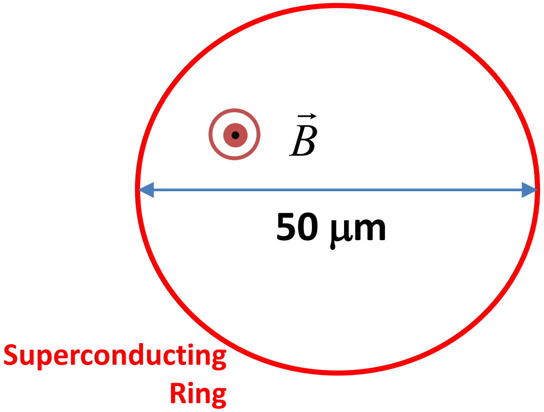
Magnetic flux is quantized in units of $\Phi_0 = h/2e$ (= 2.07 x 10^{-15} Tm^2)

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

Flux $\Phi = \oiint \vec{B} \cdot d\vec{A}$



Example of Flux Quantization

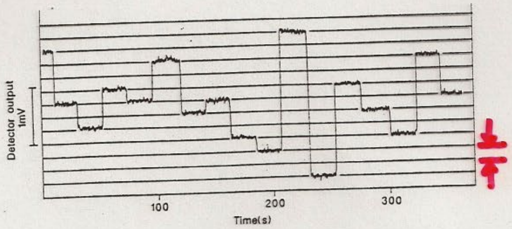


One flux quantum in this loop requires a field of B = Φ_0/Area = 1 μT

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

Flux Quantization in a High-T_c SC

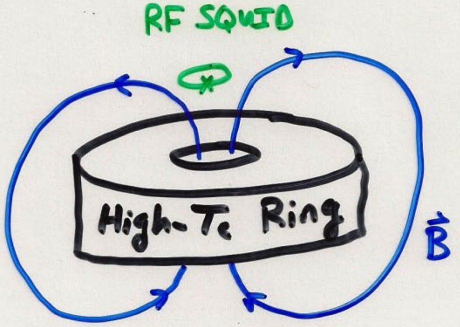
C. E. Gough, et al. Nature 326, 855 (1987).



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

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

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

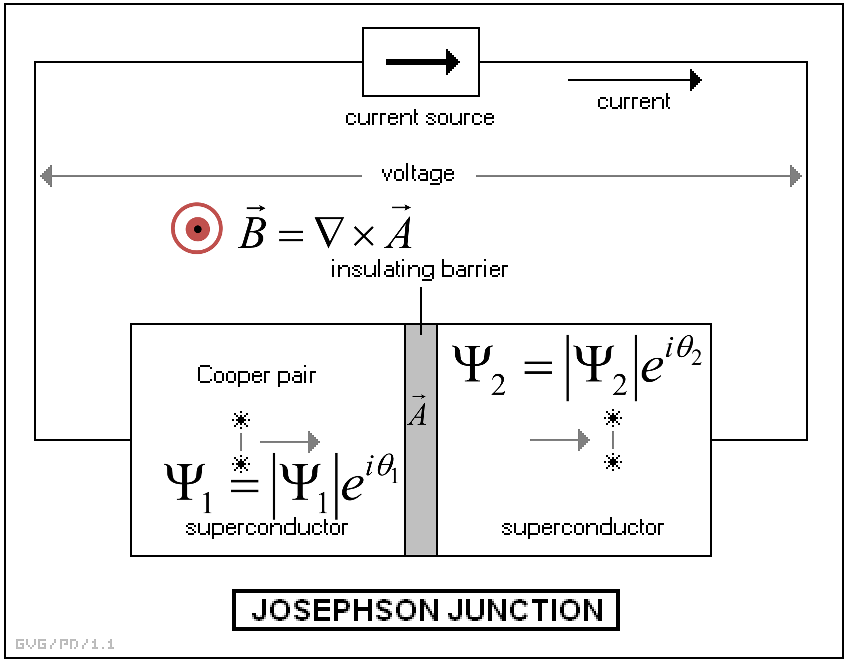
SQUID magnetometer output stable for 1000 s

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

Macroscopic Quantum Effects

Continued

Josephson Effects (Tunneling of Cooper Pairs)

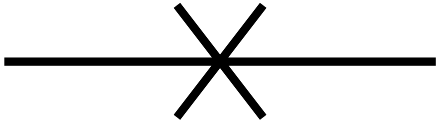


$$I = I_c \sin(\delta)$$ **DC**

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

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

Gauge-invariant phase difference

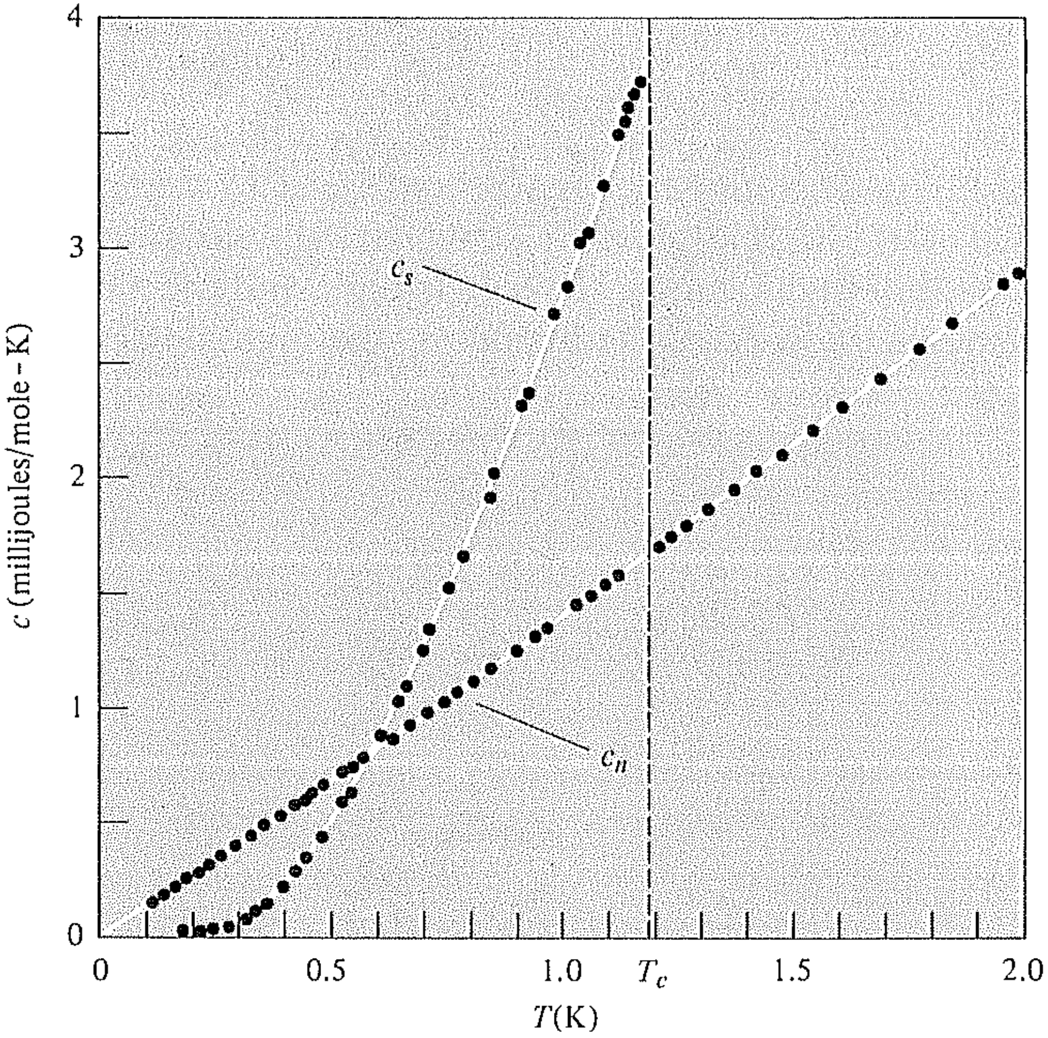


Circuit representation of a JJ

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

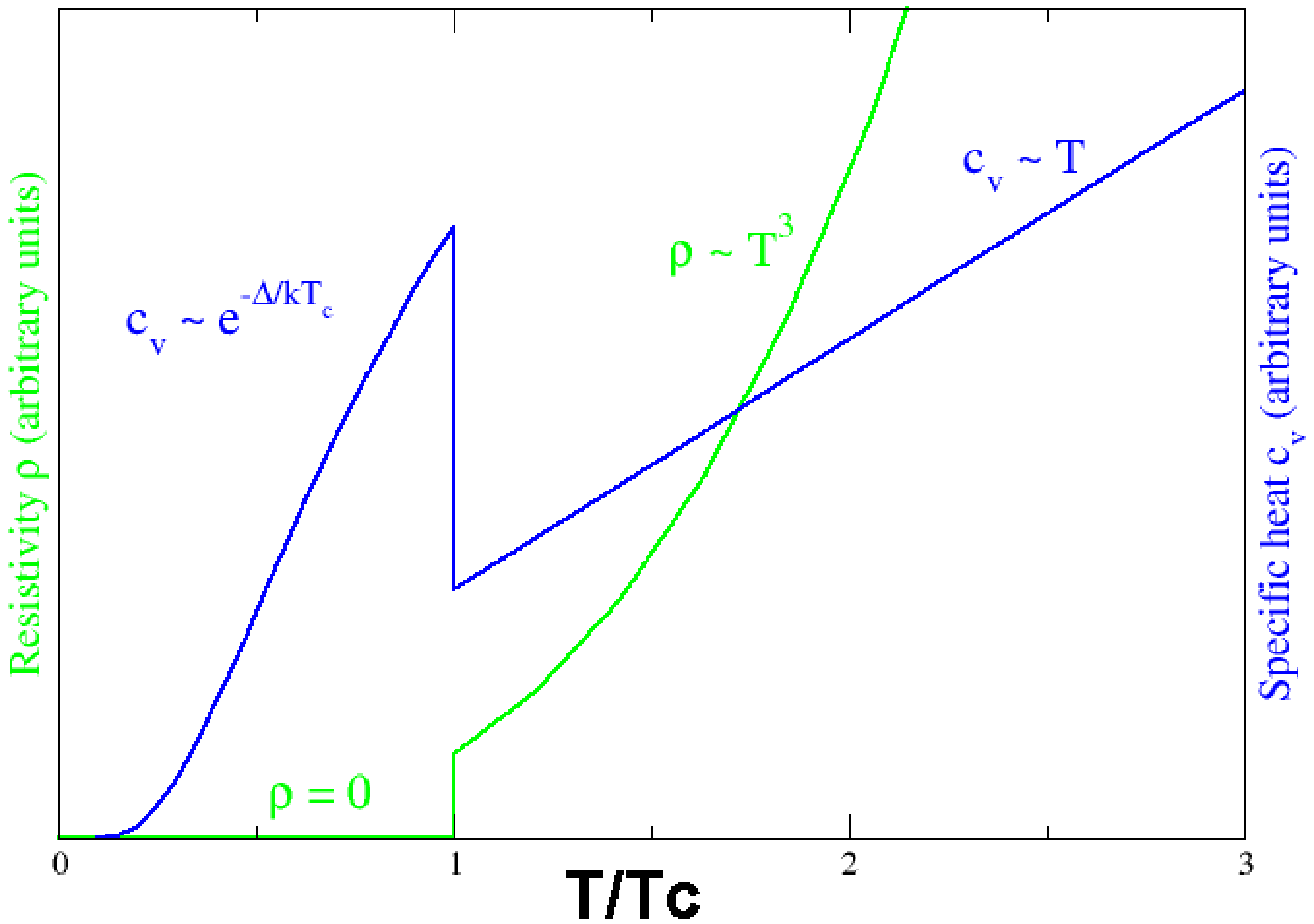
The Thermodynamics of Superconductors

Low Temperature Specific Heat of Aluminum



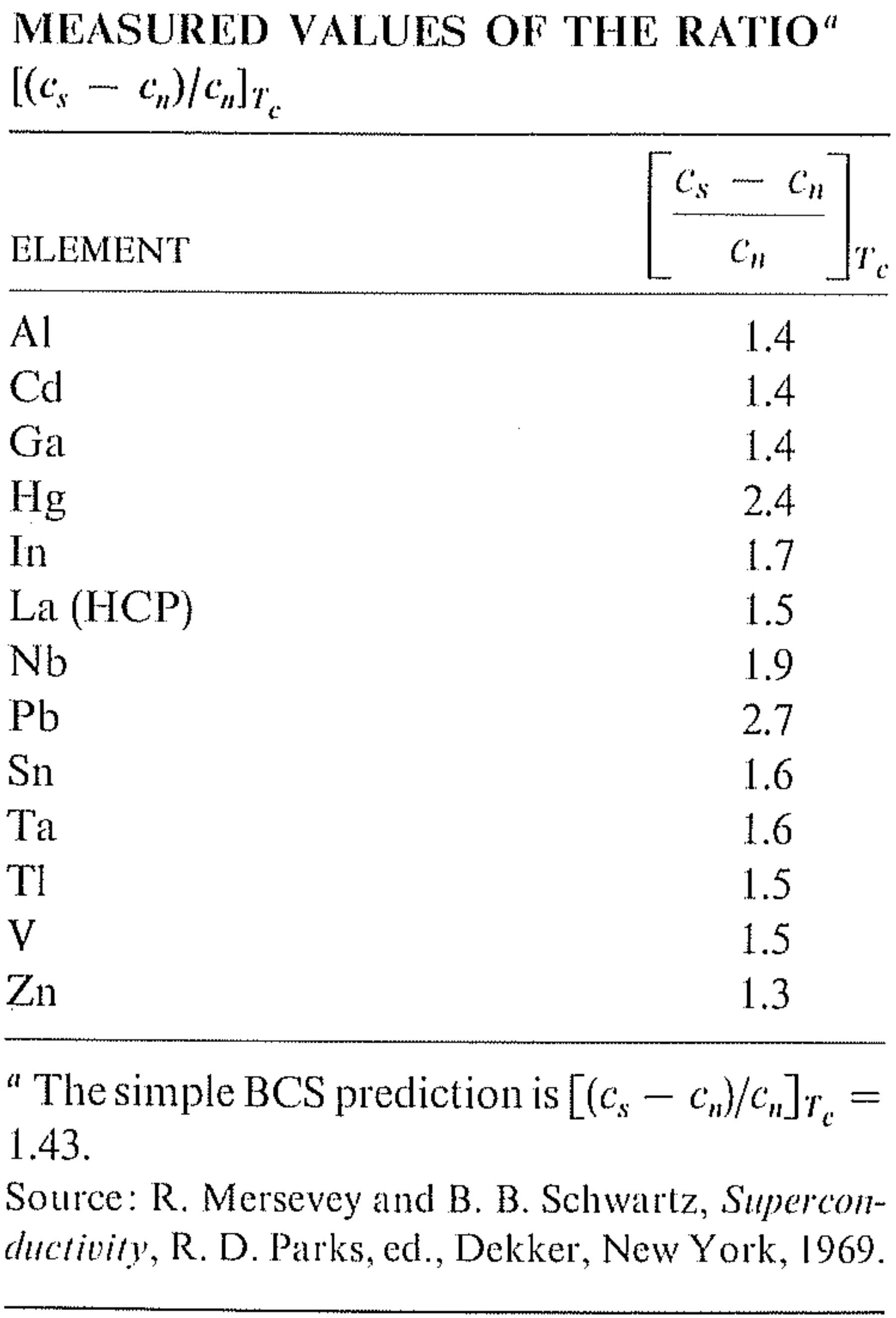
Low-temperature specific heat of normal and superconducting aluminum. The normal phase is produced below T_c by application of a weak (300-gauss) magnetic field, which destroys the superconducting ordering but has otherwise negligible effect on the specific heat. The Debye temperature is quite high in 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

The ‘Universal’ Heat Capacity Jump at T_c



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

ELEMENT	$\left[\dfrac{c_s - c_n}{c_n}\right]_{T_c}$
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

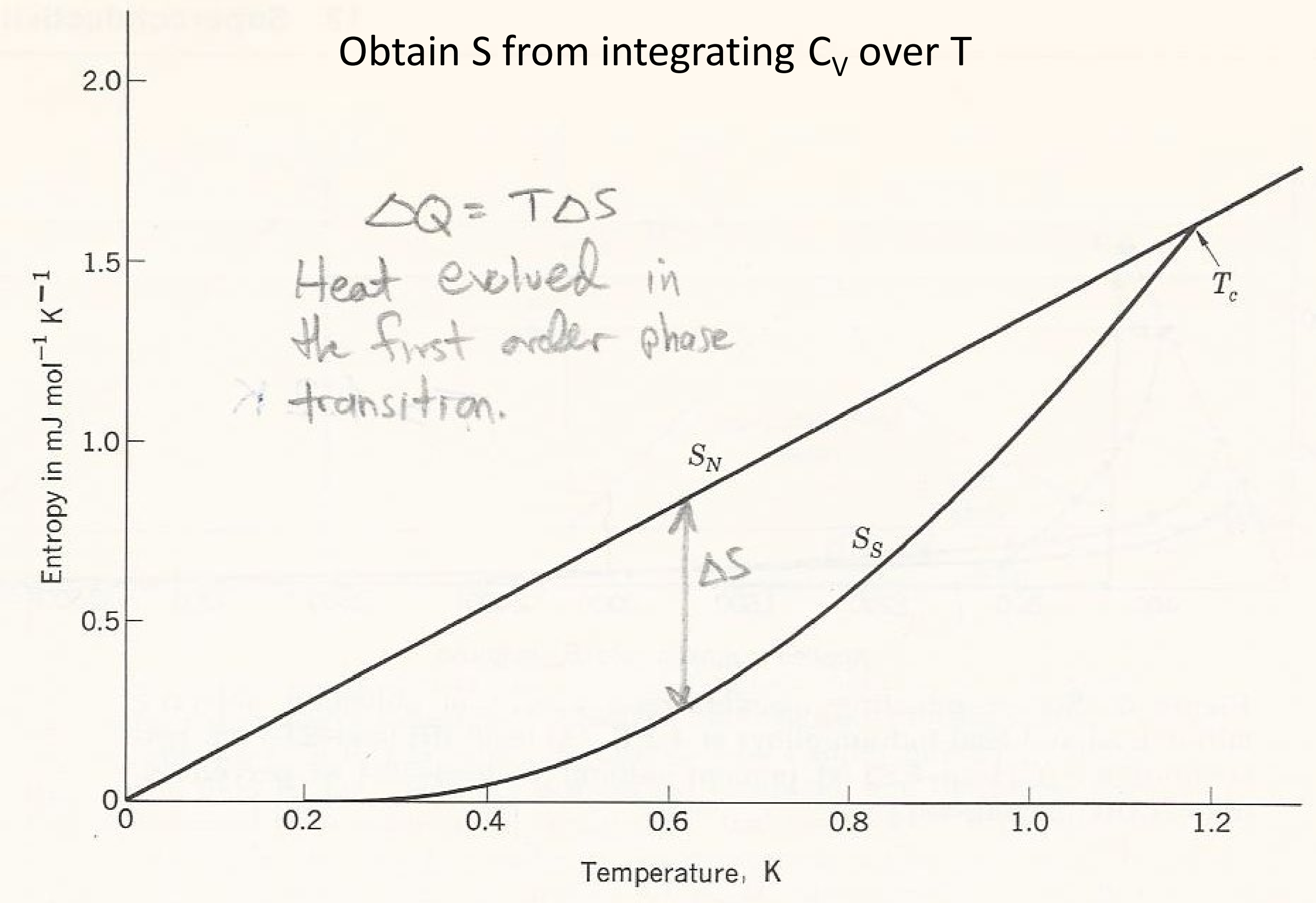
[a] The simple BCS prediction is $[(c_s - c_n)/c_n]_{T_c} = 1.43$.

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

The 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

$\Delta Q = T\Delta S$

Heat evolved in the first order phase transition.

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

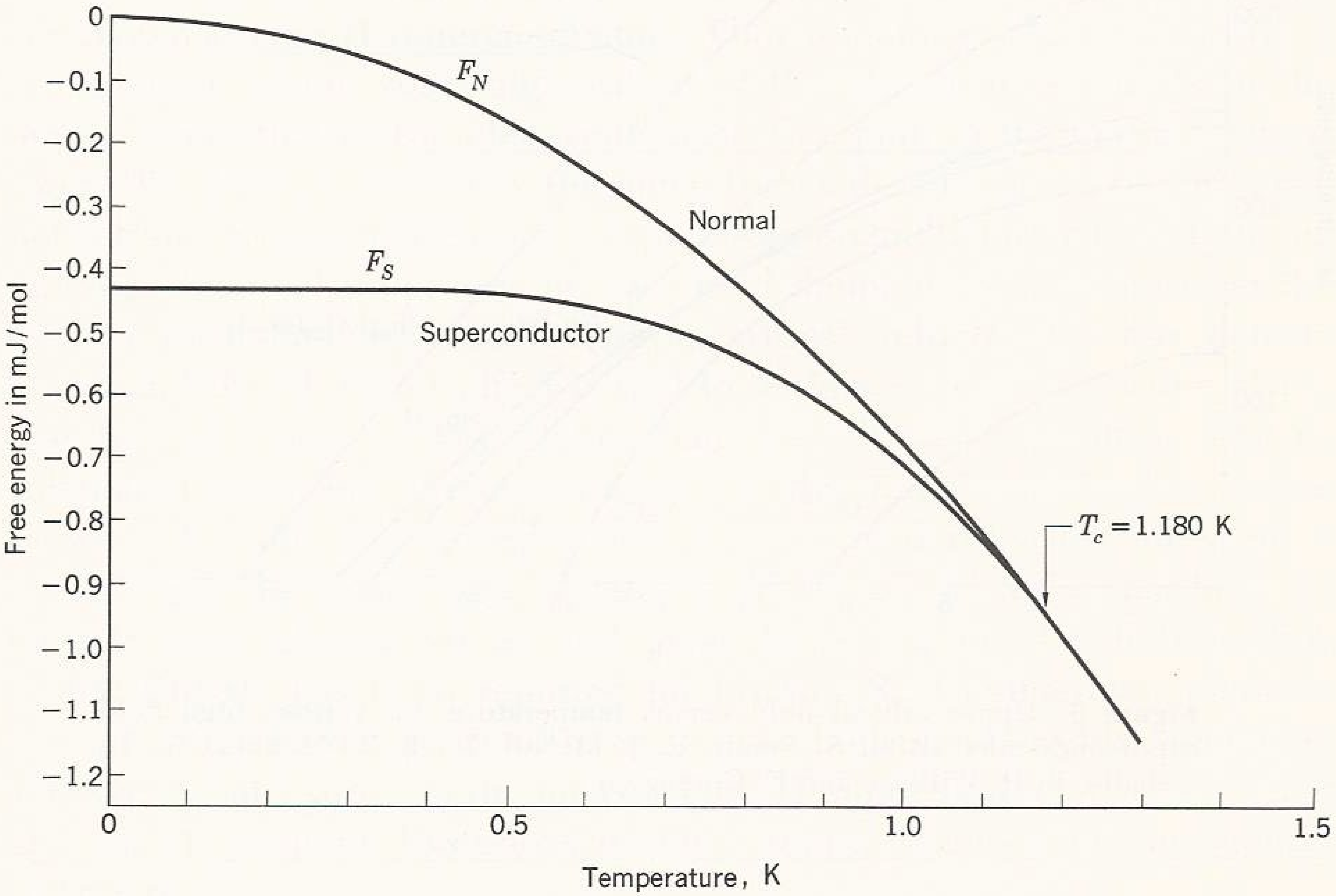
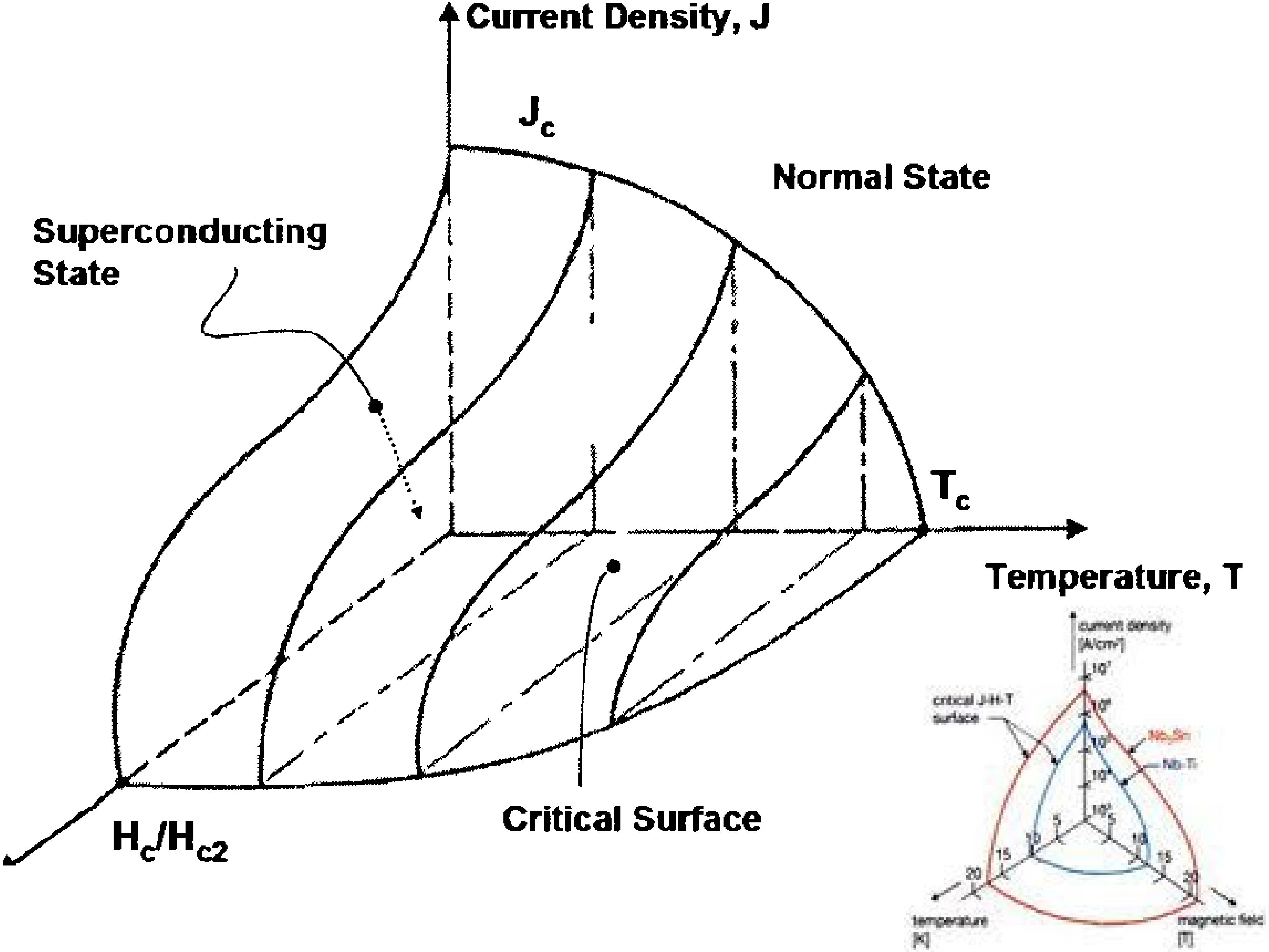


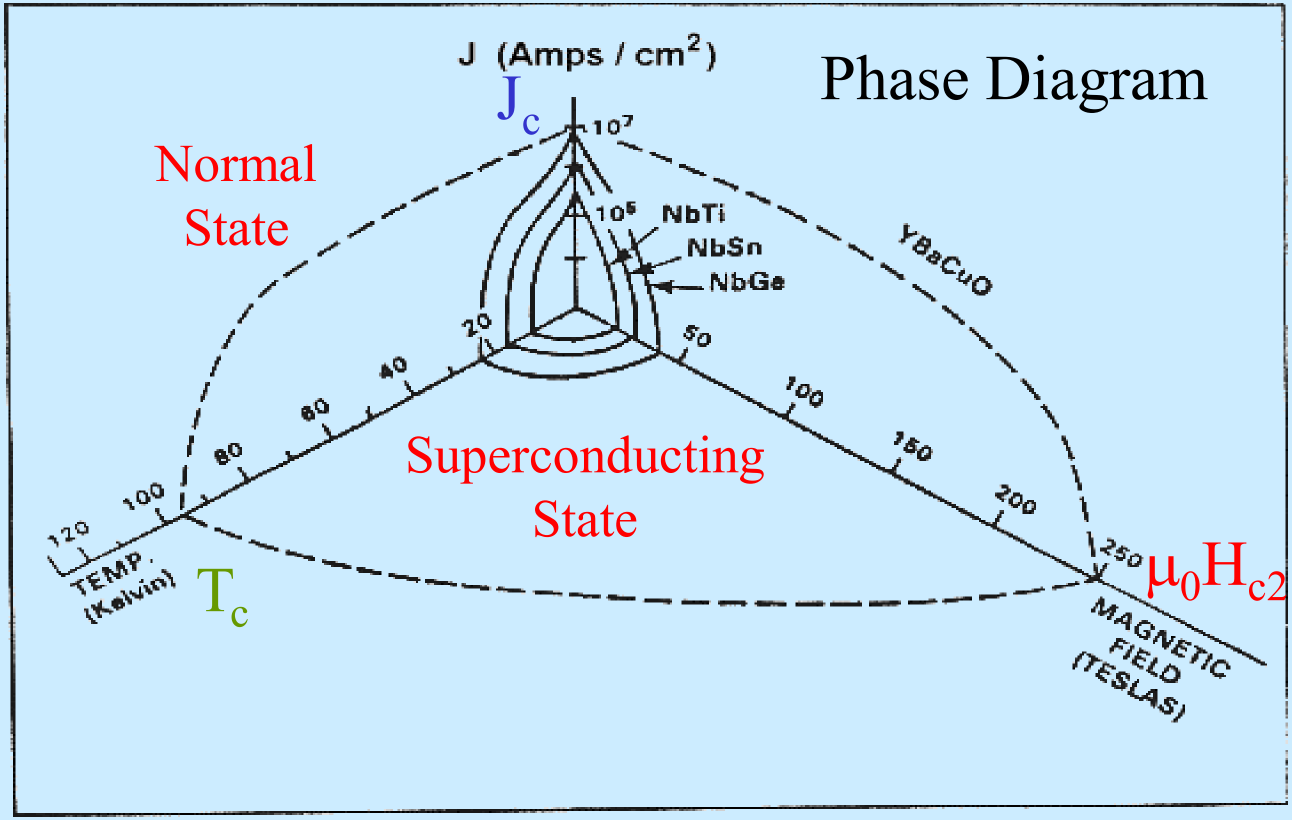
Figure 7b Experimental values of the free energy as a function of temperature for aluminum in the superconducting state and in the normal state. Below the transition temperature $T_c = 1.180$ K the free energy is lower in the superconducting state. The two curves merge at the transition temperature, 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
H_c/H_{c2}
Critical Surface
current density [A/cm²]
10^7
10^6
10^5
10^4
10^3
critical J-H-T surface
Nb_3Sn
Nb-Ti
5
10
15
20
5
10
15
20
temperature [K]
magnetic field [T]

What are the Limits of Superconductivity?



Phase Diagram

Normal State

Superconducting State

J_c

T_c

$\mu_0 H_{c2}$