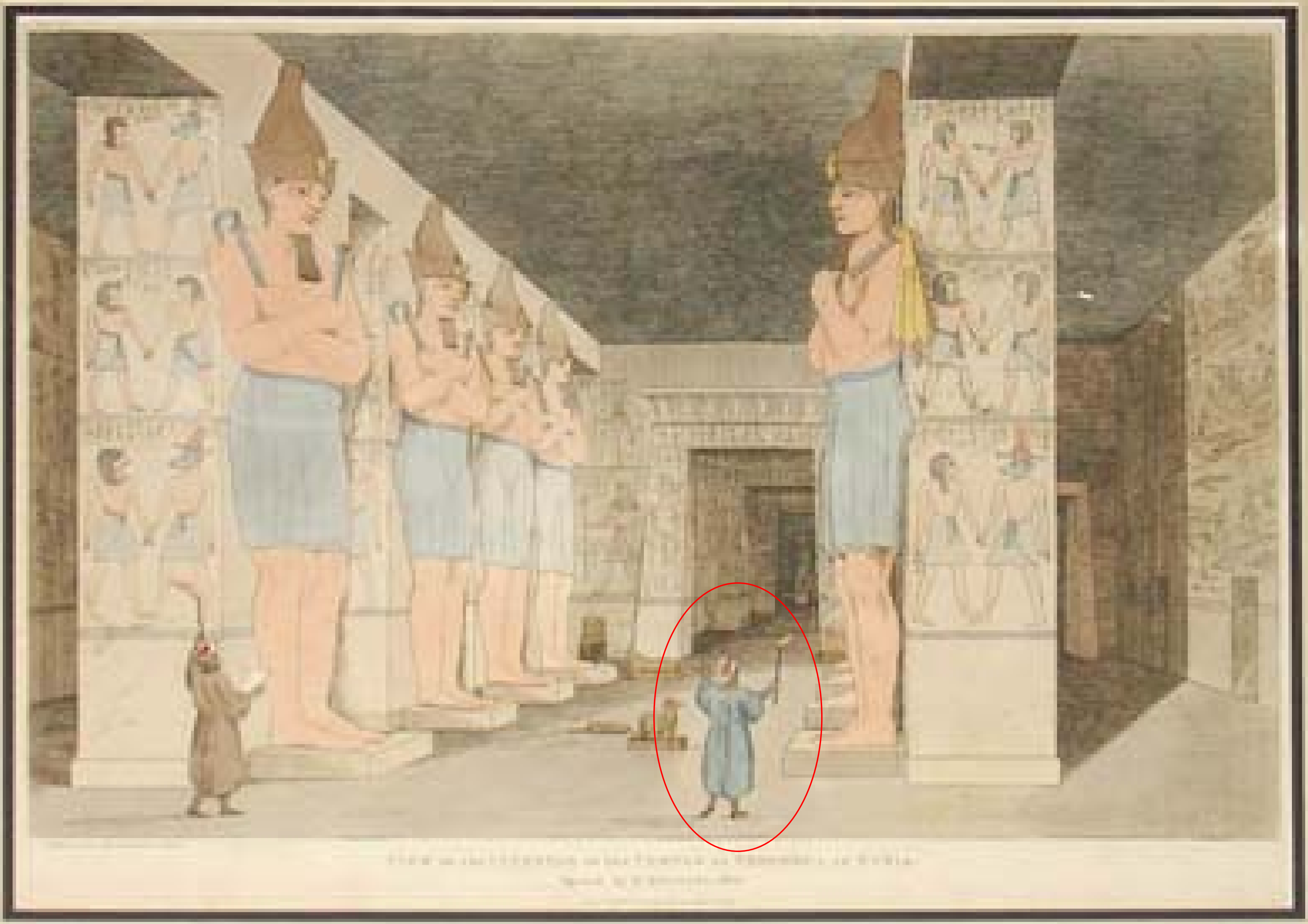
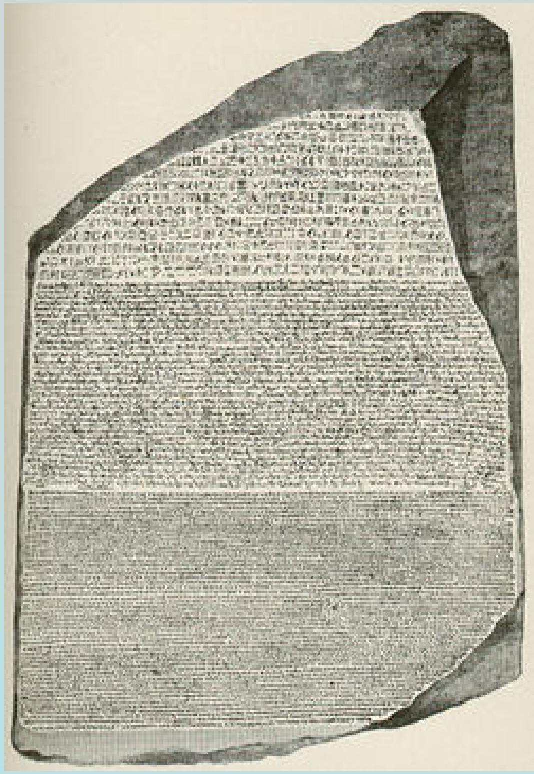
EXTERIOR VIEW of the TWO TEMPLES at IPSAMBUL



Jean François Champollion was a young student, when he met in Grenoble the famous mathematician Joseph Fourier, secretary of the Egyptian Institute of Cairo.

Fourier noticed **Champollion** and invited that student to visit his Egyptian collection.



Looking at the hieroglyphics, the young **Champollion** asked if deciphering those signs would have ever been possible or not.

Once obtained a negative answer from Fourier, **Champollion** decided that **in future he would have solved the mistery!**

The ***desire to discover and understand secrets*** *is deeply rooted inside the man-kind.*

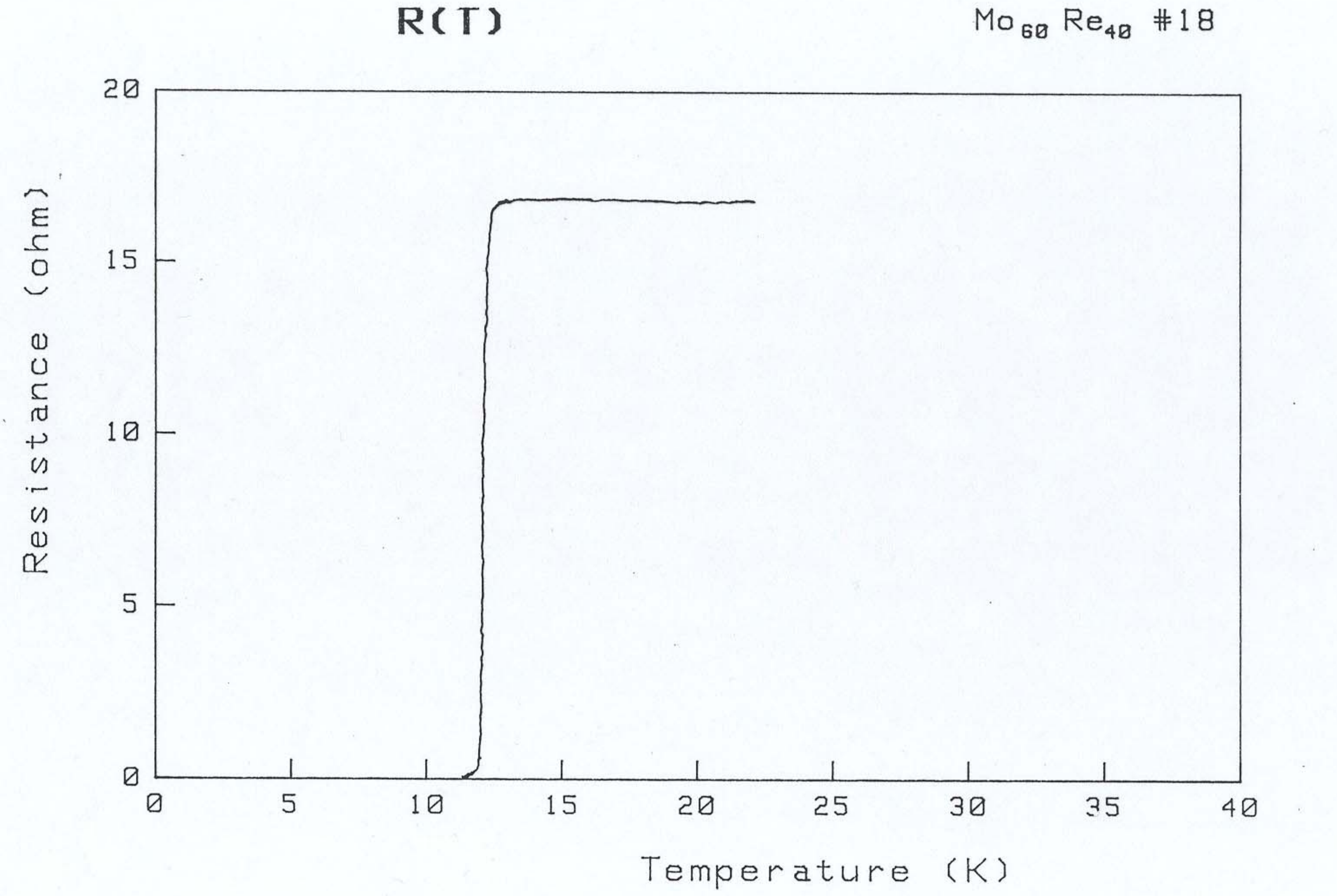
Even the less curious mind is stimulated by the perspective to ***reach knowledge levels that remain unachievable to others****.*

Someone has the ***luck to find a job that consists of the search for solving mysteries****, as the Physicist that looks for a still undiscovered elementary particle or the investigator that discovers the author of a crime!*

However the only possibility given to the majority of people for satisfying this fundamental need is the application of its "own genius" to the solution of enigmas invented for our enjoyment.

For the majority of people there are detective stories and crosswords:

The deciphering of secret codes, the discovery of a new particle, or of a new material, can only be an hobby for a limited number of lucky people!


R(T)
Mo 60 Re 40 #18
Resistance (ohm)
20
15
10
5
0
0
5
10
15
20
25
30
35
40
Temperature (K)

APPLIED SUPERCONDUCTIVITY

(Phenomenology of a Superconductor)

Enzo Palmieri

ISTITUTO NAZIONALE DI FISICA NUCLEARE
Laboratori Nazionali di Legnaro

and

PADUA UNIVERSITY
Material Science and Engineering

CERN, Academic Training, Jan 17 2007

Lecture 1 of 3

APPLIED SUPERCONDUCTIVITY

(CERN, Academic Training)

Wednesday, Jan 17, 2007

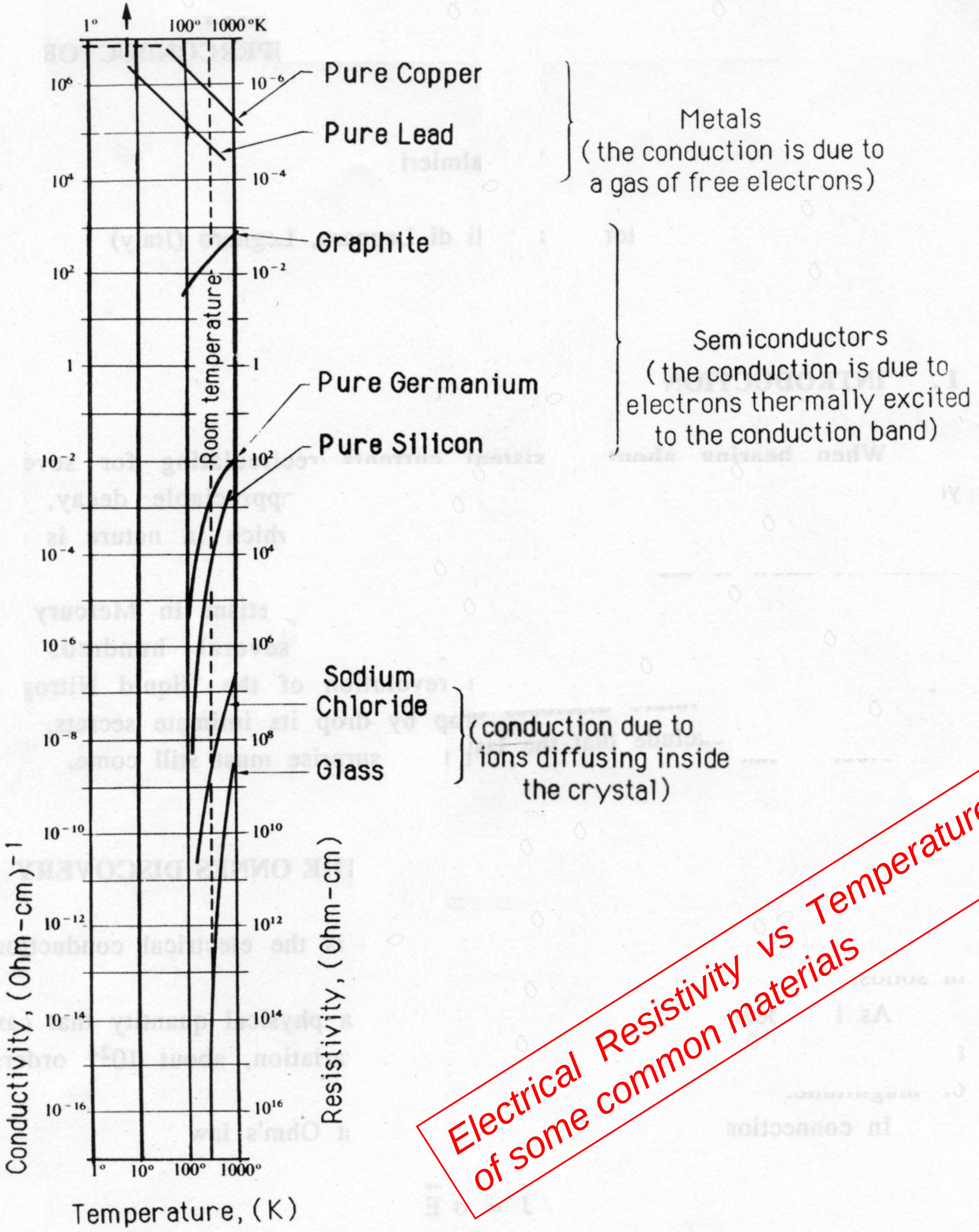
Lecture 1 / 3 **Phenomenology of a Superconductor**

Thursday, Jan 18, 2007

Lecture 2 / 3 **Some Industrial Applications**

Friday, Jan 19, 2007

Lecture 3 / 3 **Superconducting materials**

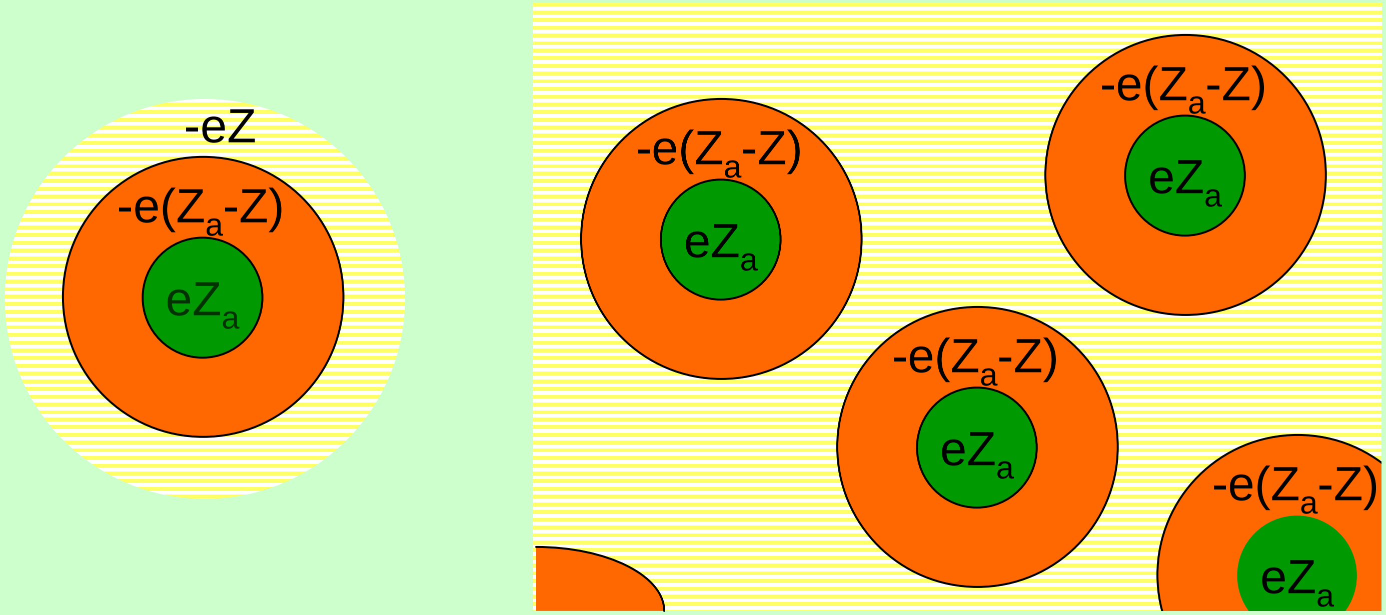


Electrical Resistivity vs Temperature of some common materials

ELECTRICAL CONDUCTION in metals

DRUDE MODEL of a free Electron Gas (1900)

“Electrons Wonder freely through a background of positive ions strongly pinned in Ordered Positions”



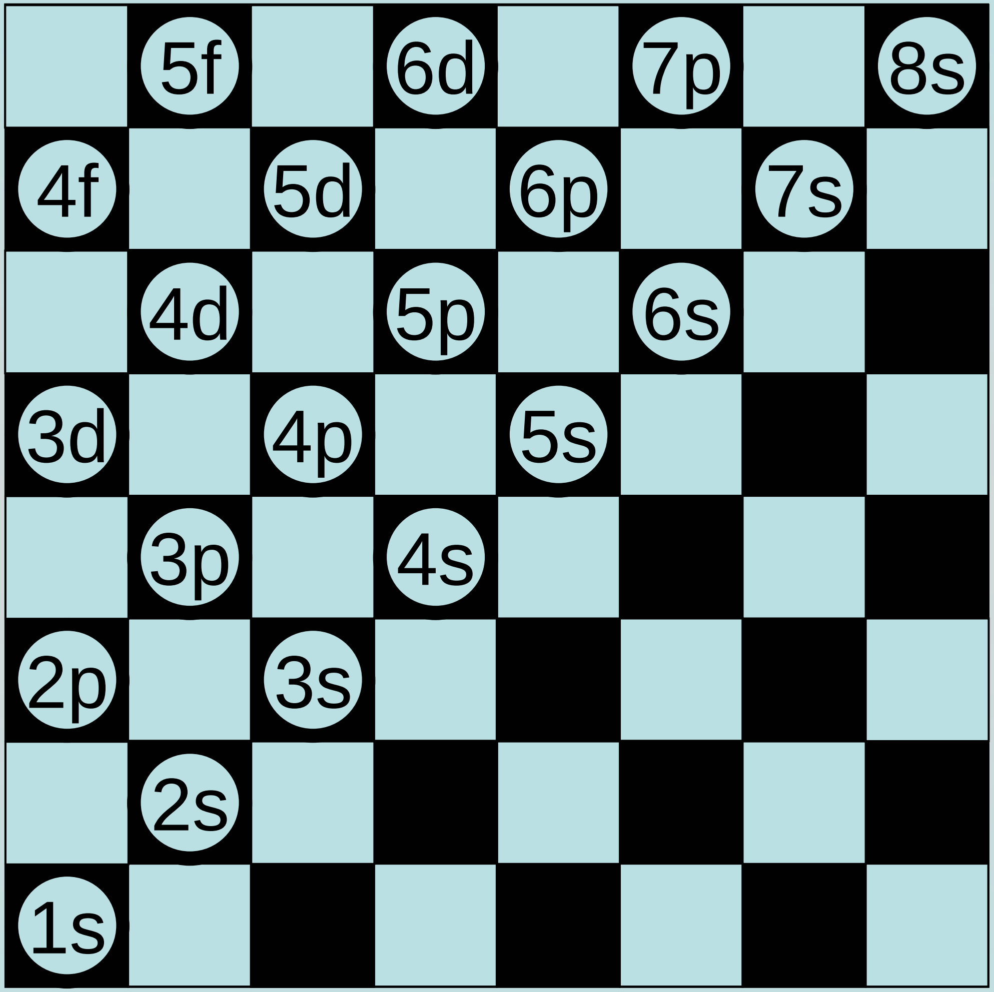
Es.:

Na $1s^2\ 2s^2\ 2p^6\ 3s^1$

🟩 Nucleus
🟧 Core Electrons
▤ Valence Electrons

Ion { 🟩 Nucleus
🟧 Core
▤ Conduction Electrons

The **Hovland Rule** for remembering the ground state electron configurations



	5f		6d		7p		8s
4f		5d		6p		7s	
	4d		5p		6s		
3d		4p		5s			
	3p		4s				
2p		3s					
	2s						
1s							

The electron configuration for a given element is then obtained by starting at the lower left and reading from left to right on successive rows

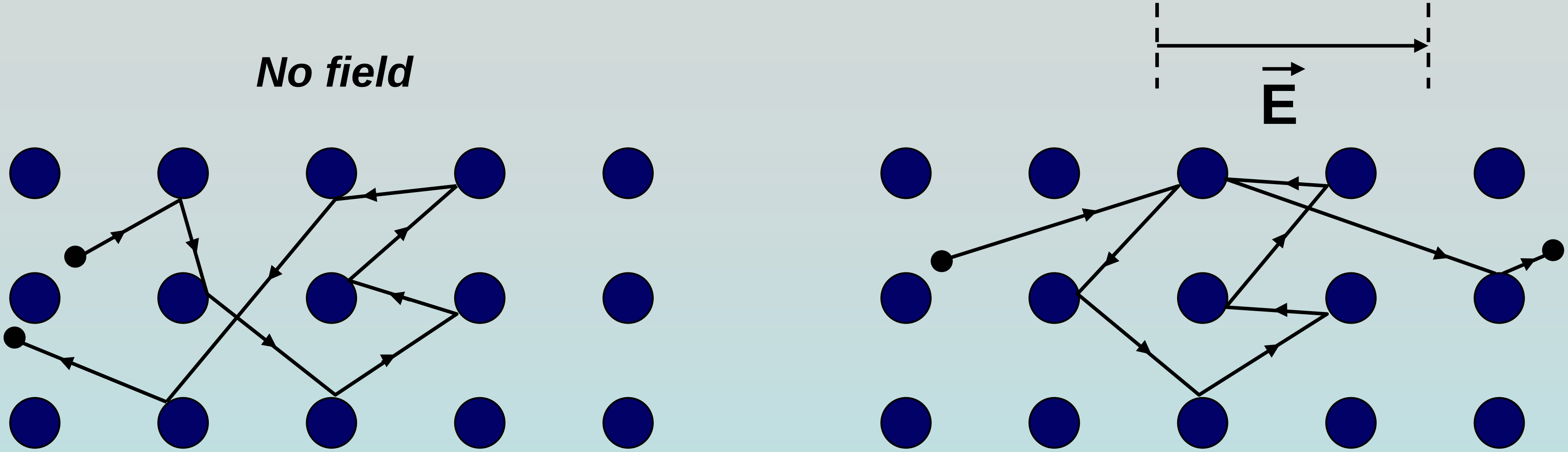
DRUDE MODEL of a free Electron Gas

Approximations:

i. e-e interactions and e-ion interactions are neglected

ii. Fixed ions, instantaneous collisions

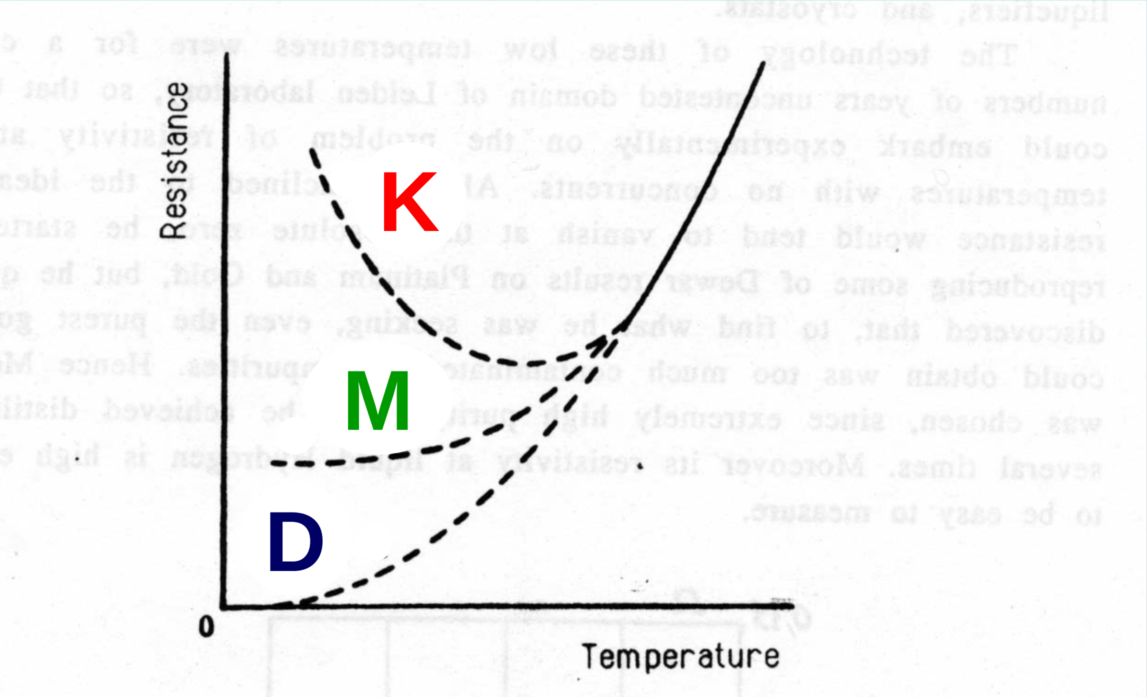
iii. After any collisions, electron loose memory



Limits:

Hall effect; Magneto-resistance; $\frac{k}{\sigma \cdot T} = f(T)$; m.f.p.; σ(T); σ(ω); Boron vs Alluminum

Low Temperature Resistivity

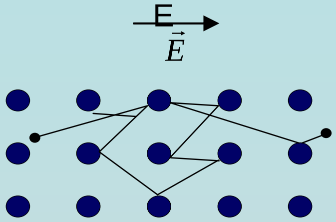


Lord Kelvin: **Electrons become free due to the thermal vibrations**

Matthiessen: **Phonons + Residual (1984)**

Sir J. Dewar: **Electron motion gets obstructed by thermal vibrations**

Dewar liquified **H_2**, but he was not able to liquify **He**, then he switched to study soap films



$$\frac{d\vec{p}}{dt} = -e\vec{E}$$

$$\vec{J} = -\frac{ne}{m}\cdot\frac{d\vec{p}}{dt}\tau = \frac{ne^{2}}{m}\cdot\tau\cdot\vec{E} = \sigma\cdot\vec{E}$$

Ohm Law

$$\sigma = {}^{1}\!/_{\rho} = \frac{ne^{2}\tau}{m}$$

$$\tau = {}^{1}\!/_{f} =$$ Time between two collisions

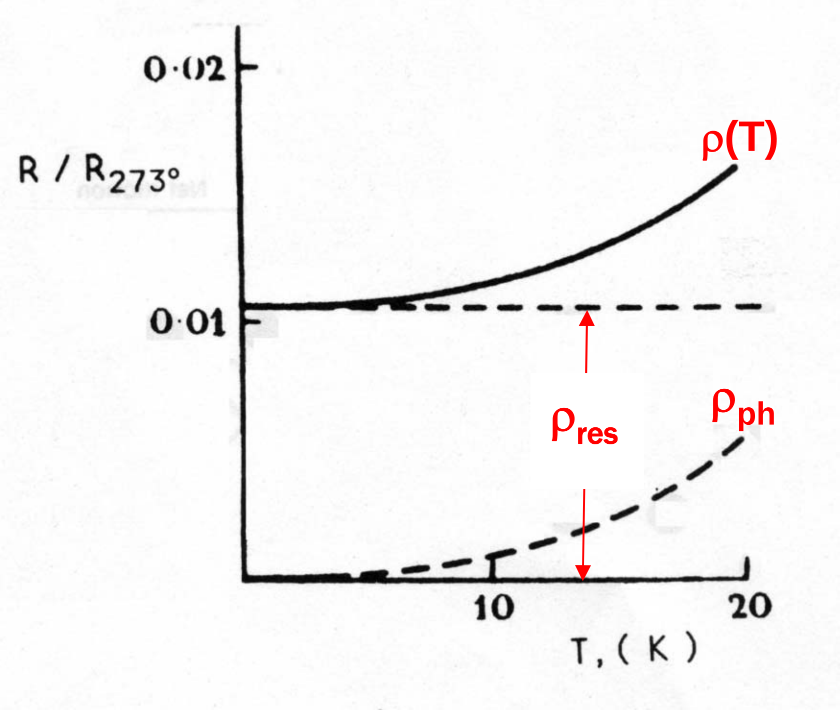
The collision frequency is addiive: $f = f_{ph} + f_{res}$ ↔ $\frac{1}{\tau} = \frac{1}{\tau_{ph}} + \frac{1}{\tau_{res}}$

$$\rho = \rho_{ph} + \rho_{res}$$

Matthiessen Law

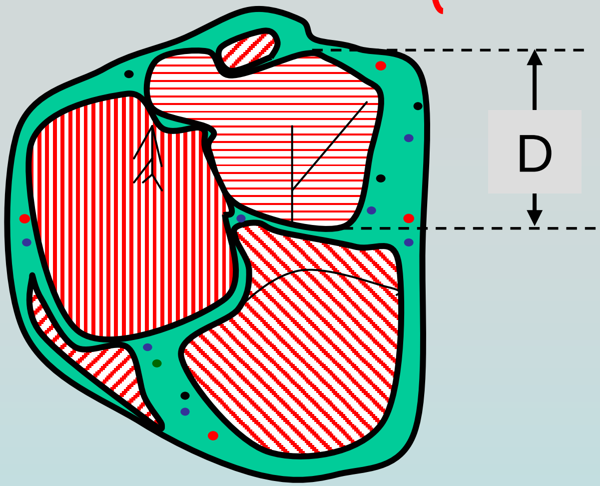
$$\rho = \rho_{ph} + \rho_{res}$$

(Valid only for low concentration of impurities)



ρ_{res}

- **Impurities**
- **Lattice imperfections**
- **Grain boudaries**



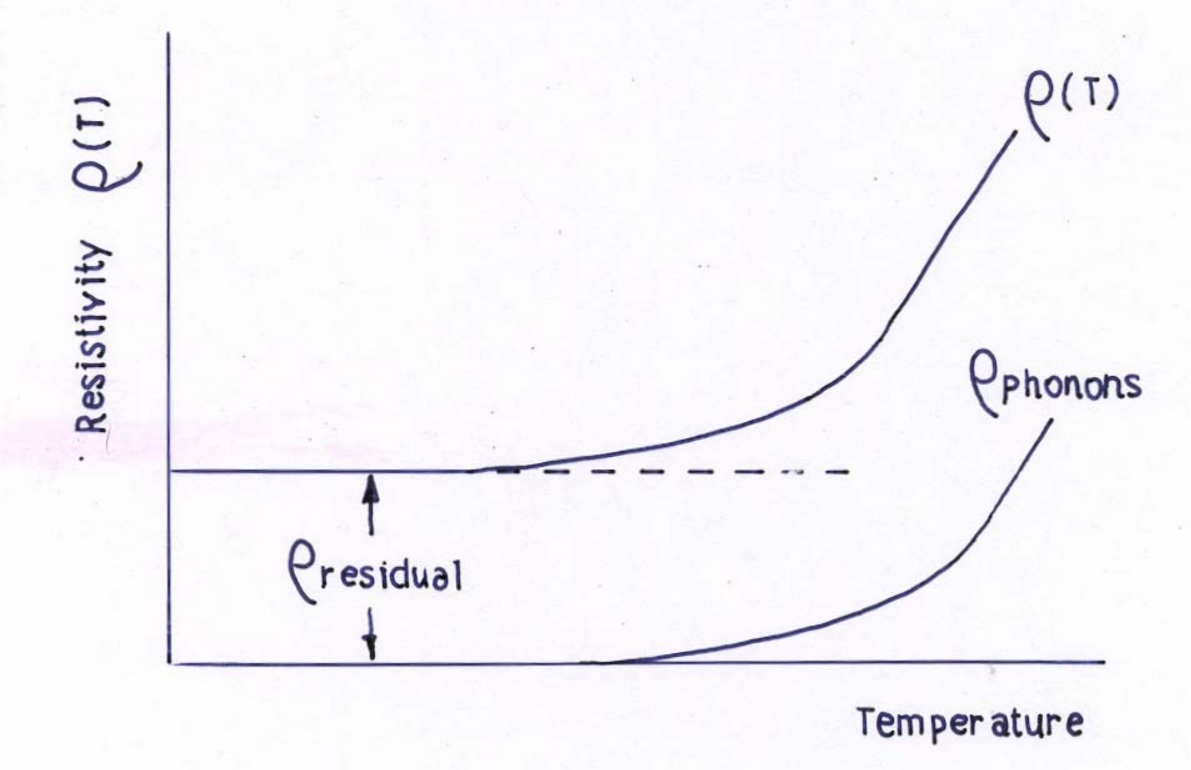
D > l_{imp}

$$\frac{1}{\tau} = \frac{1}{\tau_{ph}} + \frac{1}{\tau_{imp}}$$

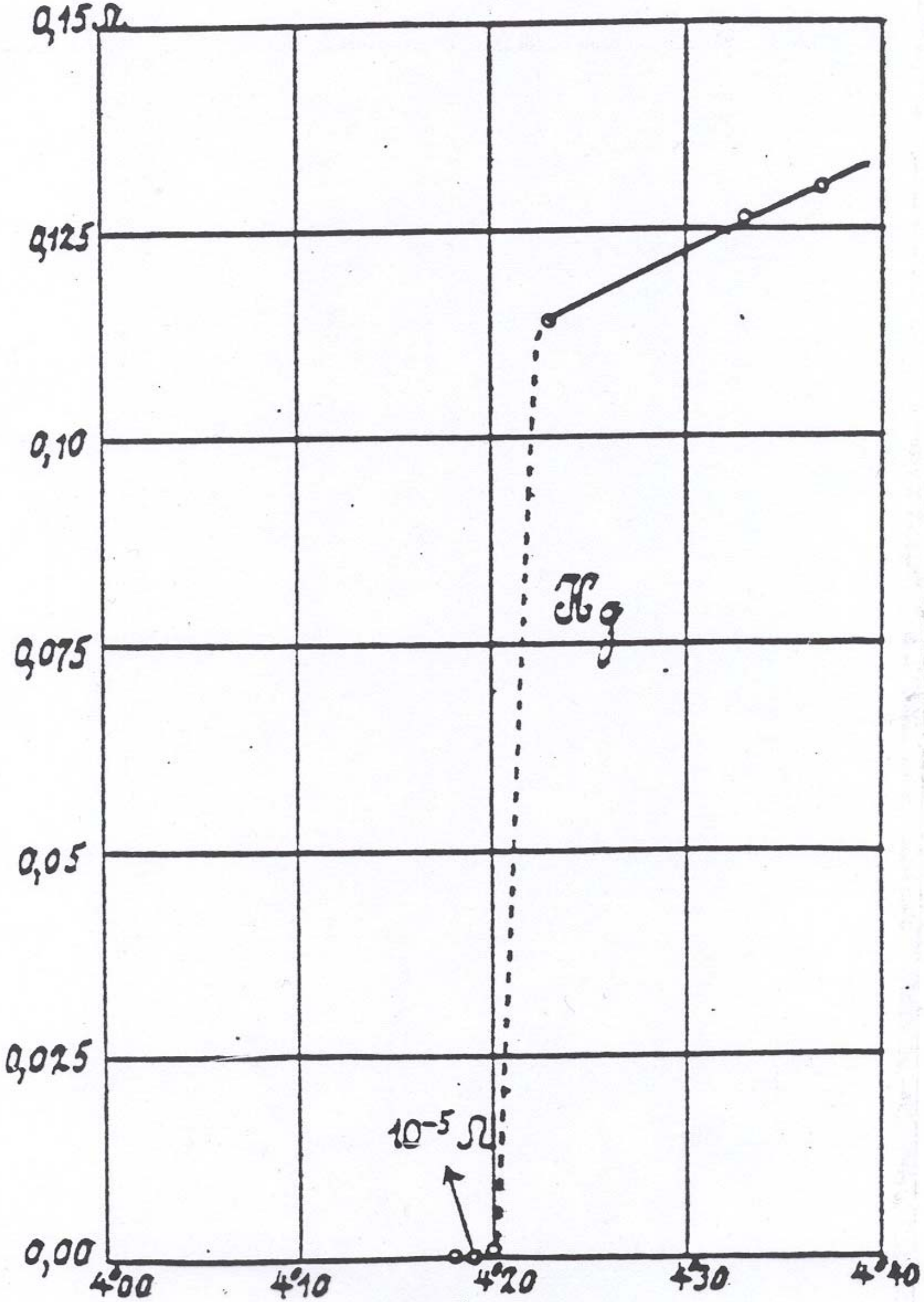
D < l_{imp}

$$\frac{1}{\tau} = \frac{1}{\tau_{ph}} + \frac{1}{\tau_{imp}} + \frac{1}{\tau_{GB}}$$

$$RRR = \frac{\rho(300K)}{\rho_{residual}} = 1 + \frac{\rho_{phonons}(300K)}{\rho_{residual}}$$



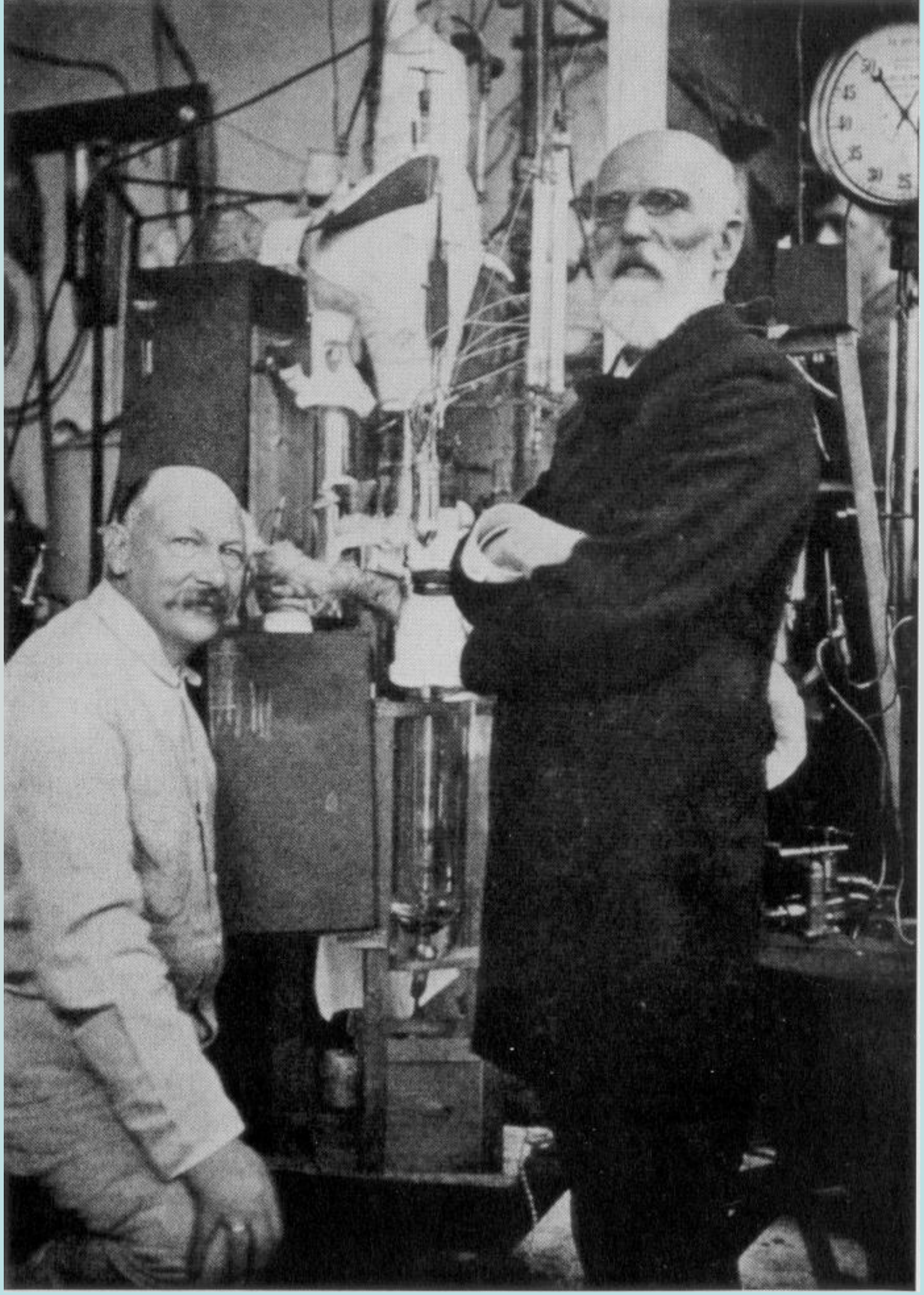
$$\lambda_{4.2K} = \frac{RRR}{4}[W \cdot m^{-1} \cdot K^{-1}]$$


0,15 Ω
0,125
0,10
0,075
0,05
0,025
0,00
4°00
4°10
4°20
4°30
4°40
Hg
10⁻⁵ Ω

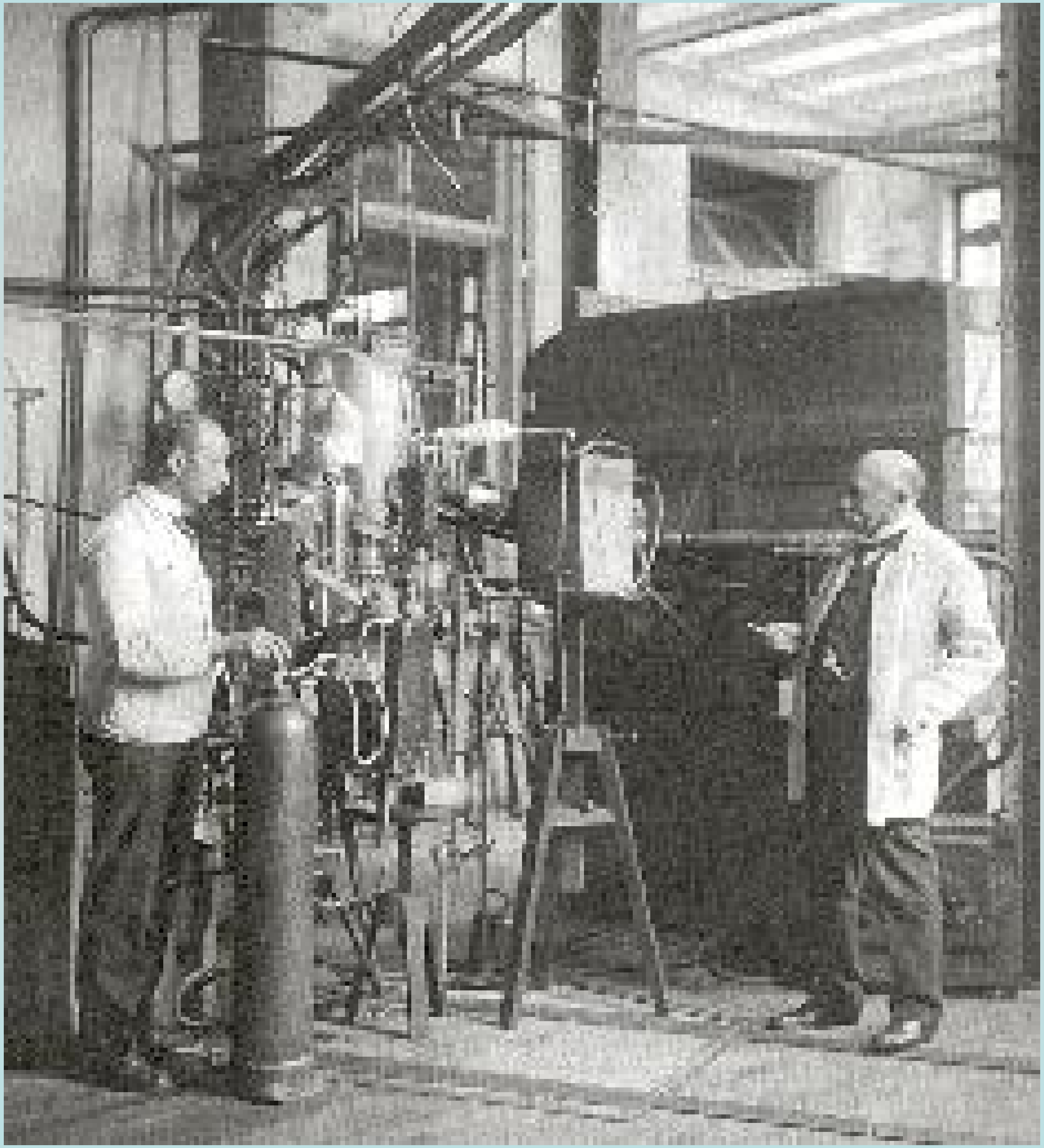

WERNER · KAMERLINGH-ONNES
NOBELPRIS 1913
SVERIGE 75
LASSE SÖDERBERG
1973
ARNE WALLHORN sc

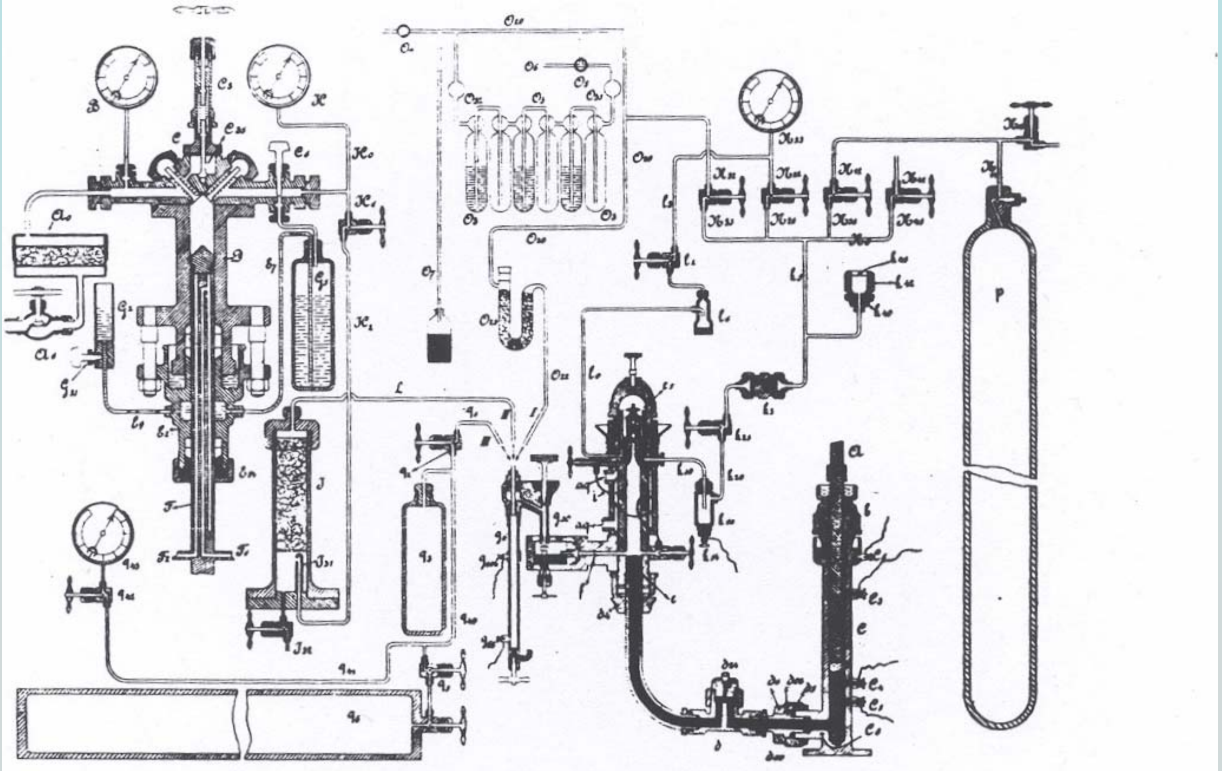

H·KAMERLINGH ONNES
1853 1926
1½ct
NEDERLAND
CULTUREELE & SOCIALE ZORG


GRENADA
Heike Kamerlingh Onnes.
Physics 1913
$1.50



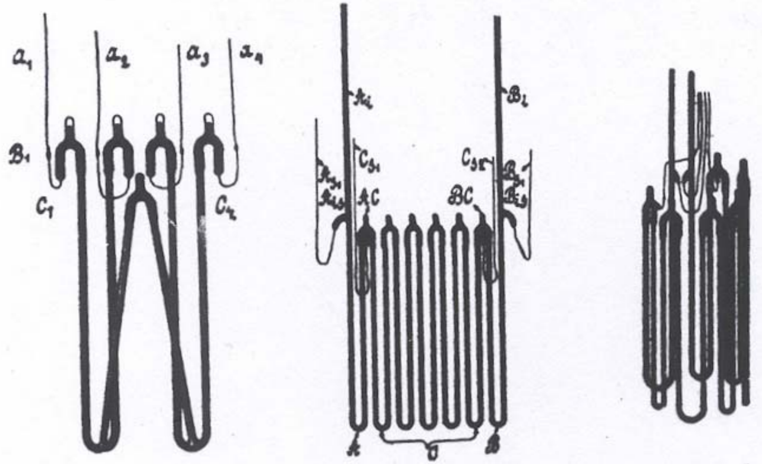
Heike Kamerlingh Onnes (left)** a**nd Van der Waals in Leiden at the helium 'liquefactor' (1908)

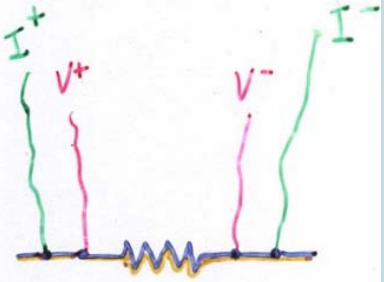


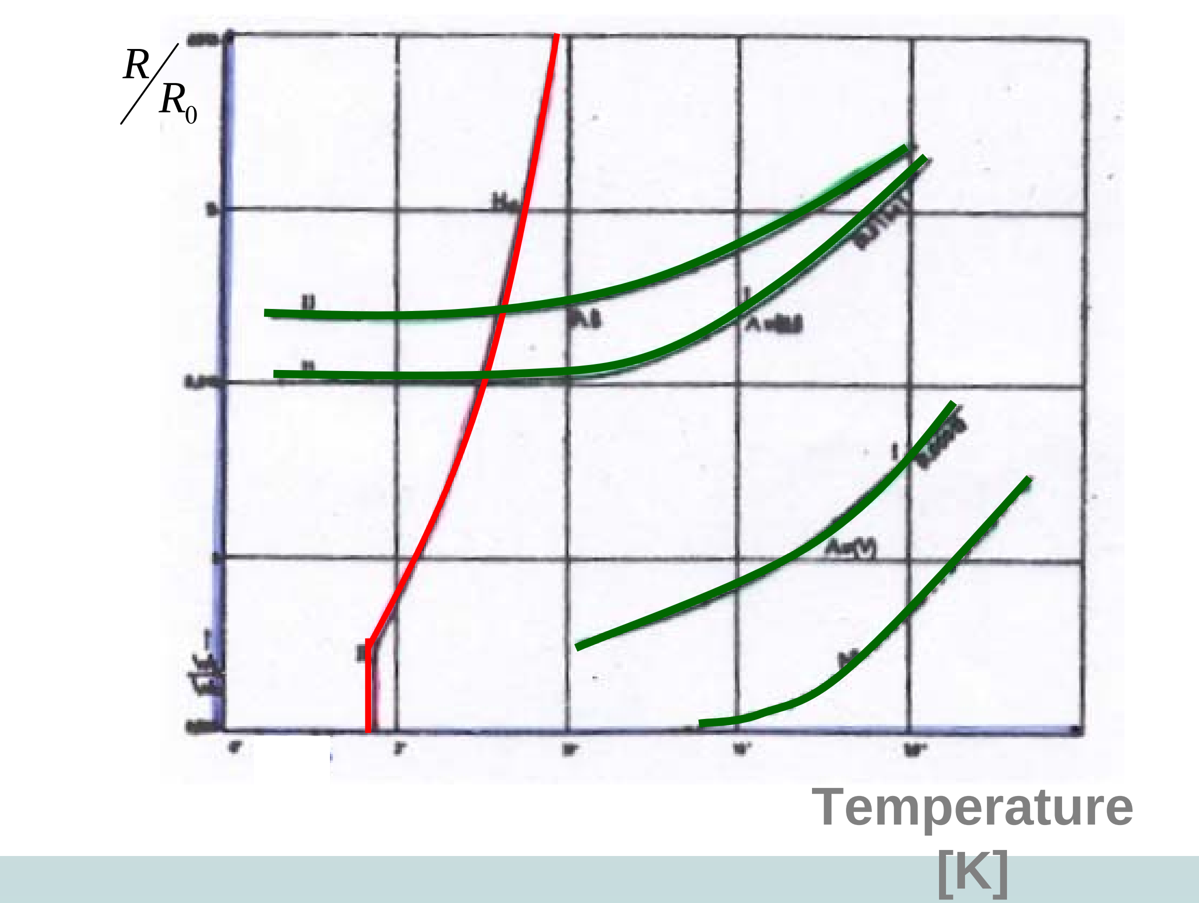


Dr. H. KAMERLINGH ONNES. Methods and apparatus used in the Cryogenic Laboratory II: Mercury pump for compressing pure and costly gases under high pressure.

Figure 2

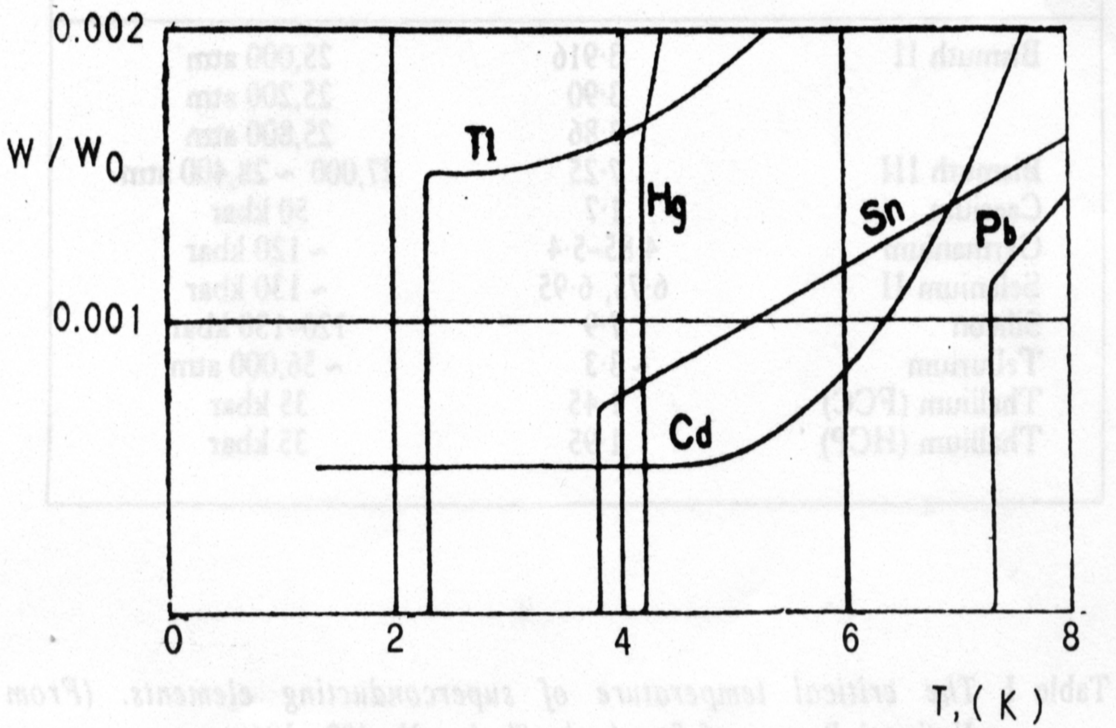






🟩 **Au in pure form**

🟥 **Hg distilled**
(28th° Apr 1911)



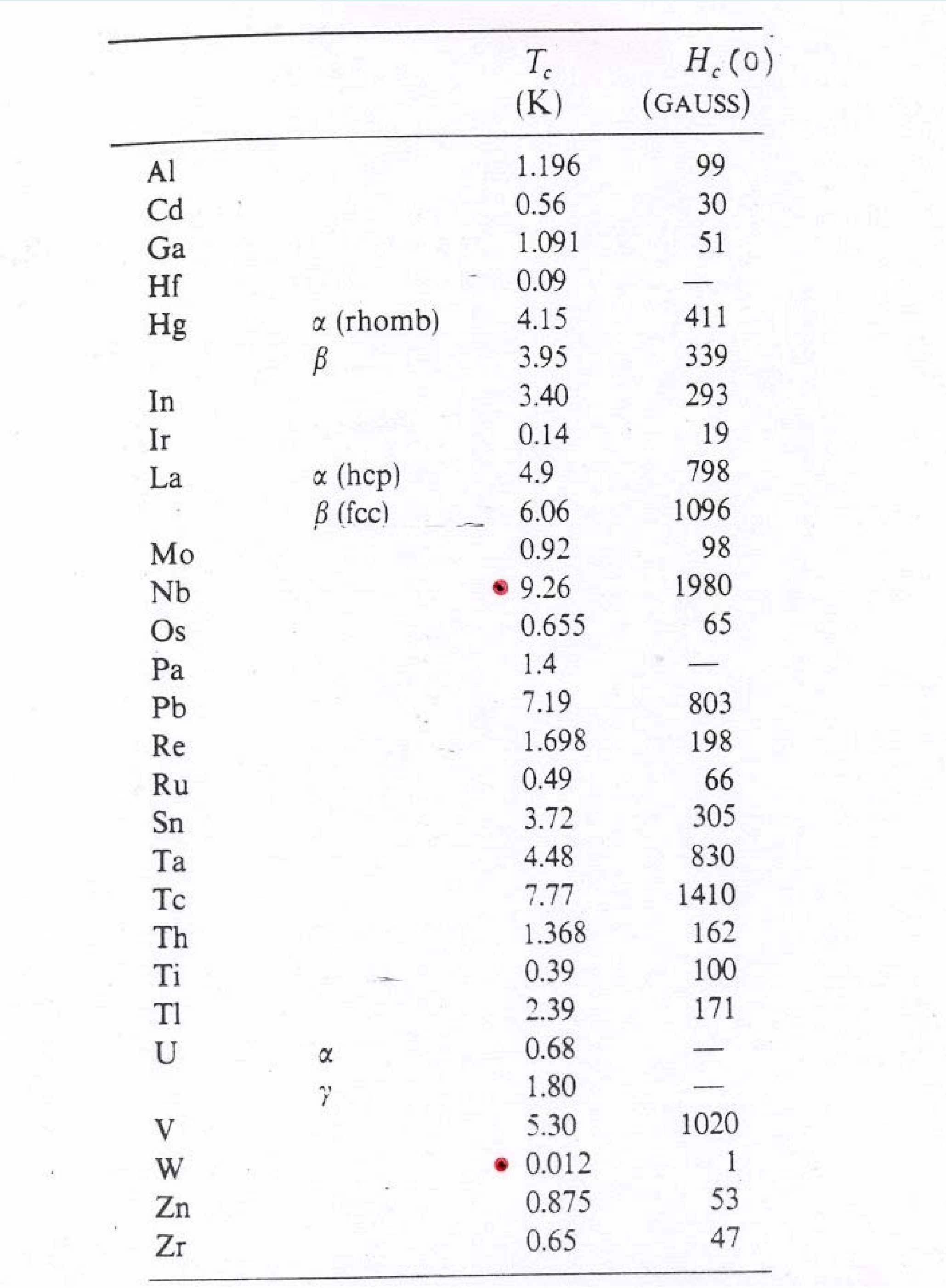
The resistive superconducting transition of other elements investigated by Onnes.

$$I = I(0)\exp(-\frac{R}{L}t)$$

Persistent currents in superconducting rings→ ~ 2,5 years of experiment

(Collings, 1956) $\rho < 10^{-21}\ \Omega$ cm

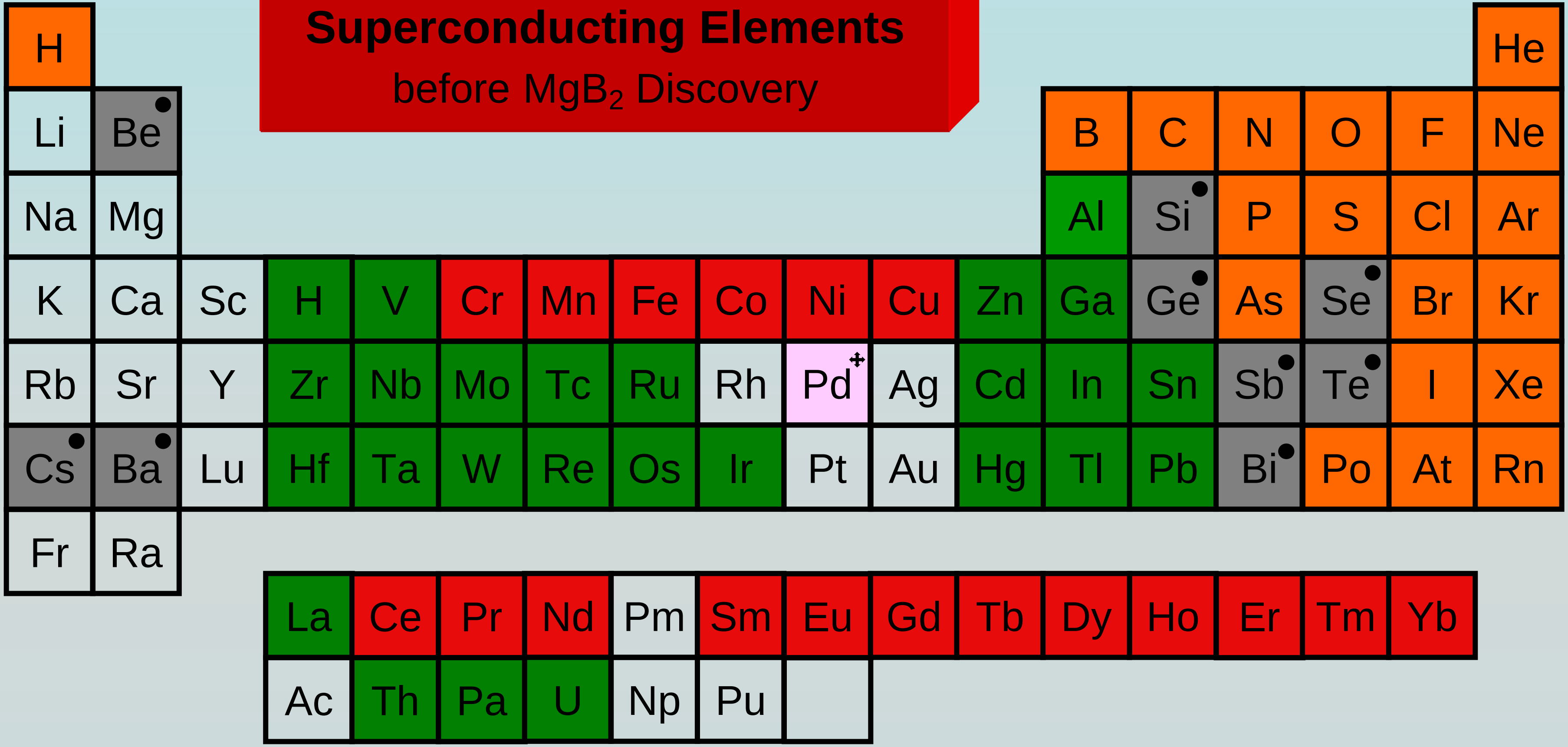
(Quinn, Ittner, 1962) $\rho < 10^{-23}\ \Omega$ cm



		T_c (K)	$H_c(0)$ (GAUSS)
Al		1.196	99
Cd		0.56	30
Ga		1.091	51
Hf		0.09	—
Hg	α (rhomb)	4.15	411
	β	3.95	339
In		3.40	293
Ir		0.14	19
La	α (hcp)	4.9	798
	β (fcc)	6.06	1096
Mo		0.92	98
Nb		● 9.26	1980
Os		0.655	65
Pa		1.4	—
Pb		7.19	803
Re		1.698	198
Ru		0.49	66
Sn		3.72	305
Ta		4.48	830
Tc		7.77	1410
Th		1.368	162
Ti		0.39	100
Tl		2.39	171
U	α	0.68	—
	γ	1.80	—
V		5.30	1020
W		● 0.012	1
Zn		0.875	53
Zr		0.65	47

Superconducting Elements

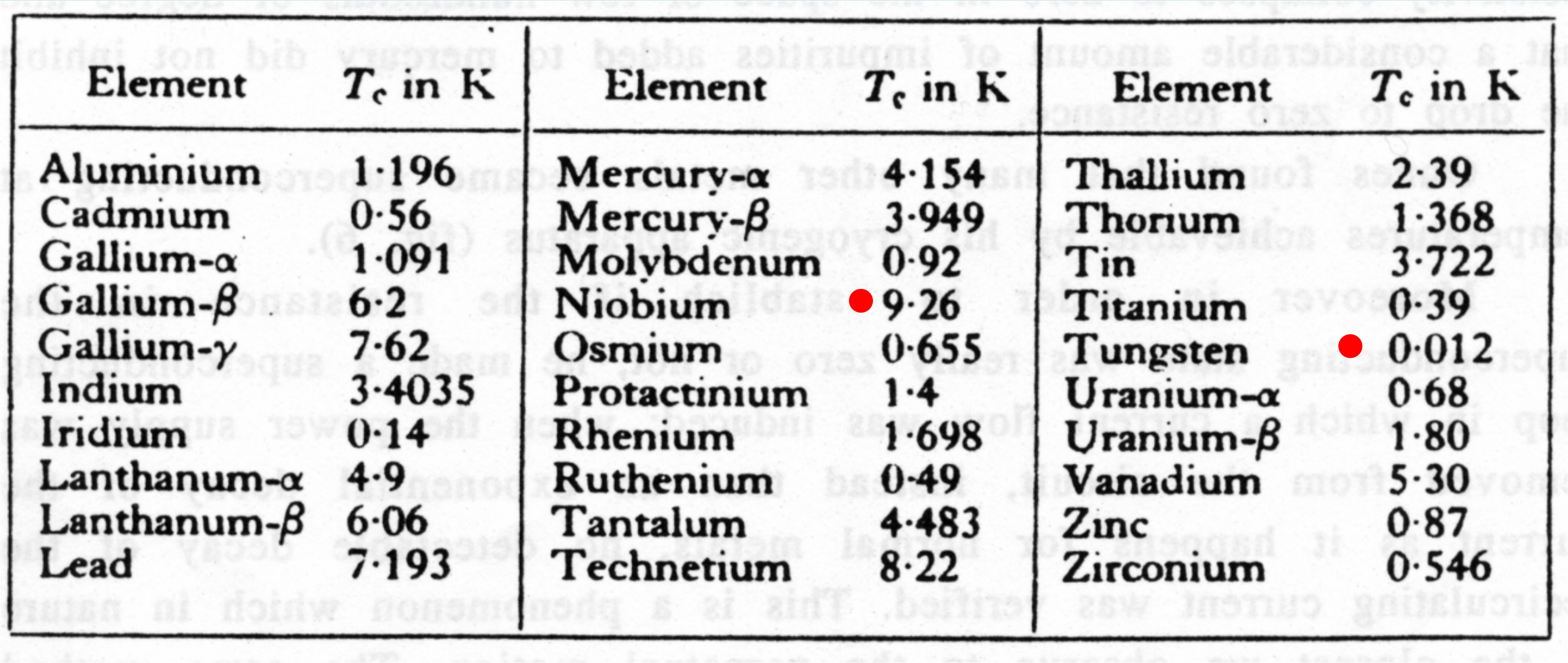
before MgB_2 Discovery



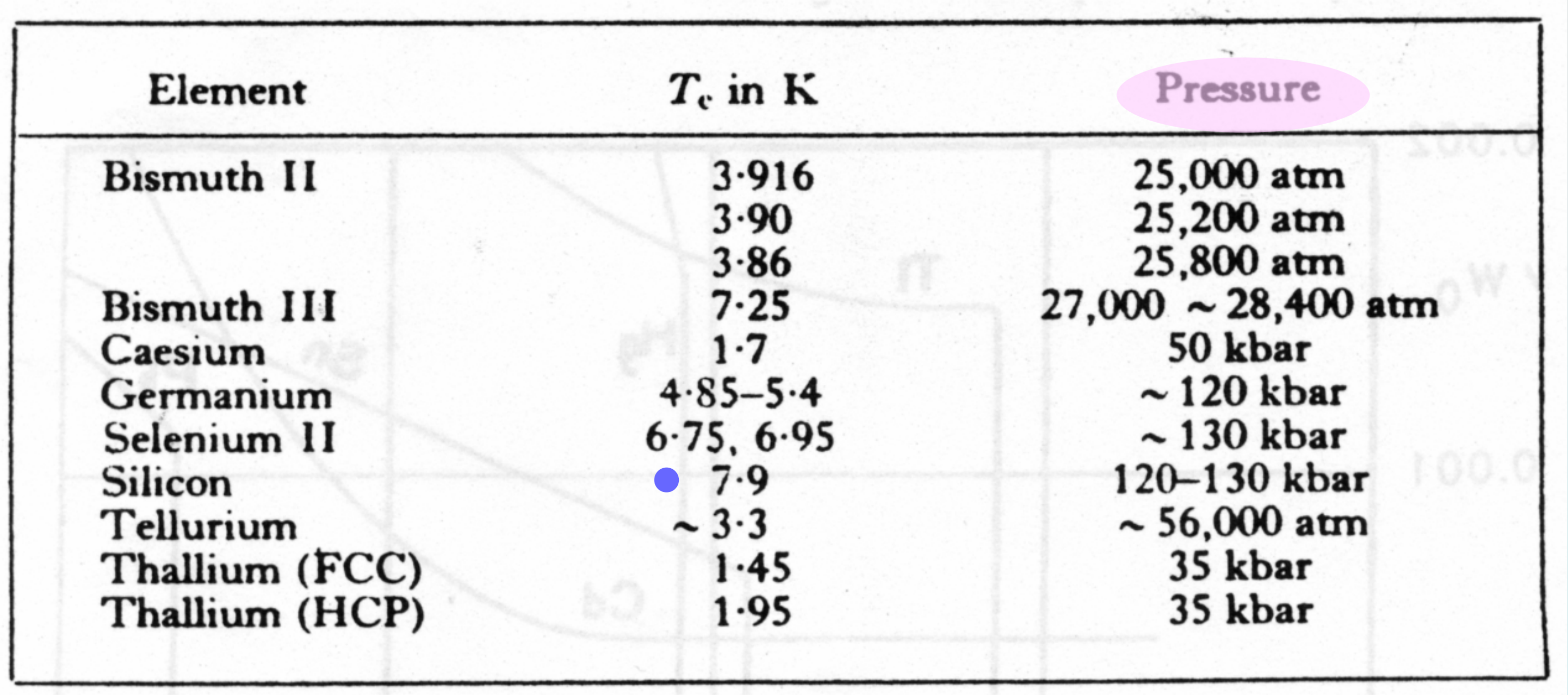
H																	He
Li	Be ●											B	C	N	O	F	Ne
Na	Mg											Al	Si ●	P	S	Cl	Ar
K	Ca	Sc	H	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge ●	As	Se ●	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb ●	Te ●	I	Xe
Cs ●	Ba ●	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi ●	Po	At	Rn
Fr	Ra																
		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb		
		Ac	Th	Pa	U	Np	Pu										

Legend:

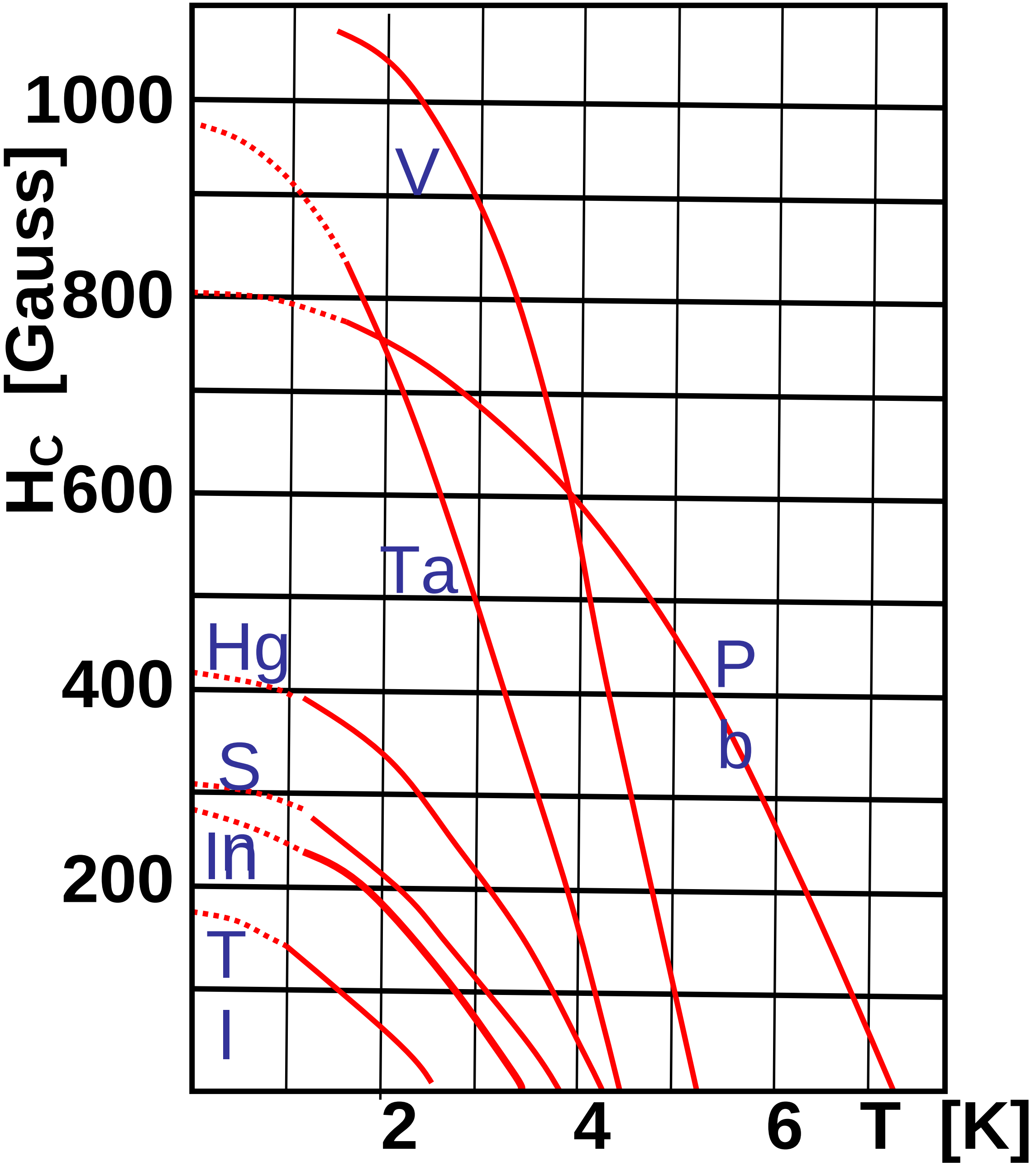
Al	**Superconducting**	B	**Non metallic elements**
Si ●	**Superconducting under high pressure or in thin films**	Fe	**Elements with Magnetic order**
Li	**Metallic but not yet found to be Superconducting**	Pd	**Superconducting in thin films when irradiated by α-particles**



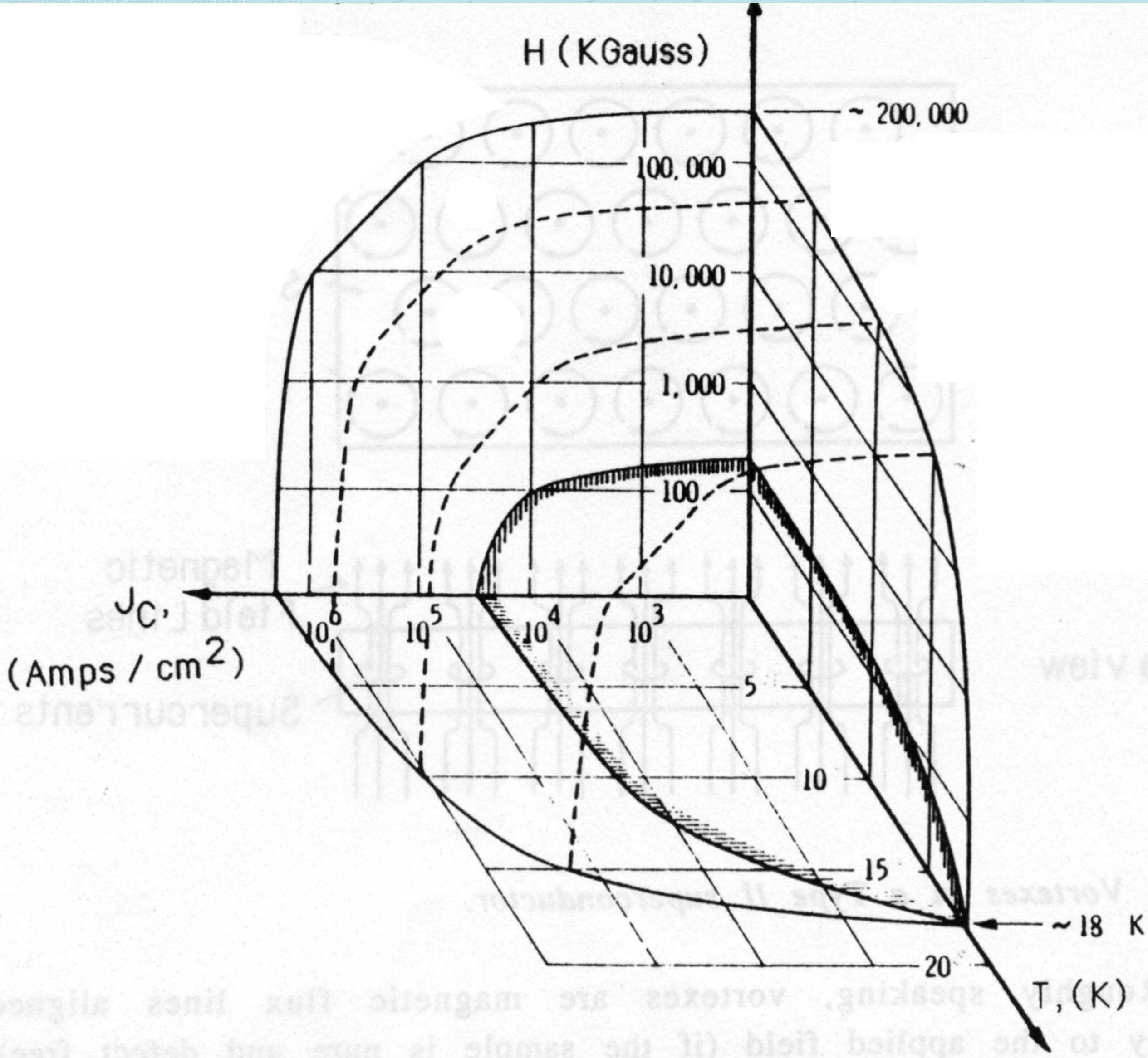
Element	T_c in K	Element	T_c in K	Element	T_c in K
Aluminium	1·196	Mercury-α	4·154	Thallium	2·39
Cadmium	0·56	Mercury-β	3·949	Thorium	1·368
Gallium-α	1·091	Molybdenum	0·92	Tin	3·722
Gallium-β	6·2	Niobium	● 9·26	Titanium	0·39
Gallium-γ	7·62	Osmium	0·655	Tungsten	● 0·012
Indium	3·4035	Protactinium	1·4	Uranium-α	0·68
Iridium	0·14	Rhenium	1·698	Uranium-β	1·80
Lanthanum-α	4·9	Ruthenium	0·49	Vanadium	5·30
Lanthanum-β	6·06	Tantalum	4·483	Zinc	0·87
Lead	7·193	Technetium	8·22	Zirconium	0·546



Element	T_c in K	Pressure
Bismuth II	3·916	25,000 atm
	3·90	25,200 atm
	3·86	25,800 atm
Bismuth III	7·25	27,000 ~ 28,400 atm
Caesium	1·7	50 kbar
Germanium	4·85–5·4	~ 120 kbar
Selenium II	6·75, 6·95	~ 130 kbar
Silicon	● 7·9	120–130 kbar
Tellurium	~ 3·3	~ 56,000 atm
Thallium (FCC)	1·45	35 kbar
Thallium (HCP)	1·95	35 kbar



1000
800
600
400
200
H_C [Gauss]
2
4
6
T [K]
V
Ta
Pb
Hg
Sn
In
Tl



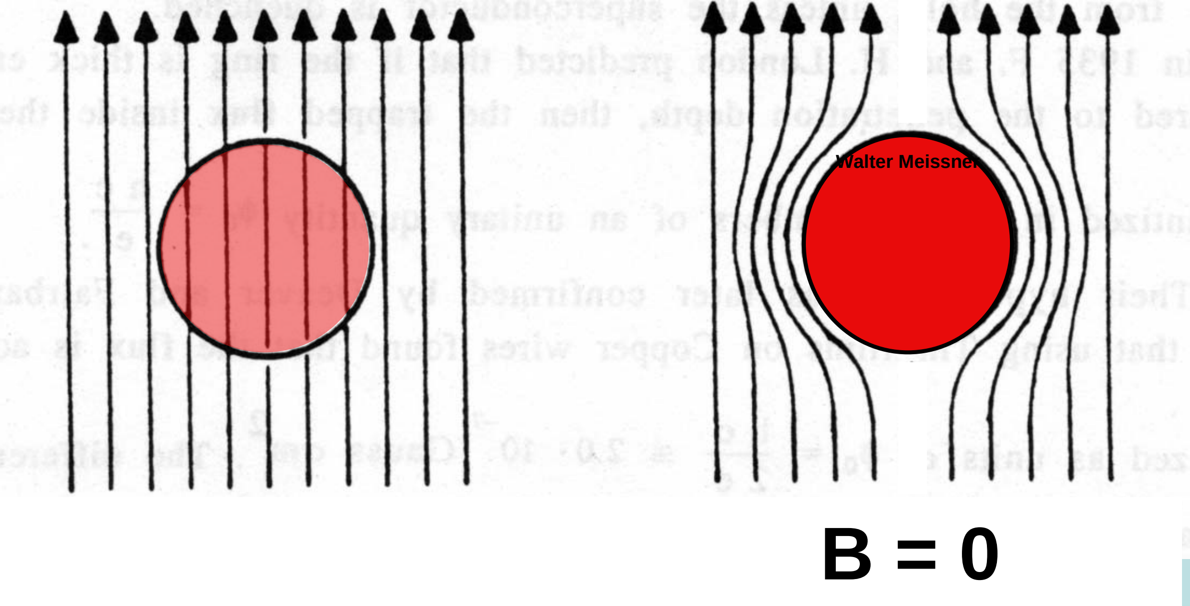
Critical current density and critical field for superconducting Nb_3Sn. The shadow line delimits the region of type I behaviour, while the type II behaviour occurs between the inner and outer surfaces.

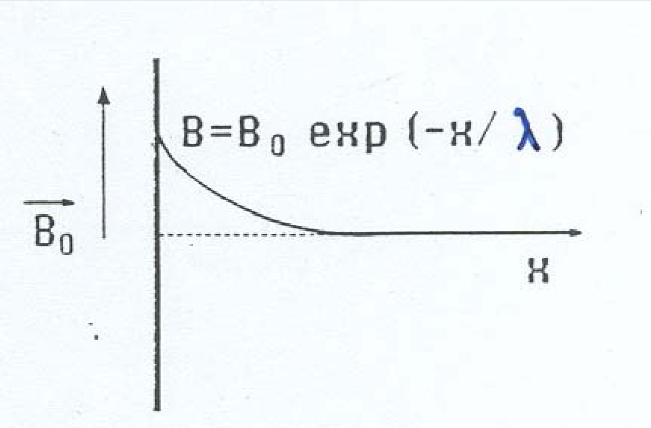
The Meissner-Ochsenfeld effect

Walter Meissner

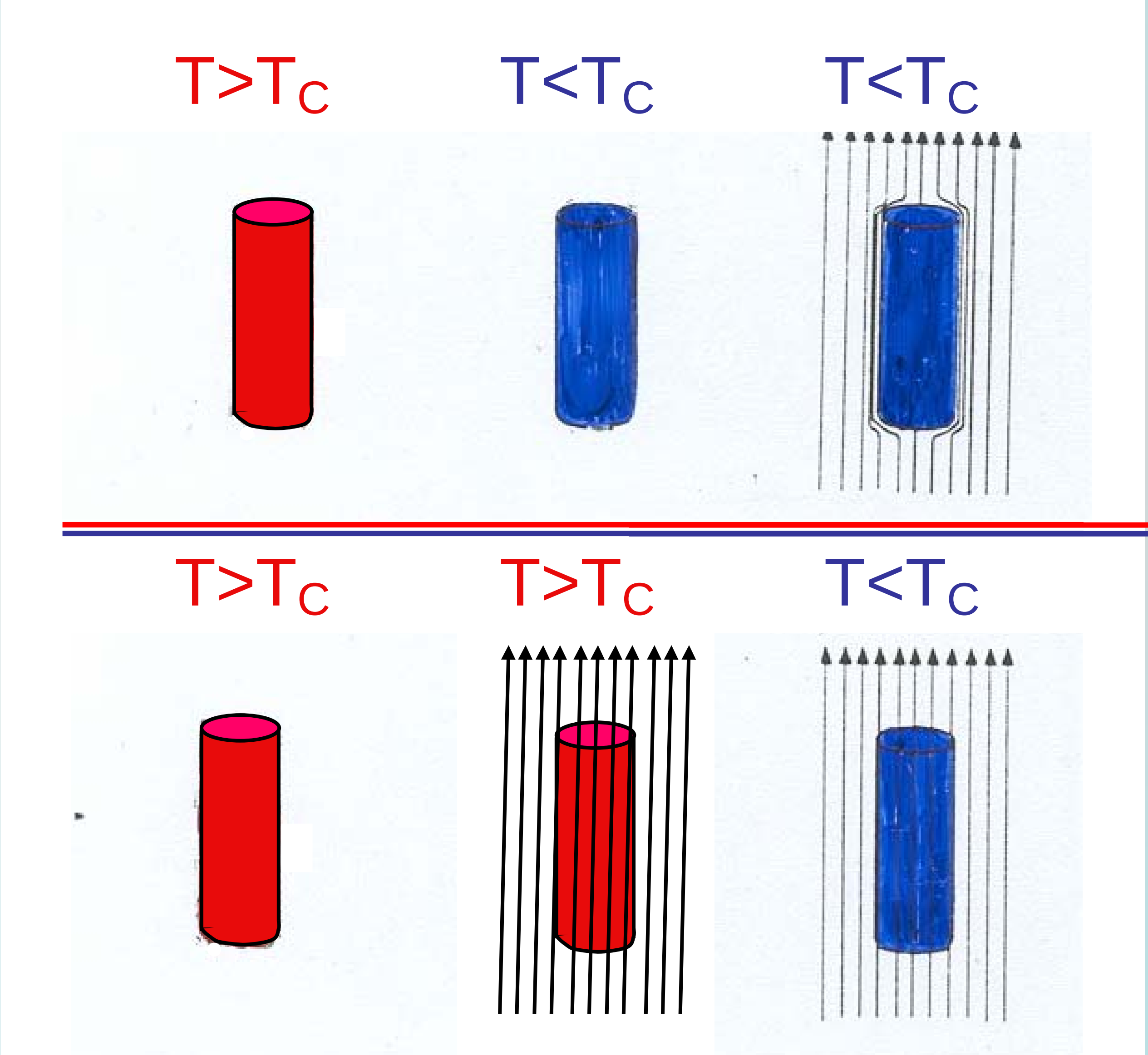
When a material undergoes the superconducting transition, the magnetic induction B is shrunk out

e



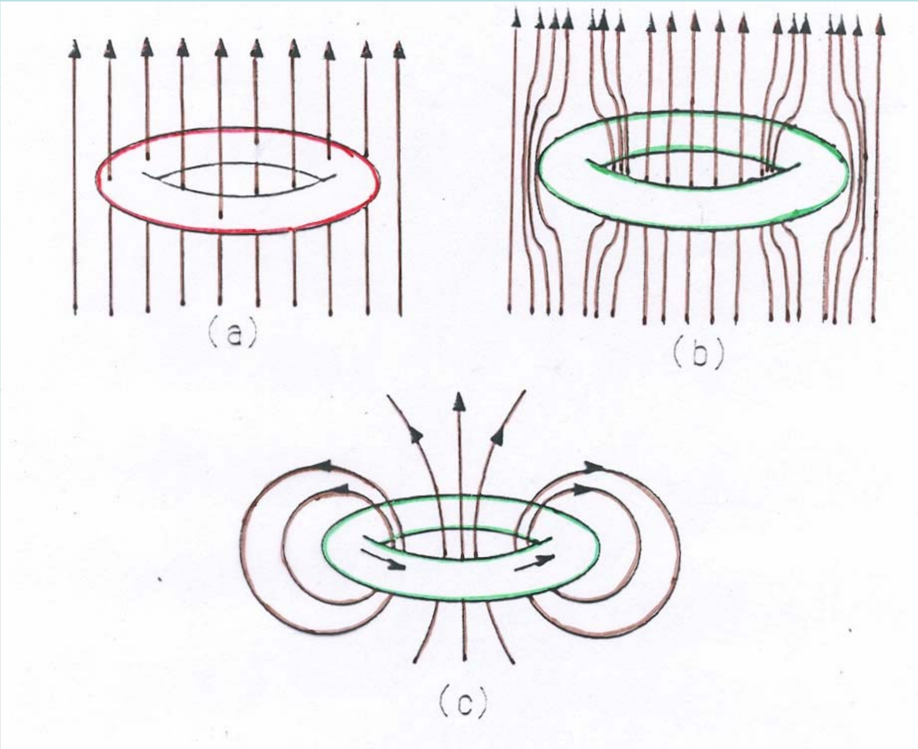


A Superconductor is not only a perfect conductor, magnet

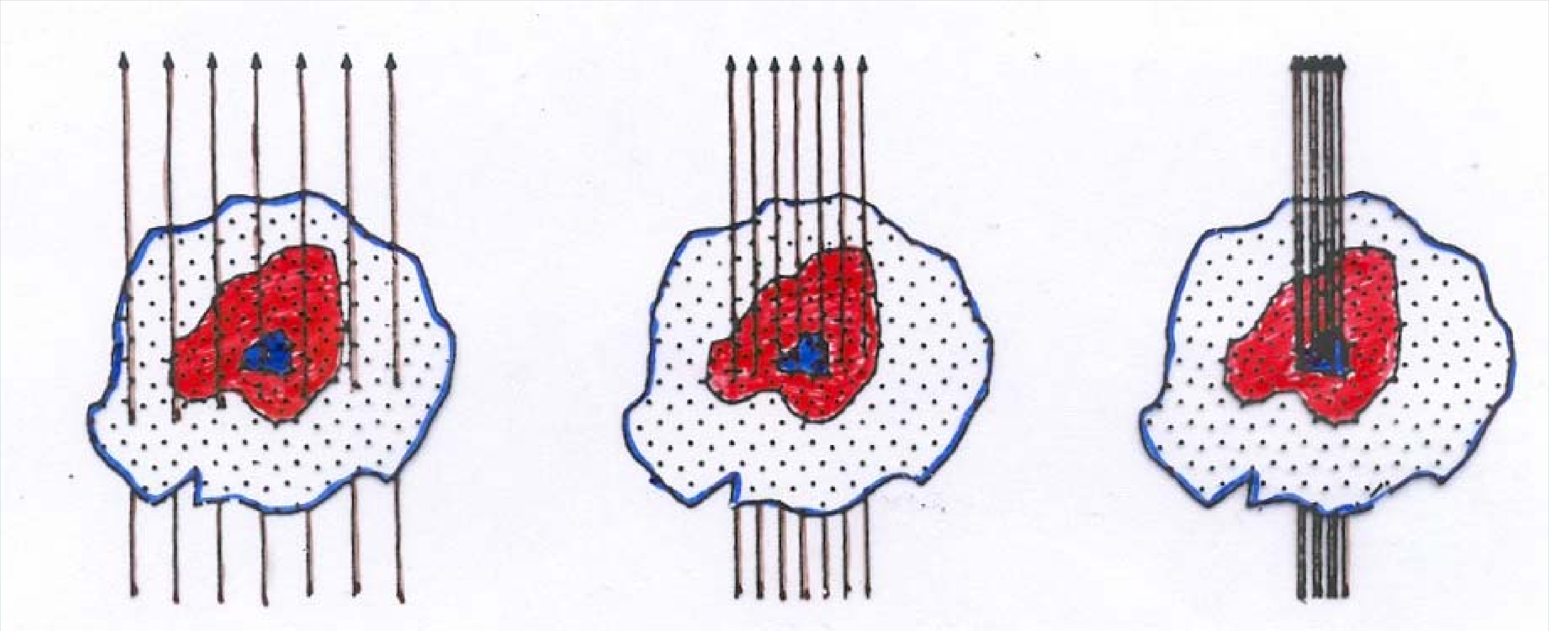


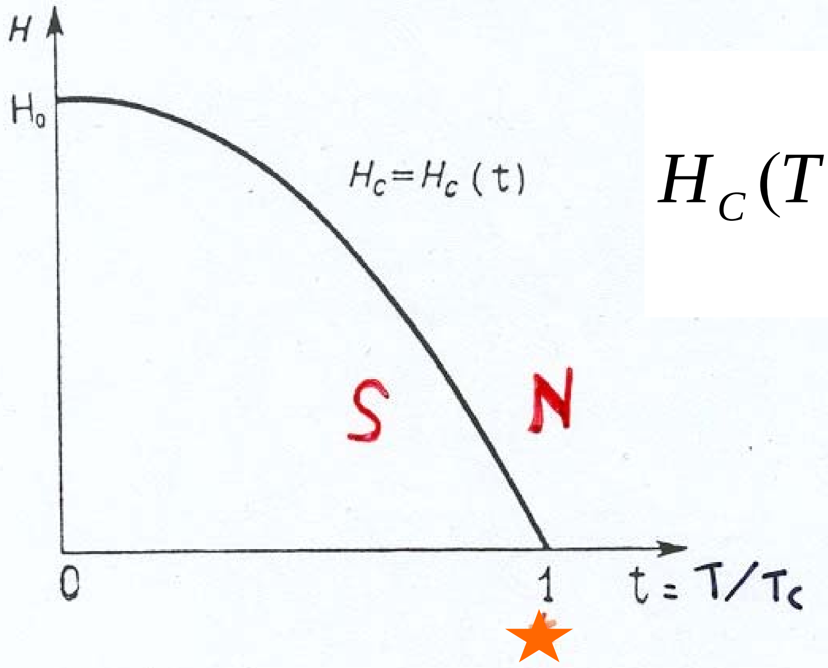
A Supercond uctor

A perfect conductor



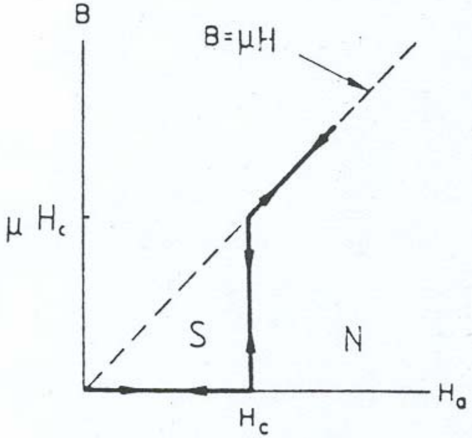
$$\Phi_0 = \frac{hc}{2e} = 2 \times 10^{-7}\, Gauss \cdot cm^2$$

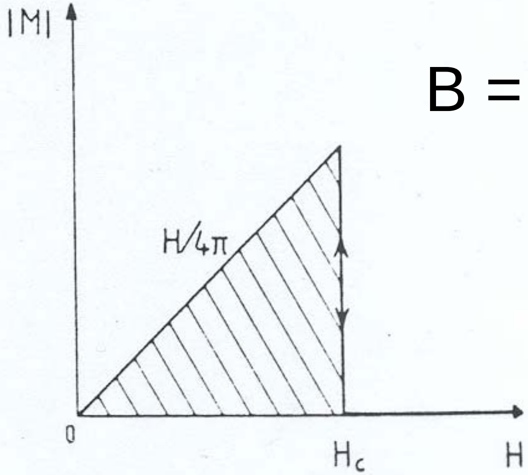




$$H_C(T) = H_C \cdot \left[1 - \left(\frac{T}{T_C} \right)^2 \right]$$

I Kind Superconductors (Sn,In, Hg,Pb,…….Soft SC)

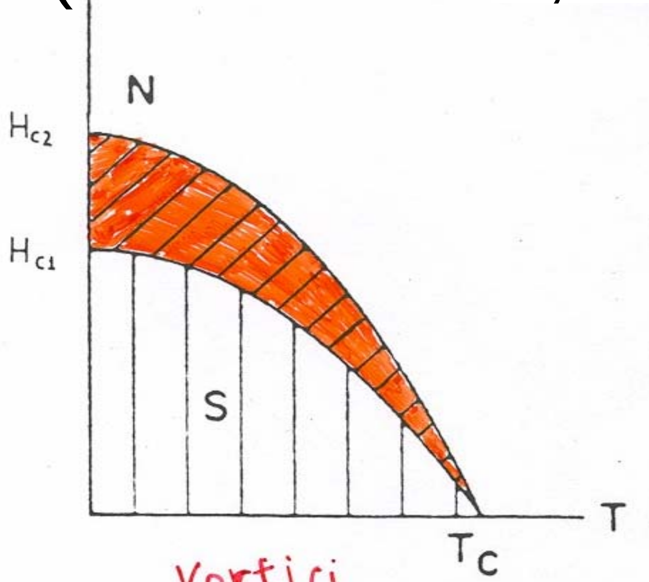


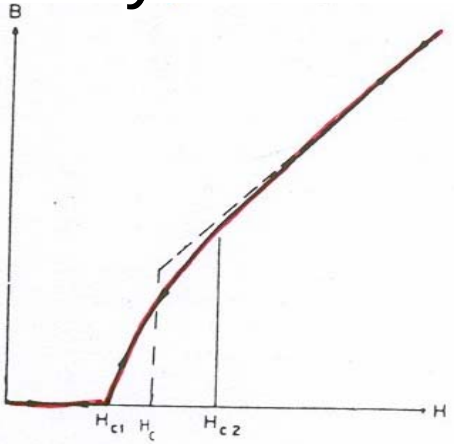


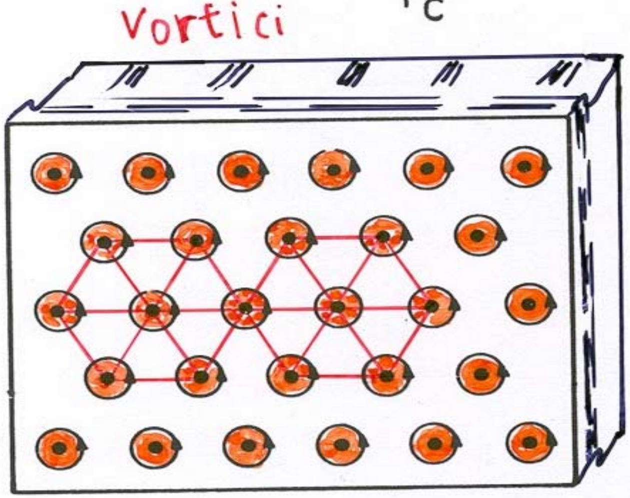
B = H + 4πM = 0

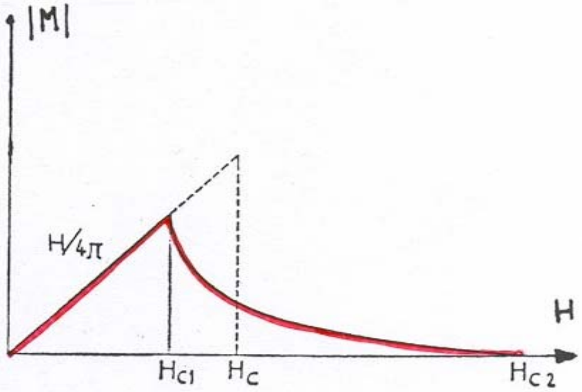
II Type Superconductors

(hard materials, alloys, Refractory Materials



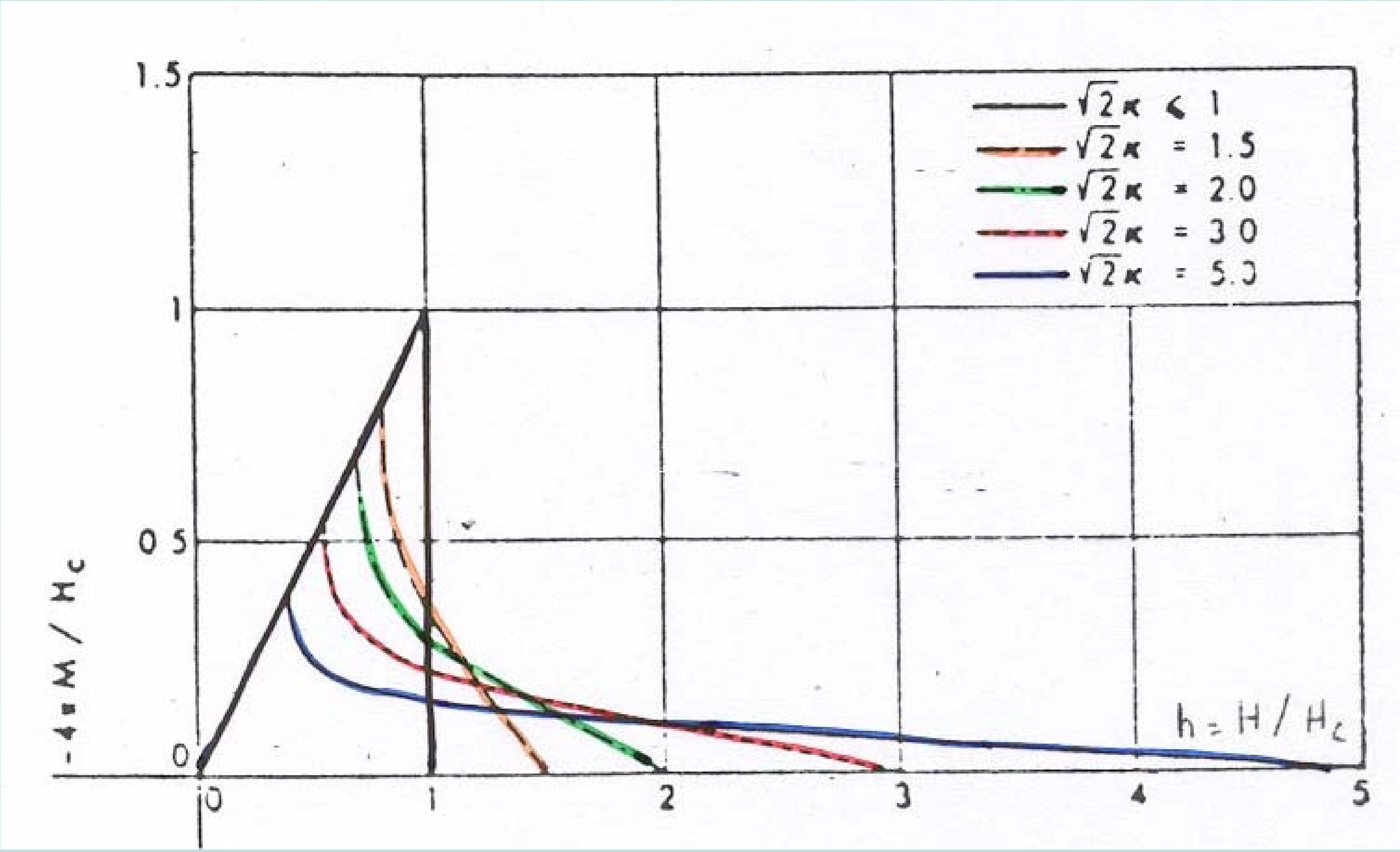






A current **$I < I_C$** will interact with Vortexes

$$\vec{F}_L = \vec{J} \times \vec{\Phi}_0$$



I Kind → II Kind

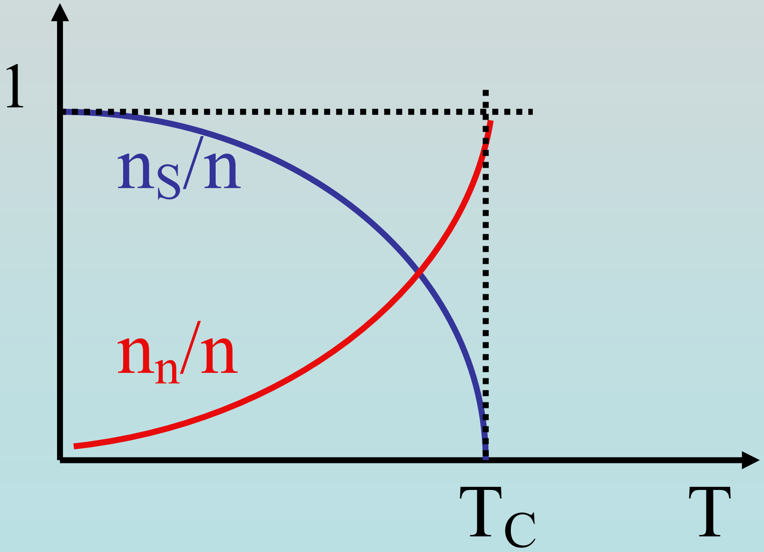
Two Fluid model

Electrical Conduction mechanism due to 2 different components

$$\vec{J} = \vec{J}_n + \vec{J}_S$$

Normal $\dfrac{n_n}{n}$

Superfluid $\dfrac{n_S}{n} = 1 - \dfrac{n_n}{n}$



$$\vec{J} = \vec{J}_n + \vec{J}_S$$

$$\vec{J}_n = \sigma\, \vec{E}$$

$$\vec{J}_S = n_s\, e\, \vec{v}_s$$

$$m\, \dot{\vec{v}}_S = -e\, \vec{E}$$

London equation

$$\vec{J}_S = -\frac{\vec{A}}{\lambda_L{}^2 \mu_0}$$

→ Is the Analogous of the “Ohm Law” for Superconductors

$$\nabla^2 \vec{B} = \frac{\vec{B}}{\lambda_L{}^2} \longrightarrow B(x) = B(0) \cdot e^{\left(-x/\lambda_L{}^2\right)}$$

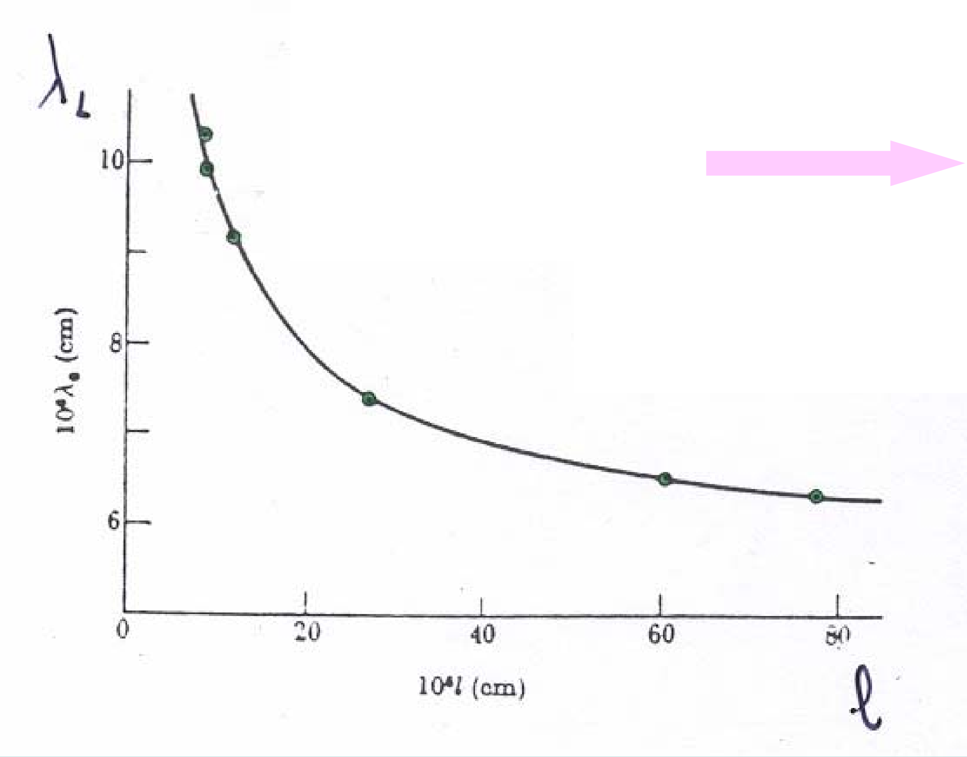
I type

II type

Superconductors

Pippard

London



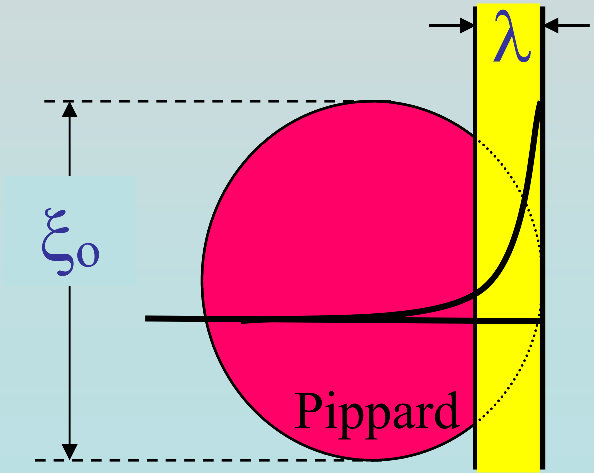
The l dependence vs mfp induced Pippard to modify London's model

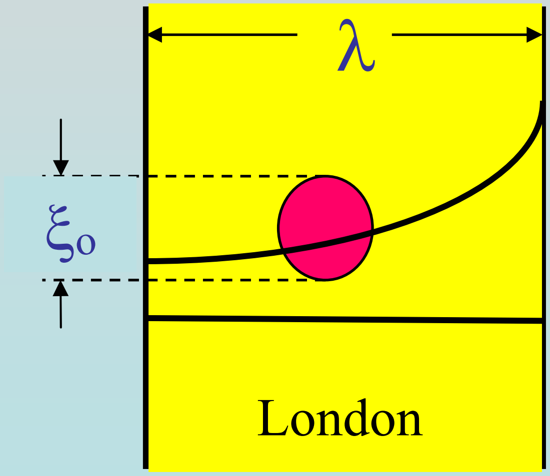
He borrowed from Chambers the non local approach that relates Current and Electric field

Strong Correlations among Superelectrons within a coherence length ξ_0

$$\vec{J}_s(\vec{r}) = \int_{\xi_0} f(\vec{r}_1 - \vec{r}) \cdot \vec{A}(\vec{r}_1)\, d\vec{r}_1$$

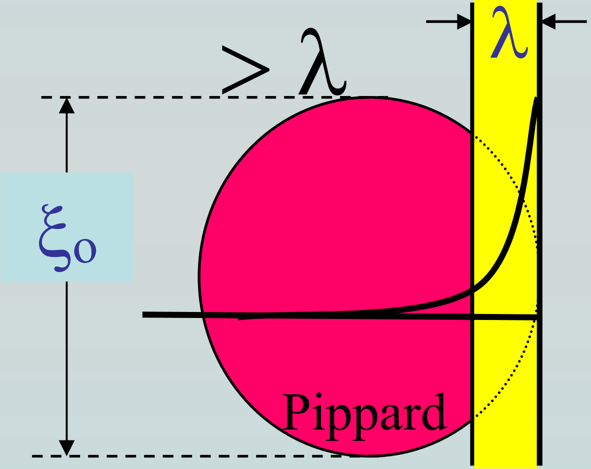
instead of $$\vec{J}_S = -\frac{\vec{A}}{\lambda_L{}^2 \mu_0}$$



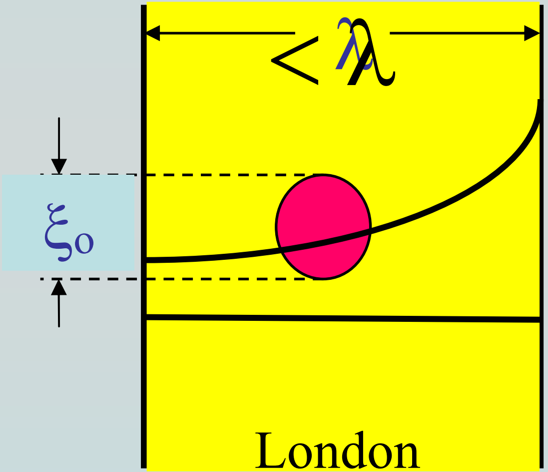


$\xi = \xi_0$ if $l \to \infty$ otherwise $\frac{1}{\xi} = \frac{1}{\xi_0} + \frac{1}{\ell}$

Pippard ξ



London ξ



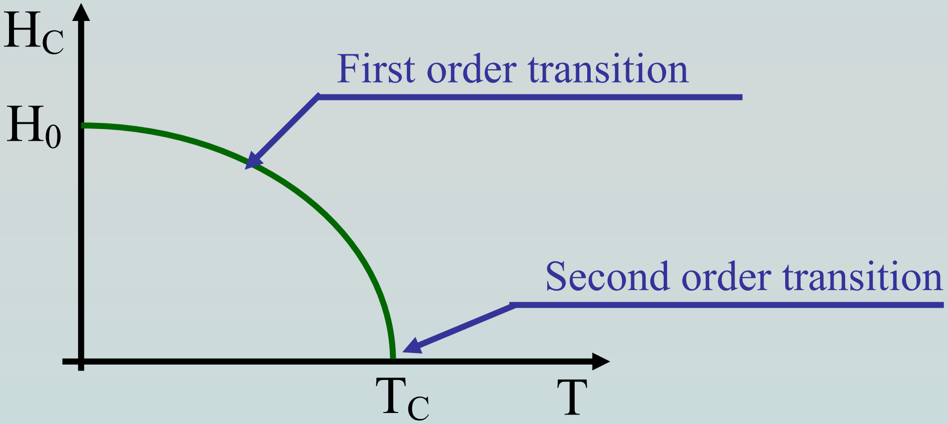
If $l \searrow$ then $\begin{cases} \xi \searrow \\ \lambda \nearrow \end{cases}$

$$\lambda = \lambda_L \cdot \left(\frac{\xi_0}{\xi}\right)^{\frac{1}{2}} = \lambda_L \cdot \left(1 + \frac{\xi_0}{\ell}\right)^{\frac{1}{2}}$$

$$dG = -SdT + VdP - MdH$$

$$G_s(T,H) - G_N(T,H) = \frac{1}{8\pi}[H^2 - H_C^2(T)]$$

The SC-state is an equilibrium state for $H < H_C$



✦ $$S_s(T,H) - S_N(T,H) = \frac{H_C(T)}{4\pi}\frac{dH_C(T)}{dT}$$

The SC Transition is a transition to an ordered state

Properties that do not change when crossing T_C:

- ✓ X-Ray diffraction pattern
- ✓ Optical and Photoelectrical properties (reflectivity)
- ✓ Elastic Properties (thermal expansion)

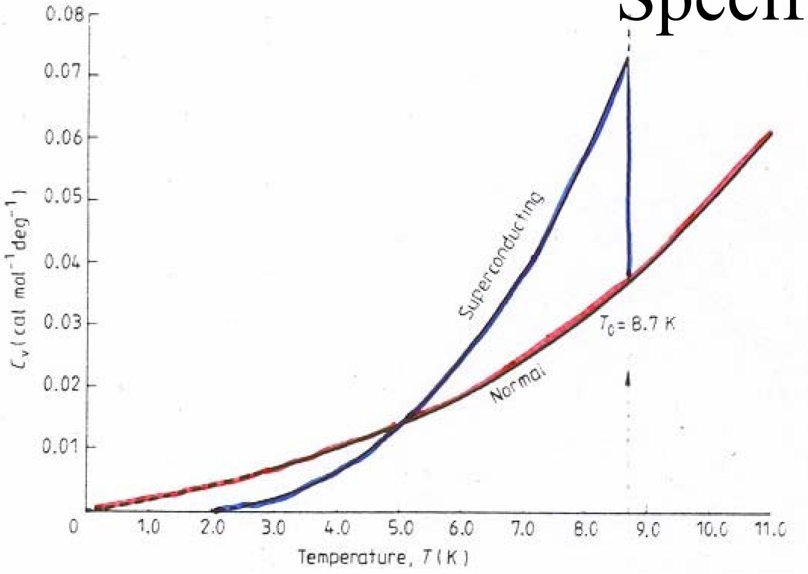
No transition in lattice structure

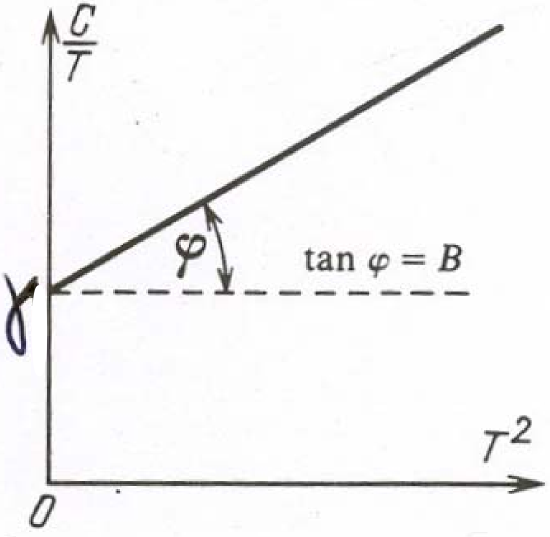
Properties that change when crossing T_C:

- ✓ Exponential behavior of specific heat and thermal conductivity
- ✓ Sharp edge in adsorption in microwave spectrum
- ✓.., Ultrasonic attenuation, Tunneling, Nuclear spin-lattice relaxation time, …

The electronic structure change

Specific heat





Metals $\longrightarrow$ $C = \gamma\,T + B\,T^3$ $\gamma = \dfrac{\pi^2}{3} k_B{}^2 N(E_F)$

Electrons + Phonons

Superconductors $\longrightarrow$ $C = e^{-\frac{\Delta}{k_B T}}$

In the energy spectrum of electrons there is a GAP between the fundamental state and the first excited state

Resuming:

For a Superconductor

$T_C \nearrow$, if $P \nearrow$

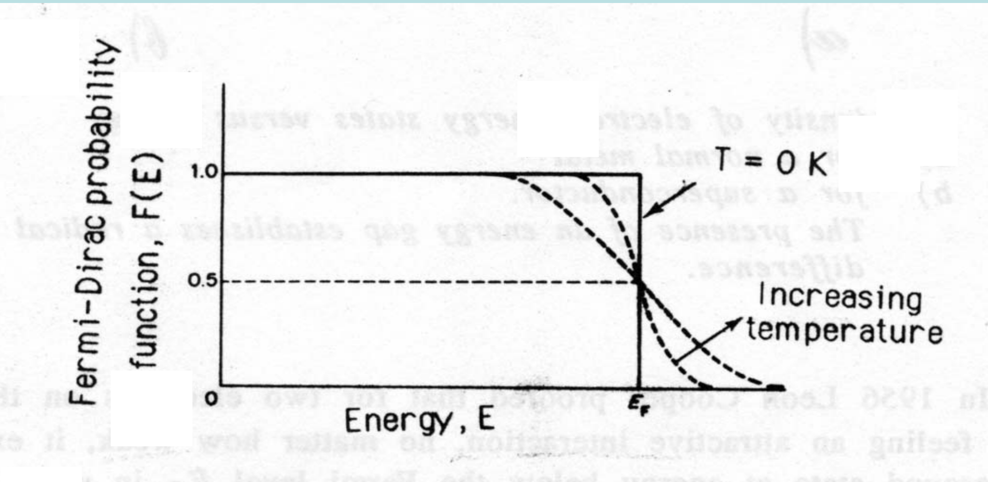
H_C, I_C

$$\phi_0 = \frac{hc}{2e}$$

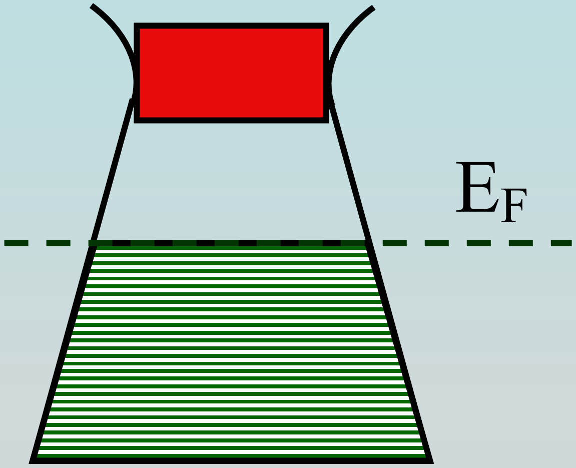
An Ordered State

There is a GAP

J. Bardeen L. Cooper
R.Schrieffer



The Fermi-Dirac distribution at 0 K,
and at temperatures above 0 K.

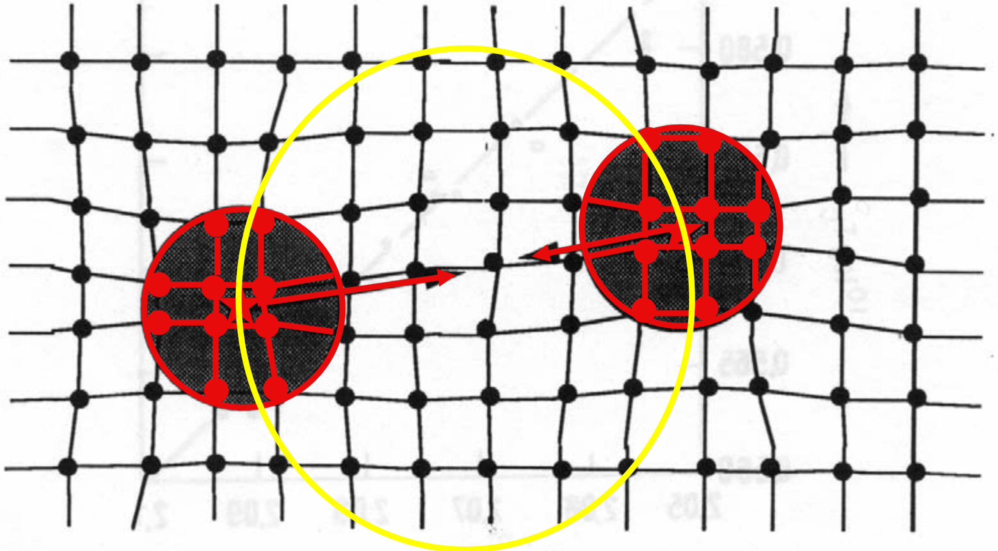


Cooper Principle:

Between 2 electrons excited above Fermi Energy, it exists a pair bound state separated by Δ from E_F, however weak an attractive interaction is supposed

-p , p ↗↙ Bose Condensation

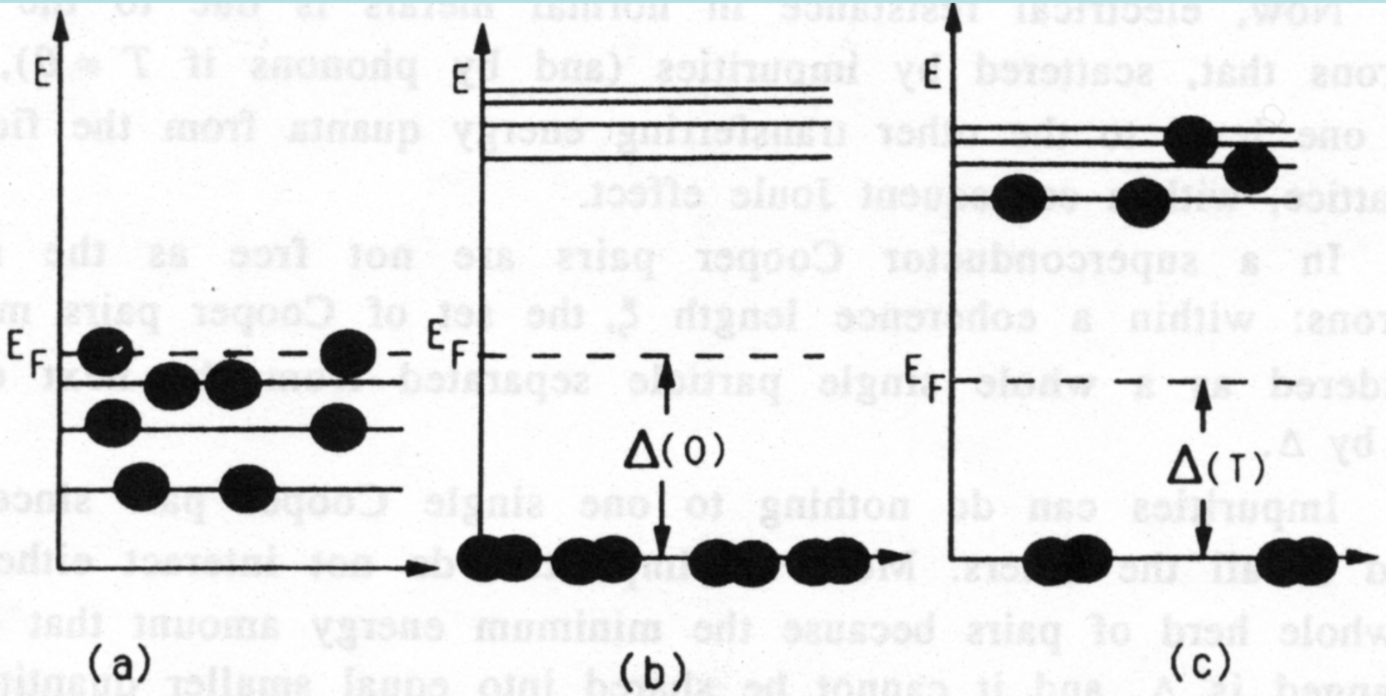
An electron moving in the lattice polarizes and distorces the adiacent portion



Two electrons interact attractively exchanging a phonon. The lattice behaves as the medium through which they interact. One of the two electrons "looks at" the other as a particle dressed of a positive ions cloud.

Fluctuations of the lattice charge distribution

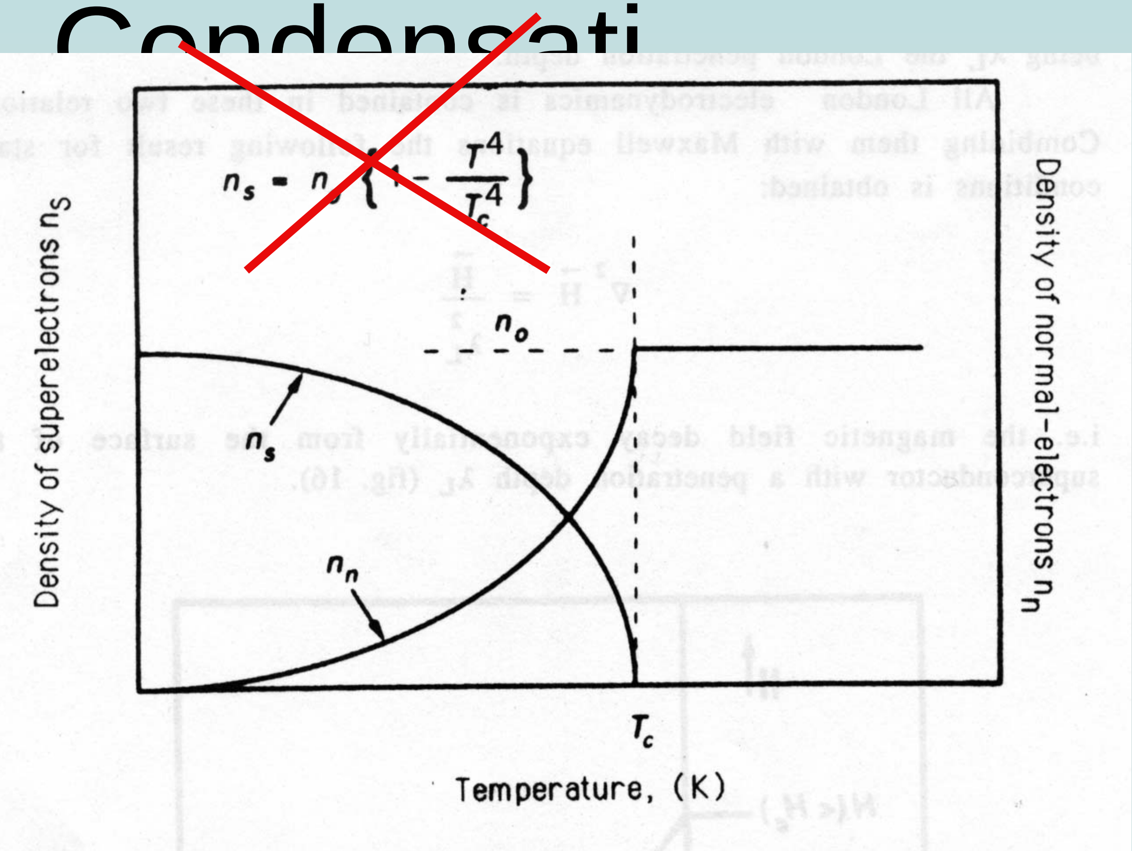
Interaction **e-e** mediated by the lattice



Energy spectrum for:
(a) a normal metal. At $T = 0\,K$ *all the electrons fill the lower energy levels up to* E_F *obeying the Pauli exclusion principle.*
(b) A superconductor at $T = 0\,K$ *. The Fermi surface is unstable against pairs formation. The Bose condensation of Cooper pairs into one stable ground state is energetically more stable.*
(c) A superconductor at $T \neq 0\,K$*. Temperature excitations start to break Cooper pairs and single particle excitations go to fill the energy levels of the "normal bound"*

Bose Condensati

Macedonian Falanx



$$\frac{n_n}{n}+\frac{n_s}{n}=1$$

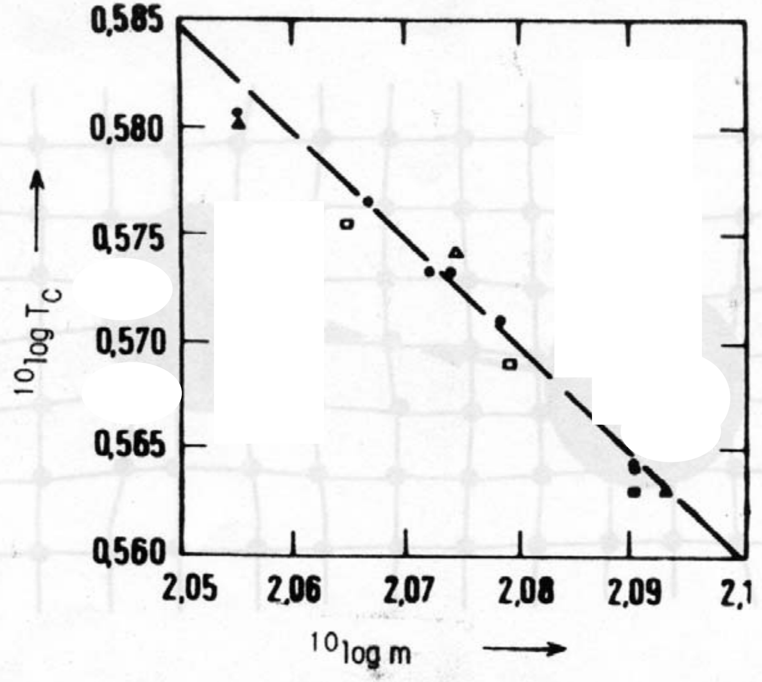
$$\frac{n_n}{n}\approx e^{-\frac{\Delta}{k_B T}}$$

$$\Delta_0=\frac{s}{2}k_B T$$

$$\Delta_0 = \frac{s}{2} k_B T$$

The Isotopical Effect

$$T_C = \frac{1}{M^{\alpha}}$$



The isotope effect for Sn.

$$T_C = 1.14\theta_D \cdot e^{-\frac{1}{\lambda}}$$

λ = (N(E$_F$) V =
= electron-phonon interaction

$$T_C = 1.14\theta_D \cdot e^{-\frac{1}{(\lambda-\mu)}}$$

μ = electron-electron interaction