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BAdW | BAYERISCHE AKADEMIE DER WISSENSCHAFTEN

Technische
Universität
München

Superconductivity and Low Temperature Physics I

Lecture Notes
Winter Semester 2021/2022

R. Gross

Chapter 1

Basic Properties of Superconductors

Chapter 1

1. Basic Properties of Superconductors

1.1 History of Superconductivity

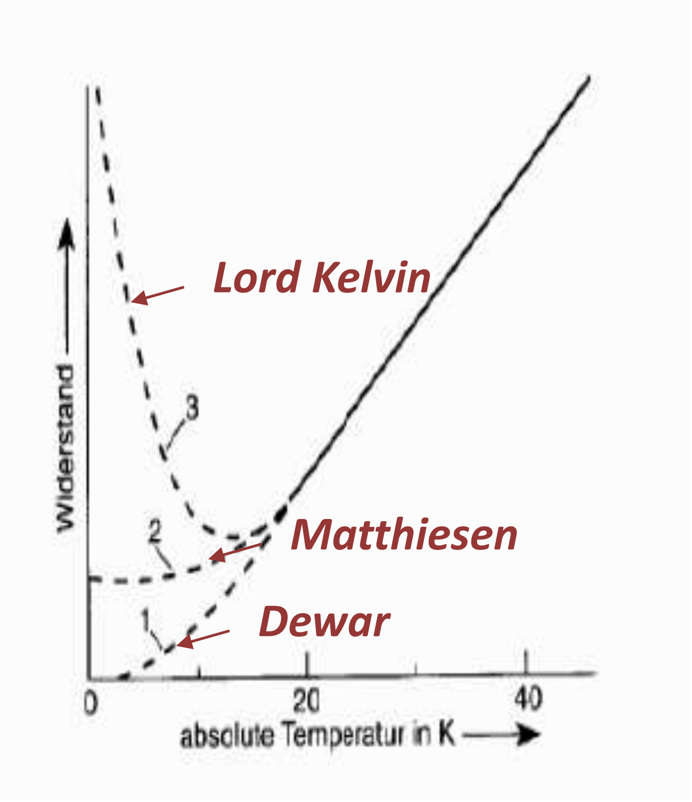
Discovery and explanation of the phenomena of superconductivity and superfluidity was honored by many Nobel Prizes

1908	Liquefaction of Helium, 4.2 K (Kamerlingh Onnes)
1911	Discovery of zero resistance (Kamerlingh Onnes)
1933	Discovery of the Meißner-Ochsenfeld effect (Meißner & Ochsenfeld)
1935	London theory (Fritz & Heinz London)
1936	type-II superconductivity (Shubnikov)
1939	Discovery of superfluid ^{4}Helium (Kapitza, Allen, and Misener)
1952	Ginzburg-Landau theory (Ginzburg & Landau)
1957	Abrikosov theory of type-II superconductivity (Abrikosov)
1957	Bardeen-Cooper-Schrieffer (BCS) theory (Bardeen, Cooper & Schrieffer)
1961	Discovery of flux quantization (Doll/Näbauer & Deaver/Fairbank)
1962	Cooper pair tunneling: Josephson effect (Josephson, Giaever)
1966	Development of Superconducting Quantum Interference Devices (Clarke)
1971	Discovery of superfluid ^{3}Helium (Lee, Richardson, Osheroff)
1975	Theory of superfluid ^{3}Helium (Leggett)
1979:	Discovery of heavy fermion superconductors (Steglich)
1981	Discovery of organic superconductors (Bechgaard)
1986	Discovery of high-temperature superconductivity (Bednorz, Müller)
2006	Discovery of superconductivity in iron pnictides (Hosono)

blue:
Nobel Prize winners

1.1 Discovery of Superconductivity (1911)

- what was the basic interest ?



temperature dependence of very pure metals for $T \rightarrow 0$ *??*

- $R \rightarrow 0$
- $R \rightarrow const.$
- $R \rightarrow \infty$

use of Hg, since very pure Hg was available

H. K. Onnes

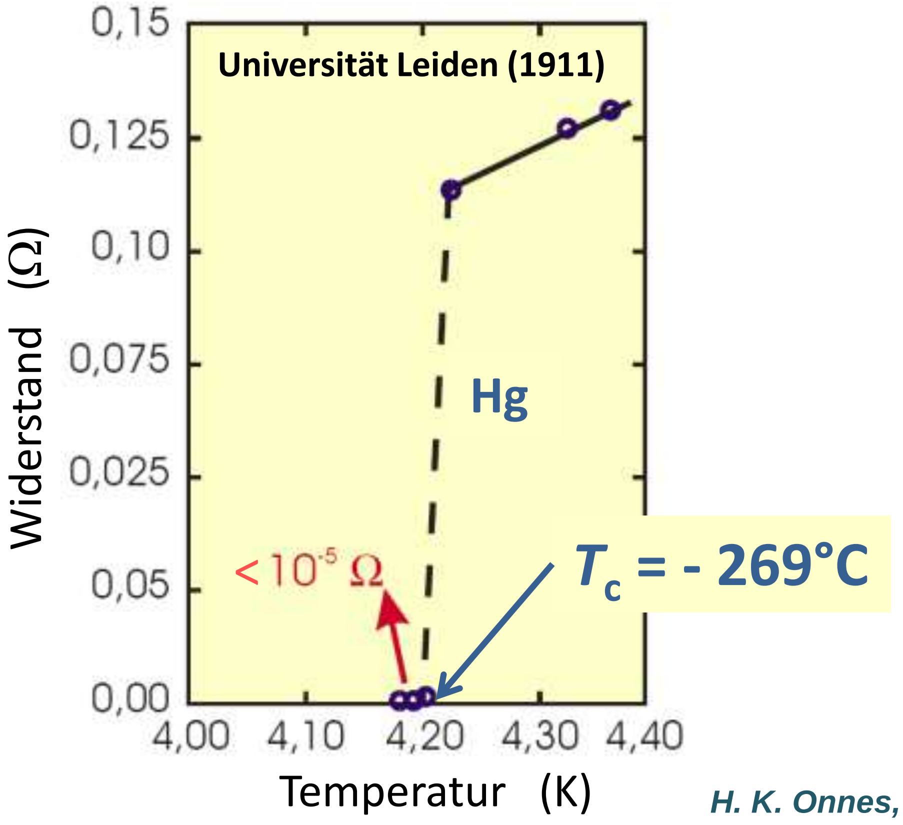
".. Mercury has passed into a new state, which on account of its extraordinary electrical properties may be called the superconductive state"

1.1 Discovery of Superconductivity (1911)

Heike Kammerlingh Onnes (1853-1926)

note: Heike = first name, Kammerlingh = „Hofrat“

- **Helium liquefaction: 1908**
- **discovery of superconductivity: 1911**



T_c = - 269°C

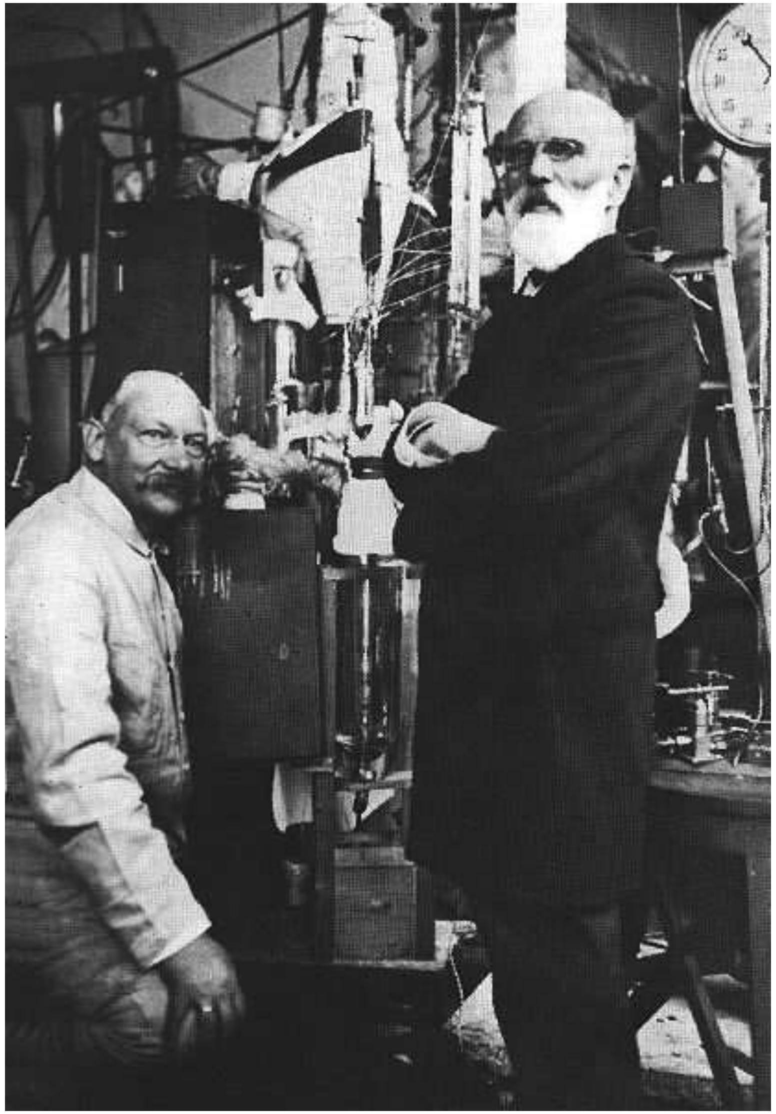
H. K. Onnes,
Comm. Leiden 120b, 122b, 124c (1911)

Nobel Price in Physics 1913

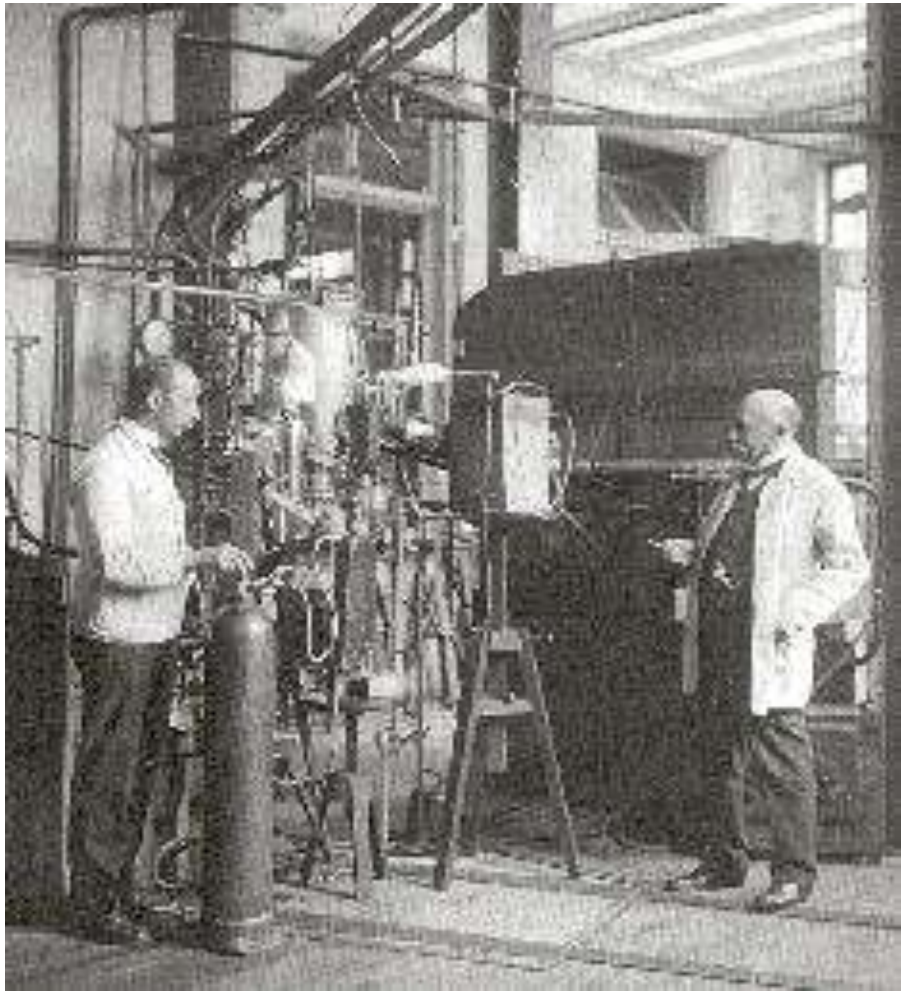
"for his investigations on the properties of matter at low temperatures which led, inter alia to the production of liquid helium"

choice of name: ***infinite electrical conductivity*** ➔ **superconductivity**

1.1 Discovery of Superconductivity (1911)



Kammerlingh Onnes and van der Waals



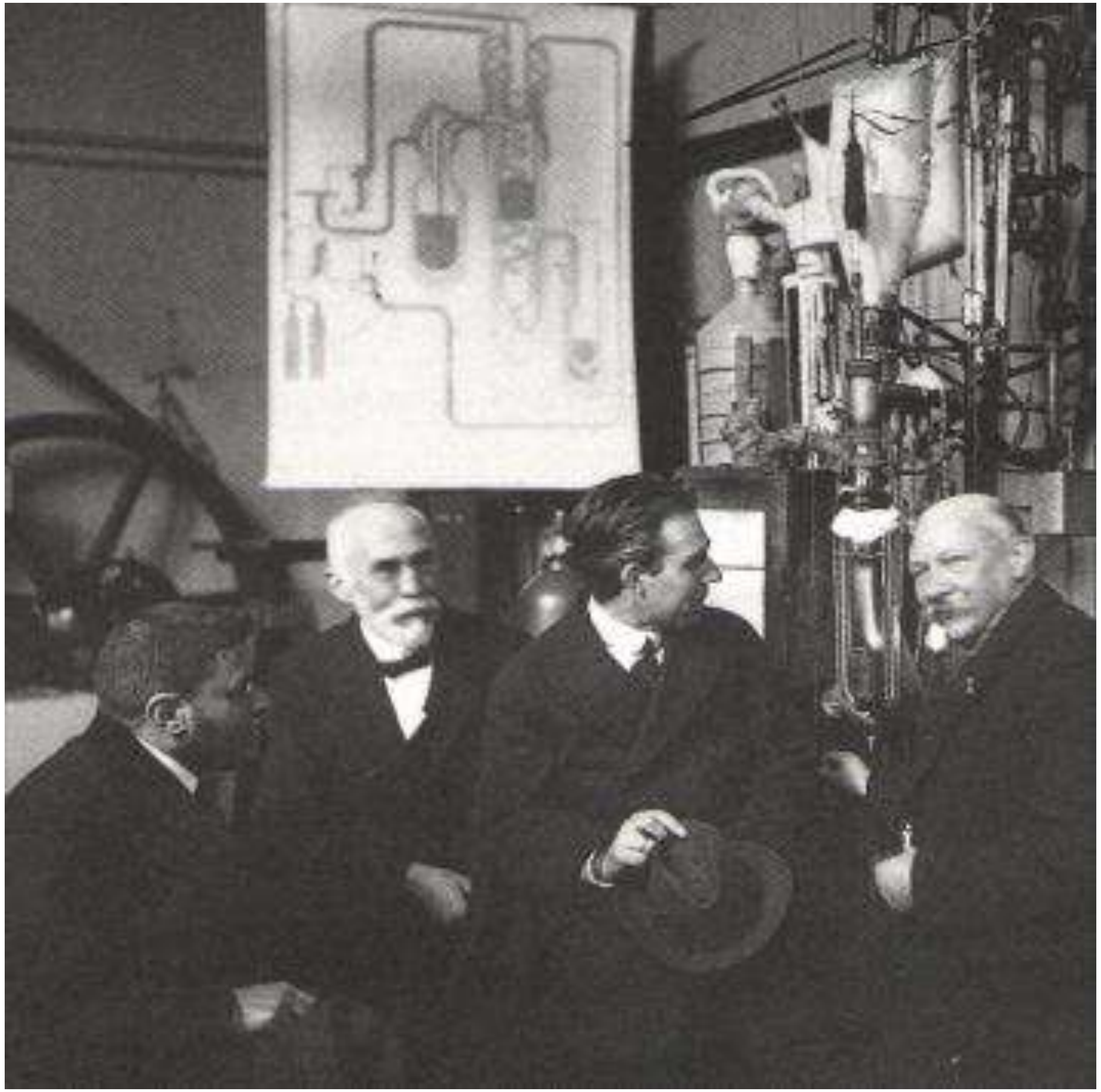
Kammerlingh Onnes and Technician Flim

1.1 Discovery of Superconductivity (1911)

an early picture of the Onnes Laboratory

Kamerlingh Onnes Laboratory, 1924

1.1 Discovery of Superconductivity (1911)



Heike Kamerlingh Onnes (*far right*) shows his helium liquefactor to three theoretical physicists: Niels Bohr (visiting from Kopenhagen), Hendrik Lorentz, and Paul Ehrenfest (*far left*).

1.1 Discovery of Superconductivity (1911)

Prof. Heike Kamerlingh Onnes and his wife with some colleages among them their friend Albert Einstein (*standing behind Mrs. Kamerlingh Onnes*), ca. 1920.

1.1 Discovery of the Meißner-Ochsenfeld Effect (1933)

Robert Ochsenfeld
(1901 – 1993)

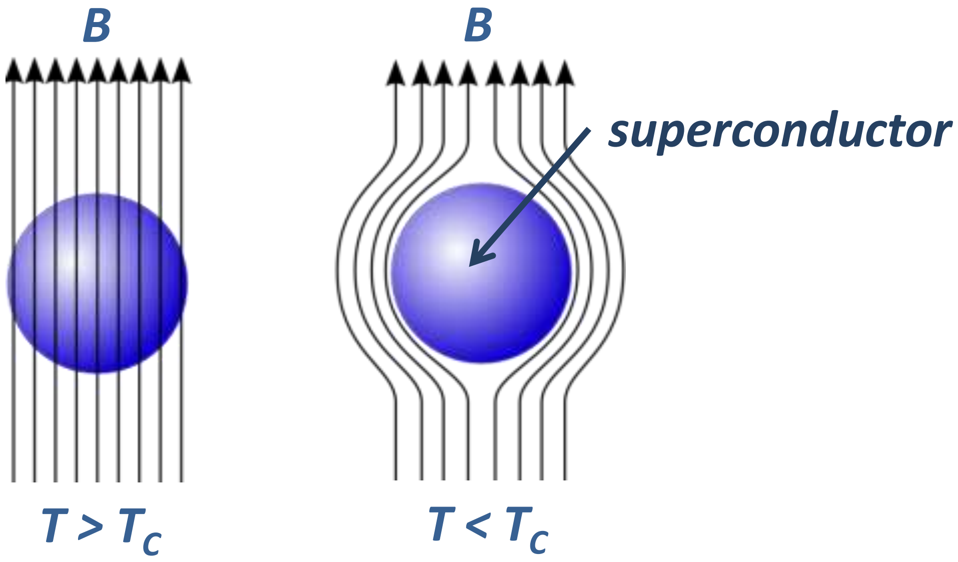
perfect diamagnetism

Walther Meißner
(1882 – 1974)

W. Meißner, R. Ochsenfeld,
Ein neuer Effekt bei Eintritt der Supraleitfähigkeit,
Naturwissenschaften 21, 787 (1933).

1.1 Discovery of the Meißner-Ochsenfeld Effect (1933)

Walther Meißner (1882 – 1974)



superconductors perfectly expel magnetic field

$$B_{\text{in}} = (1+\chi)\, B_{\text{ex}} = 0$$

(χ = magnetic susceptibility)

ideal diamagnetism, χ = – 1

choice of name for perfect diamagnetism:

Meißner-Ochsenfeld Effect

Walther Meißner (1882 – 1974)

1913 – 1934
building and heading of low temperature laboratory at the Physikalisch-Technischen-Reichsanstalt, liquefaction of H_2 (20K)

7.3.1925 first liquefaction of He in Germany (4.2 K, 200 ml), 3rd system world-wide besides Leiden and Toronto

1933 discovery of perfect diamagnetism of superconductors together with Ochsenfeld
➔ ***Meißner-Ochsenfeld Effect***

1934 offer of chair at the Technische Hochschule München (now TUM)

1946 – 1950
president of the Bayerischen Akademie der Wissenschaften

1946 foundation of the commission for Low Temperature Research
→ ***Walther-Meißner-Institut***

Walther Meißner
* 16. Dezember 1882 in Berlin
† 15. November 1974 in Munich

London Theory of Superconductivity (1935)

1935 Fritz and Heinz London

first „quantum mechanical“ theory of superconductivity
(*purely phenomenological*)

→ ***macroscopic wave function***

Fritz London
(1900 – 1954)

Shubnikov Phase, Type-I and Type-II SCs (1936)

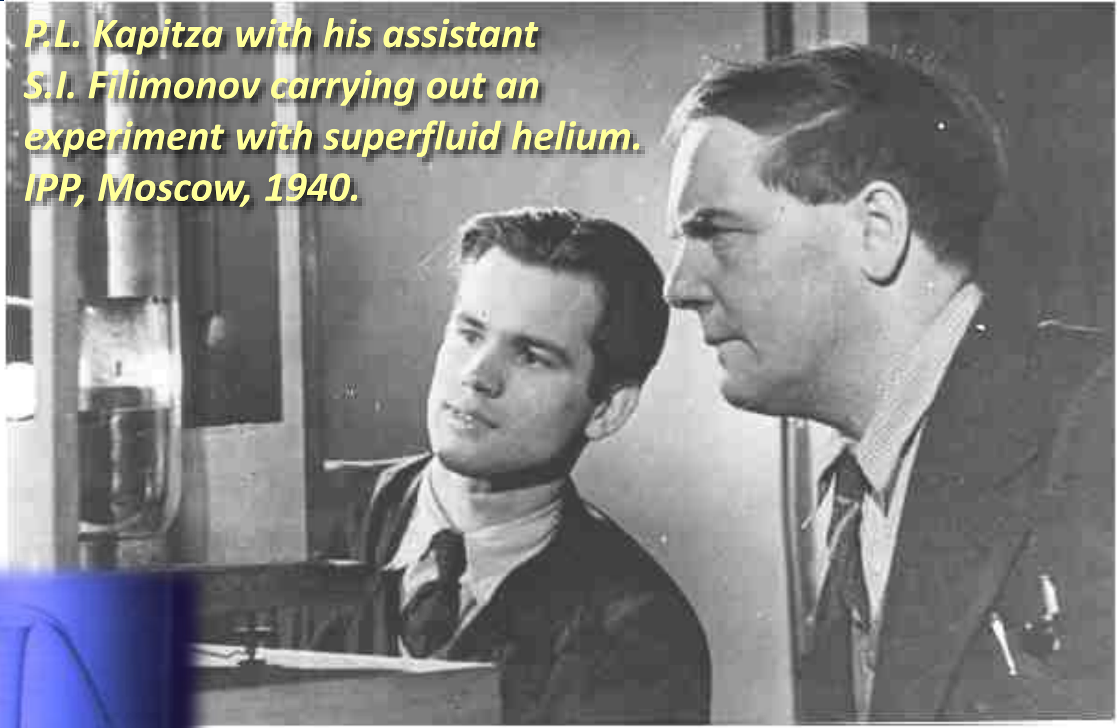
1936 **Lev W. Shubnikov**

discovery of the Shubnikov phase in superconductors

→ ***type-I and type-II superconductivity***

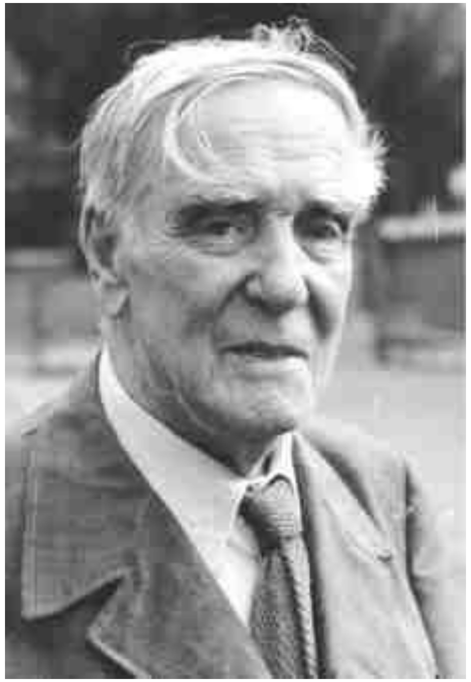
Lev Wassiljevitsch Shubnikov
(1901 – 1937)

Discovery of Superfluid ^{4}Helium (1939)



P.L. Kapitza with his assistant S.I. Filimonov carrying out an experiment with superfluid helium. IPP, Moscow, 1940.

phenomenon analogous to superconductivity is found in an uncharged system



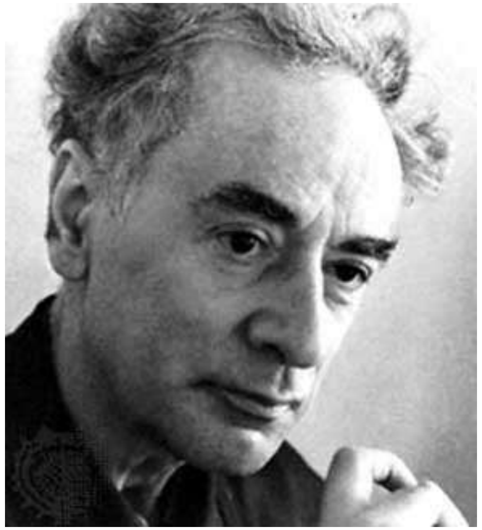
Pyotr Leonidovich Kapitza (1894-1984)

J. Allen 1970

Nobel Prize in Physics 1978

„for his basic inventions and discoveries in the area of low-temperature physics"

Ginzburg-Landau Theory (1952)



Lev Landau

Vitaly Ginzburg

application of Landau’s theory for phase transitions to superconductors using a complex order parameter

Lev Davidovich Landau

Nobel Prize in Physics 1962

"for his pioneering theories for condensed matter, especially liquid helium"

Vitaly Ginzburg

Nobel Prize in Physics 2003

(together with Alexei Abrikosov
and Anthony Leggett)

“for their pioneering contributions to the theory of superconductors and superfluids”

Non-local London Theory (1953)

Sir Alfred Brian Pippard

7. September 1920 – 21. September 2008

Pippard observed a dependence of the penetration depth on the purity of a material

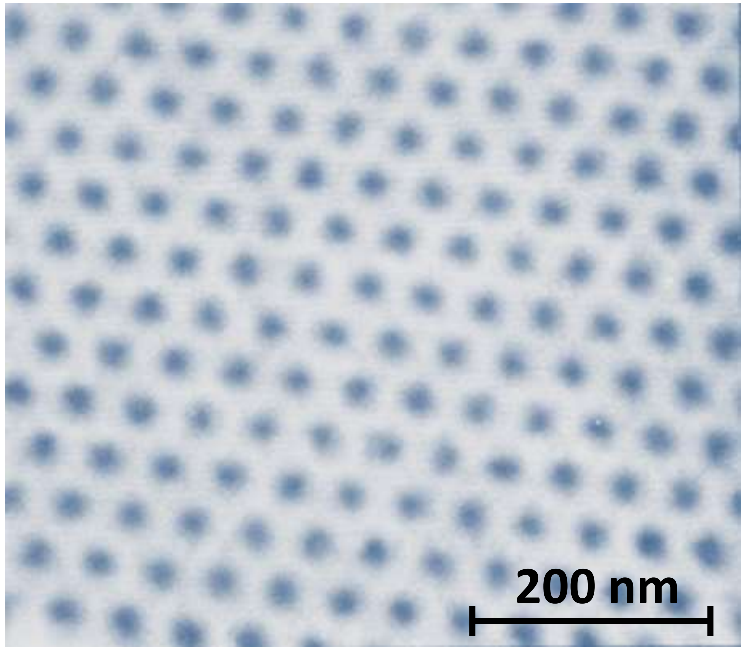
→ non-local electrodynamics must be used for a proper explanation

→ response at position r depends on the perturbation in a material dependent volume $\sim |\boldsymbol{r} - \boldsymbol{\xi_0}|^3$

Abrikosov Theory of Type-II Superconductivity (1957)

Alexei Abrikosov

Abrikosov used the Ginzburg-Landau phenomenology to derive the existence of a "mixed-state"



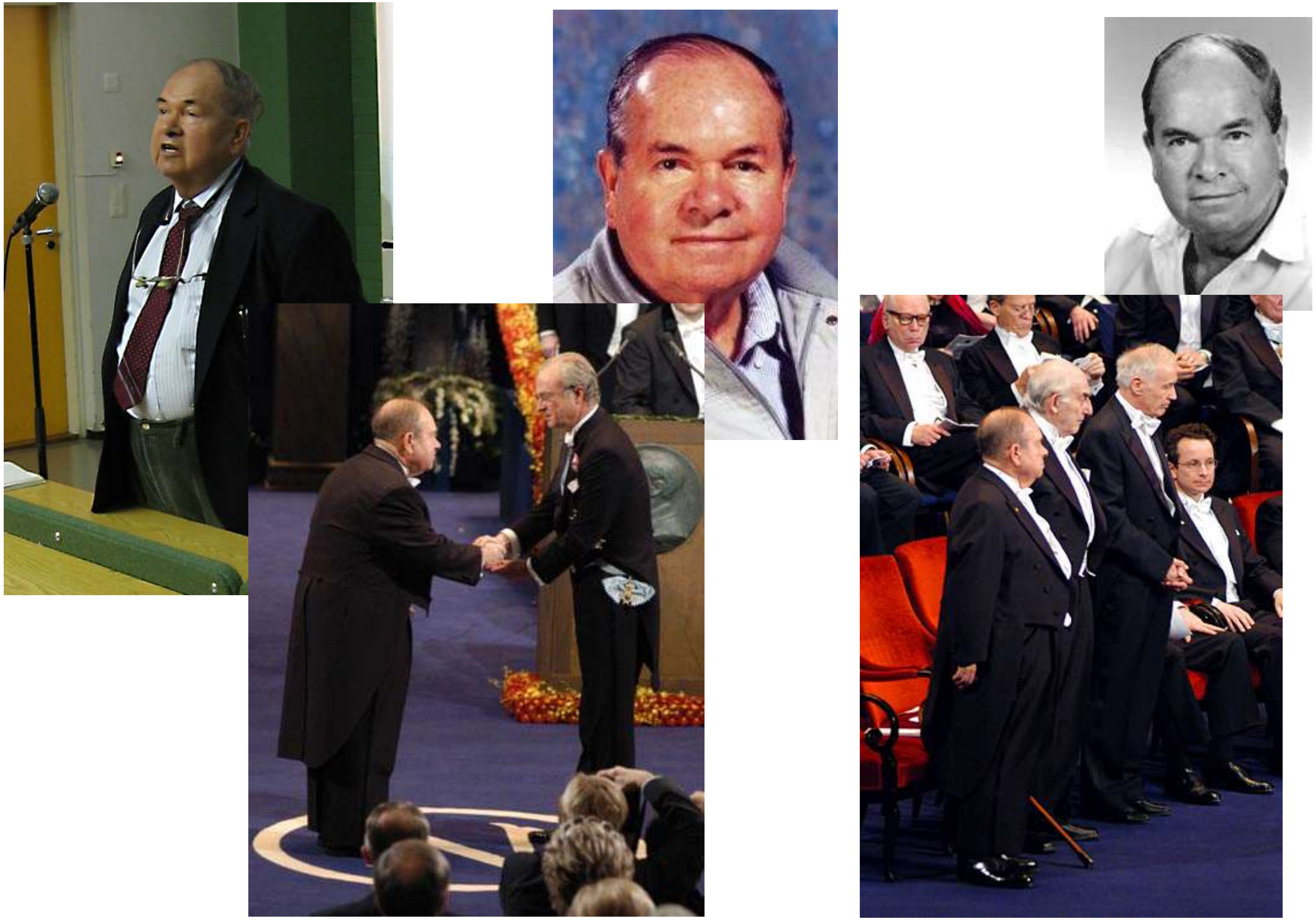
Alexei Abrikosov

Nobel Prize in Physics 2003

(together with Vitaly Ginzburg
and Anthony Leggett)

"for their pioneering contributions to the theory of superconductors and superfluids"

Alexei A. Abrikosov



The Nobel Prize in Physics 2003


Alexei A. Abrikosov

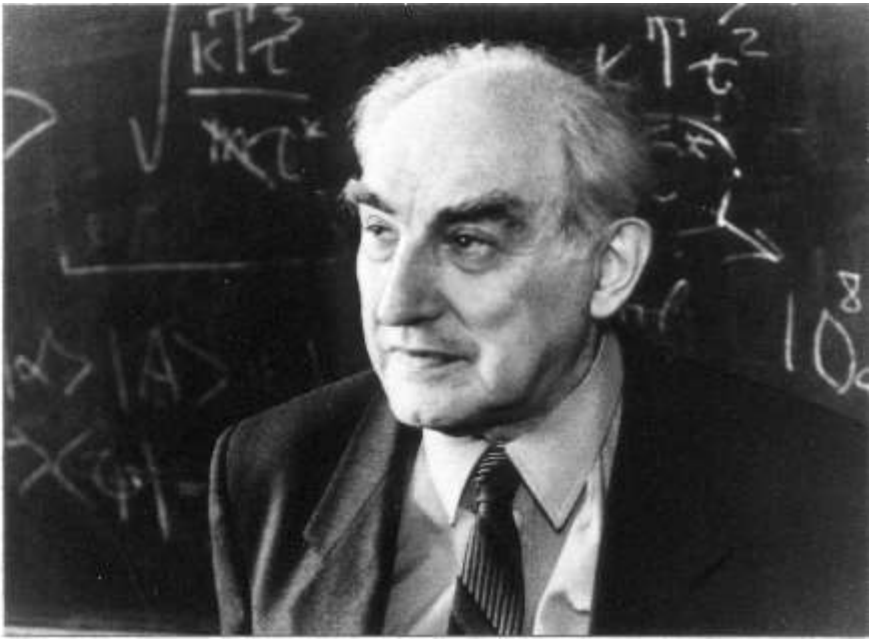

Vitaly L. Ginzburg

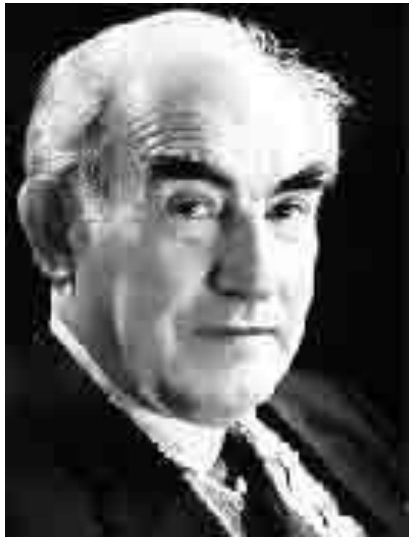

Anthony J. Leggett

….. for their pioneering contributions to the theory of superconductors and superfluids.

Lev Landau

Vitaly L. Ginzburg





Tag der Physik

07. 07. 2000

Microscopic (BCS) Theory (1957)

J. Bardeen

L. N. Cooper

R. Schrieffer

Nobel Prize in Physics 1972

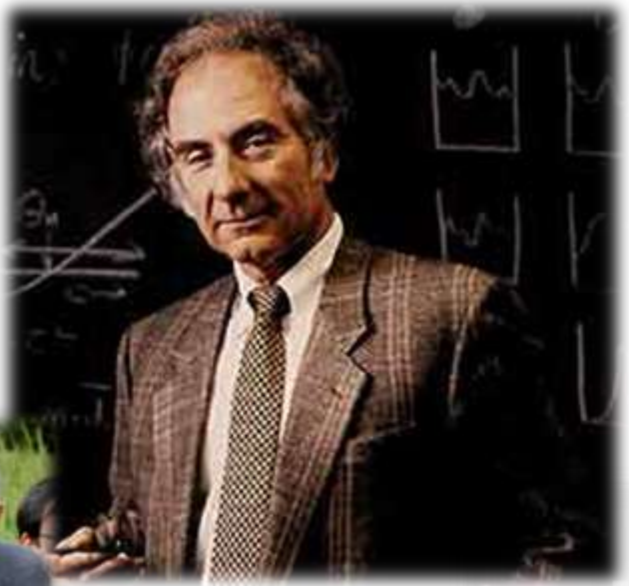
"for their jointly developed theory of superconductivity, usually called the BCS-theory"

John Bardeen

* 23 May 1908, Madison, Wisconsin
† 30 January 1991, Boston
two-times Nobel Price winner

Leon Neil Cooper

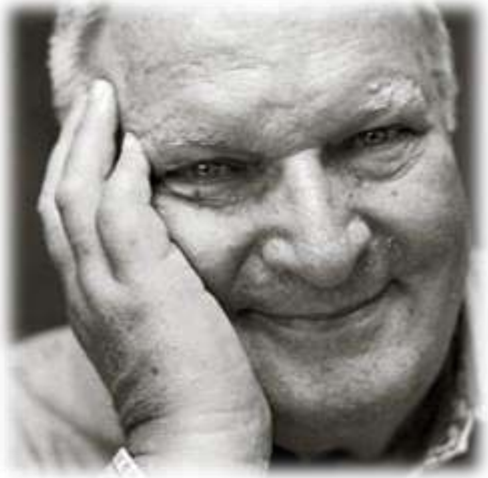
* 28 February 1930, New York
Nobel Prize in Physics 1972



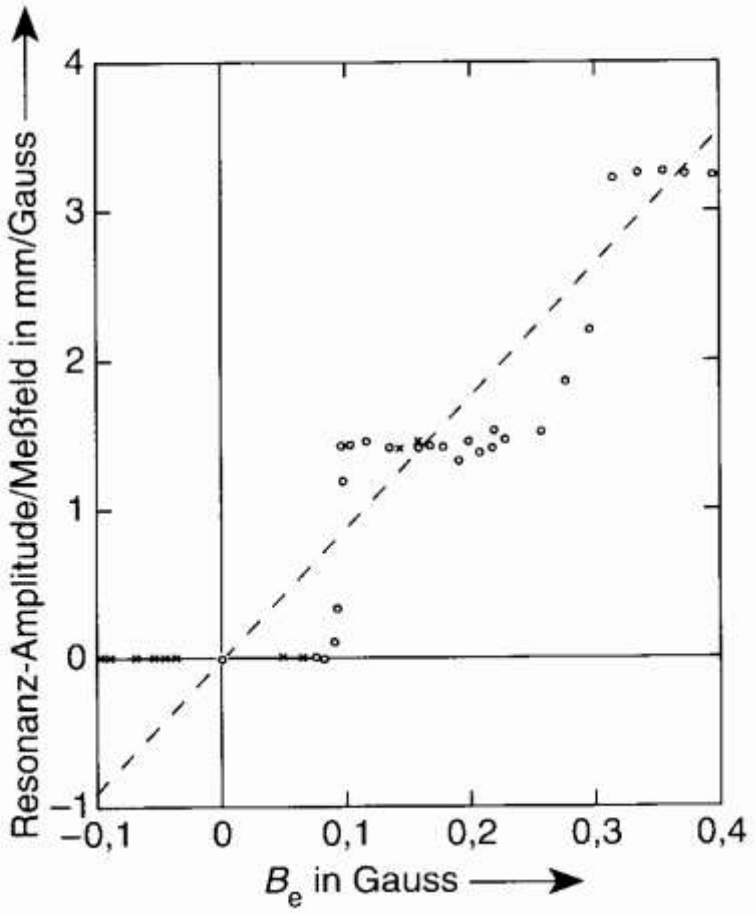
Pioneers of superconductivity honored at BCS@50
From left: Dale J. Van Harlingen, Lev Gor'kov, Charles P. Slichter, Leo Kadanoff, David Pines, Leon Cooper, Marvin Cohen, Michael Tinkham

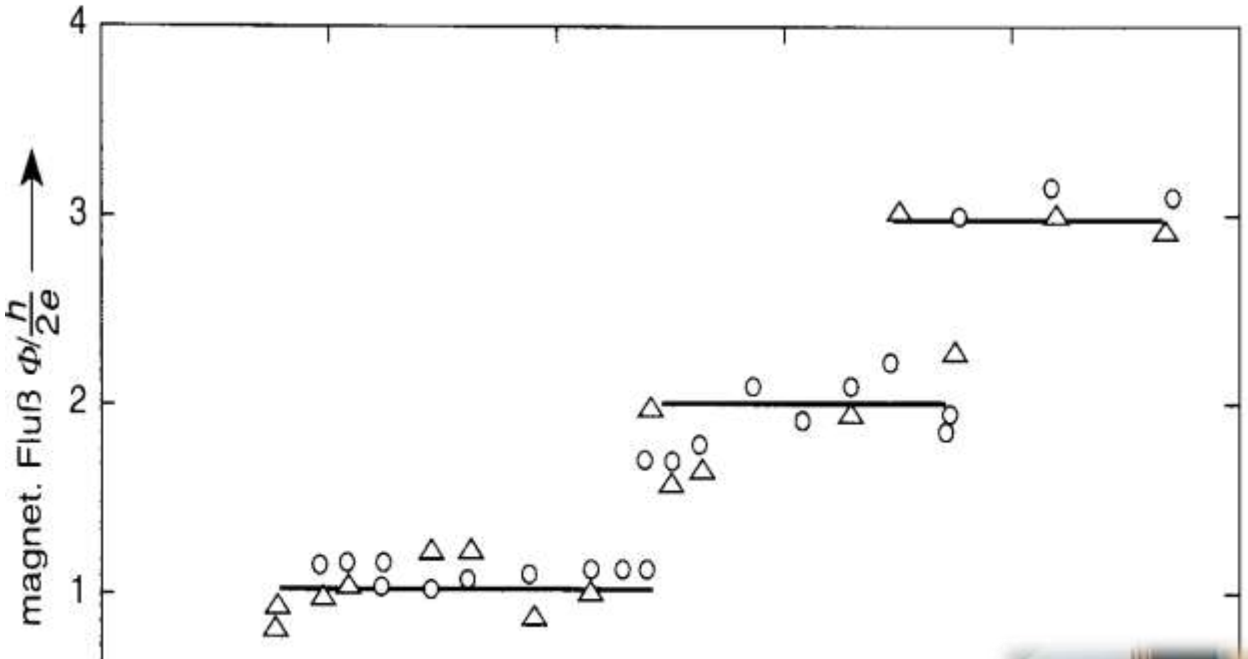
John Robert Schrieffer

* 31 May 1931, Oak Park, Illinois
Nobel Prize in Physics 1972

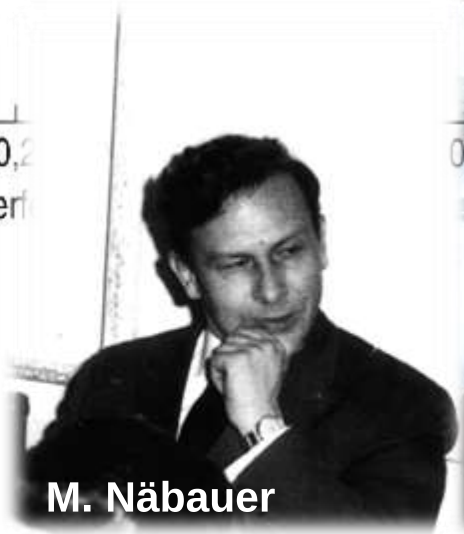


Discovery of Flux Quantization (1961)





Robert Doll and Martin Näbauer, WMI


M. Näbauer

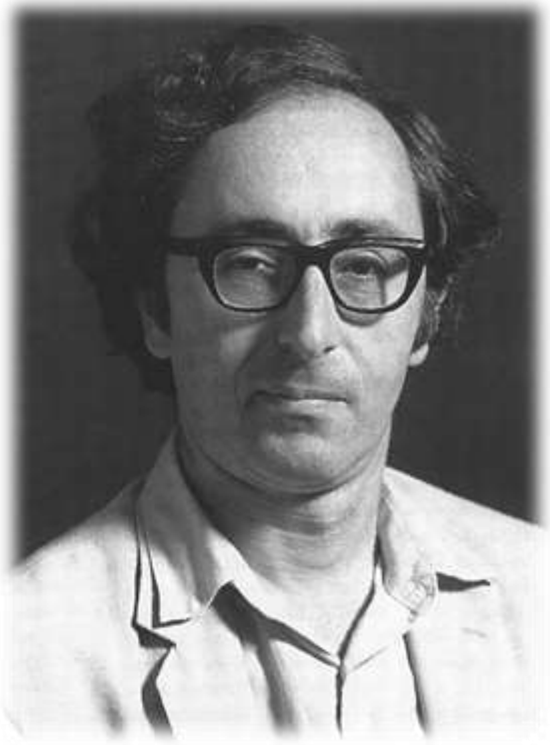

R. Doll

R. Doll, M. Näbauer, Phys. Rev. Lett. 7, 51 (1961).
B.S. Deaver Jr., W.M. Fairbank, Phys. Rev. Lett. 7, 43 (1961).

Discovery of Flux Quantization (1961)

Measuring the flux quantum. Graduate student Bascom Deaver refills his apparatus with liquid nitrogen at Stanford University in 1961, a necessary step in maintaining a superconductor at liquid helium temperature. He and William Fairbank used this setup to show that the magnetic field threading a superconducting loop is always quantized. [Credit: J. Mercado/Stanford News Service]

Prediction of the Josephson Effect (1962)



Brian David Josephson (geb. 1940)

Nobel Prize in Physics 1973

"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"

(together with Leo Esaki and Ivar Giaever)

Discovery of Superfluid ^{3}Helium (1971/72)

Douglas D. Osheroff,
Stanford University,
Stanford, California, USA

David M. Lee,
Cornell University, Ithaca,
New York, USA

Robert C. Richardson,
Cornell University, Ithaca,
New York, USA

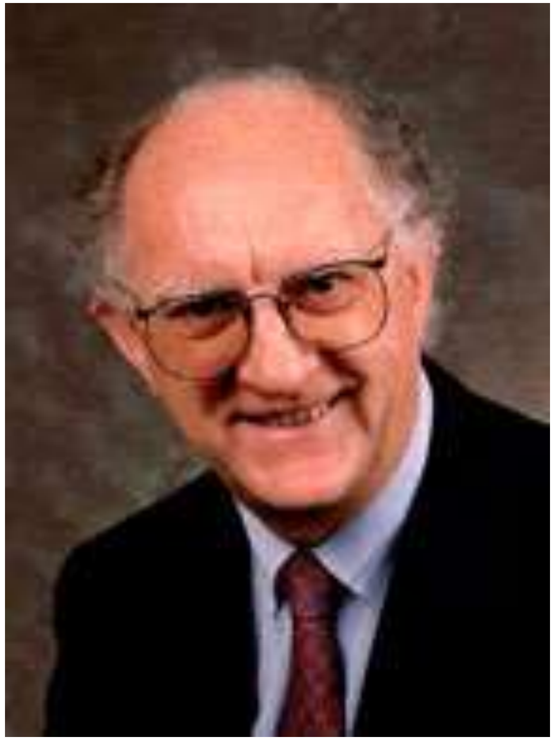
Nobel Prize in Physics 1996

"for their discovery of superfluidity in helium-3"

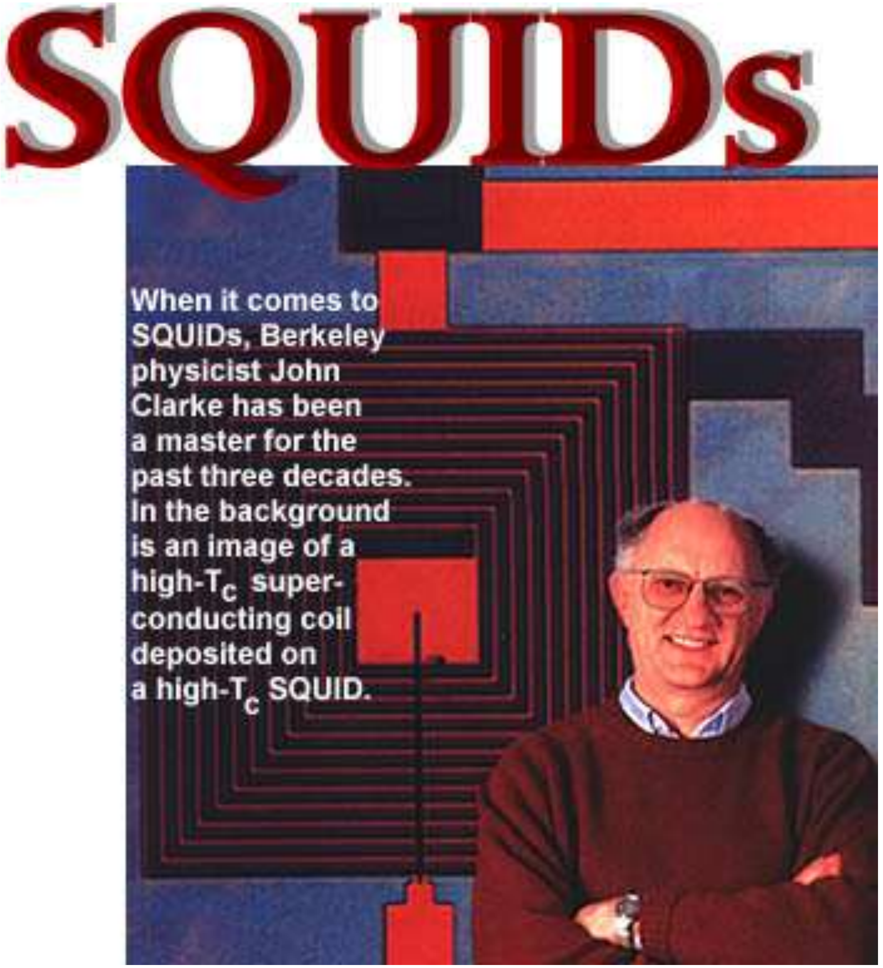
$T_c = 2.6$ mK

1966 ^{3}He/^{4}He dilution refrigerator: Hall, Neganov **2 mK .... 500 mK**

Development of SQUID (1966)



John Clarke



SQUIDs

When it comes to SQUIDs, Berkeley physicist John Clarke has been a master for the past three decades. In the background is an image of a high-T_c superconducting coil deposited on a high-T_c SQUID.

Superconducting Quantum Interference Devices

Theory of Superfluid ^{3}Helium (1975)

Anthony J. Leggett

Nobel Prize in Physics 2003

….. for their pioneering contributions to the theory of superconductors and superfluids.

(together with Alexey A. Abrikosov and Vitaly Ginzburg)

Discovery of the High T_c Superconductivity (1986)

J. Georg Bednorz (b. 1950) **K. Alexander Müller (b. 1927)**

Nobel Prize in Physics 1987

"for their important break-through in the discovery of superconductivity in ceramic materials"

Discovery of the High T_c Superconductivity (1986)

Karl Alexander Müller
* 20. April 1927 in Basel

Johannes Georg Bednorz
* 16. Mai 1950 in Neuenkirchen
im Kreis Steinfurt

Chapter 1

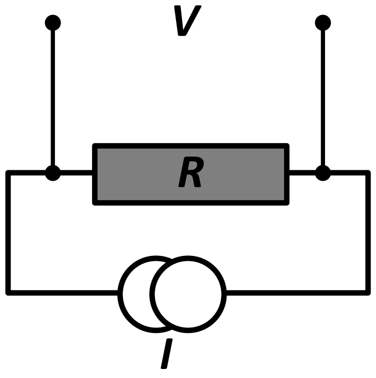
1. Basic Properties of Superconductors

1.2 Perfect Conductivity

- can we measure *R* = 0 ?

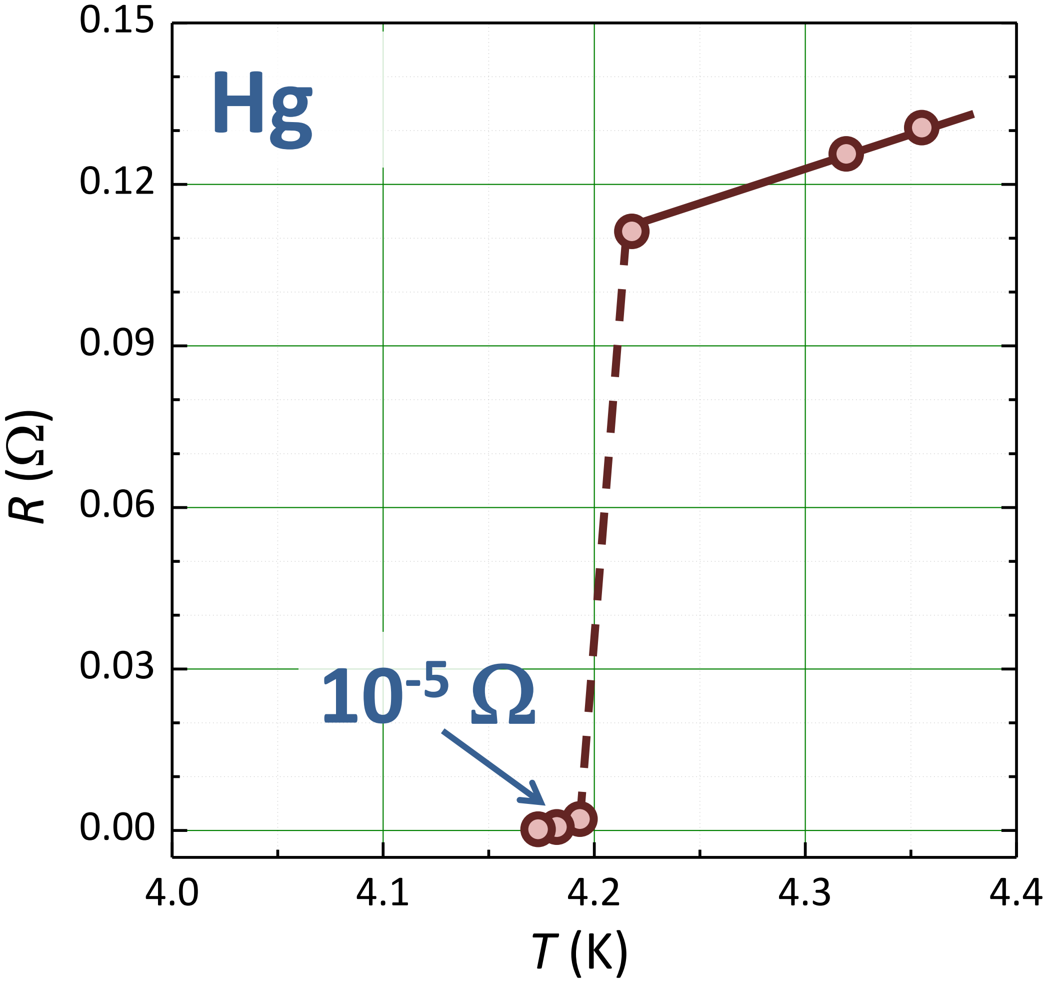
no, only lower threshold
can be obtained in experiment

limited resolution of voltage measurement



$$\Delta R = \Delta V / I \approx 10^{-8}\ \Omega$$

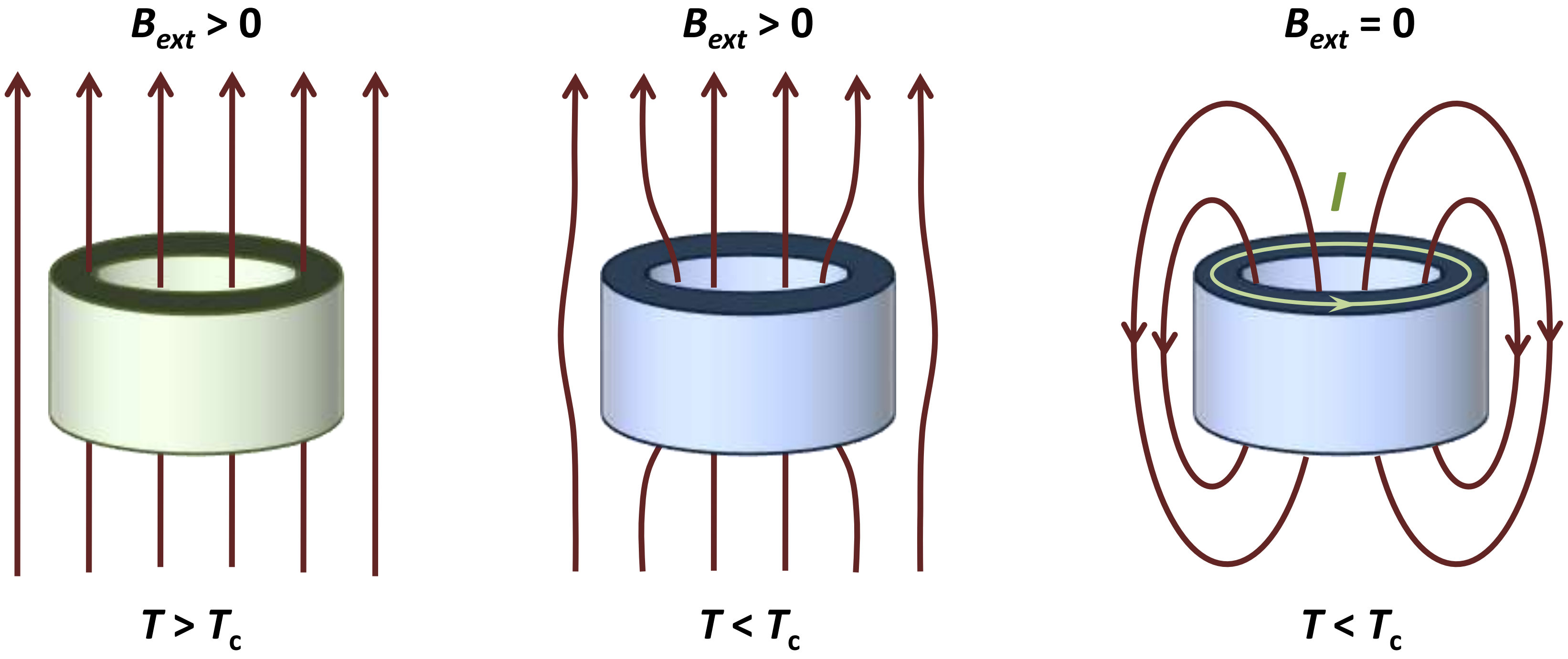
@ ΔV = 10 nV, I = 1 A



H. K. Onnes: resistance drops by about 4 orders of magnitudes (later 14)

1.2 Perfect Conductivity

improvement of resistance mesurement by study of decay of persistent current



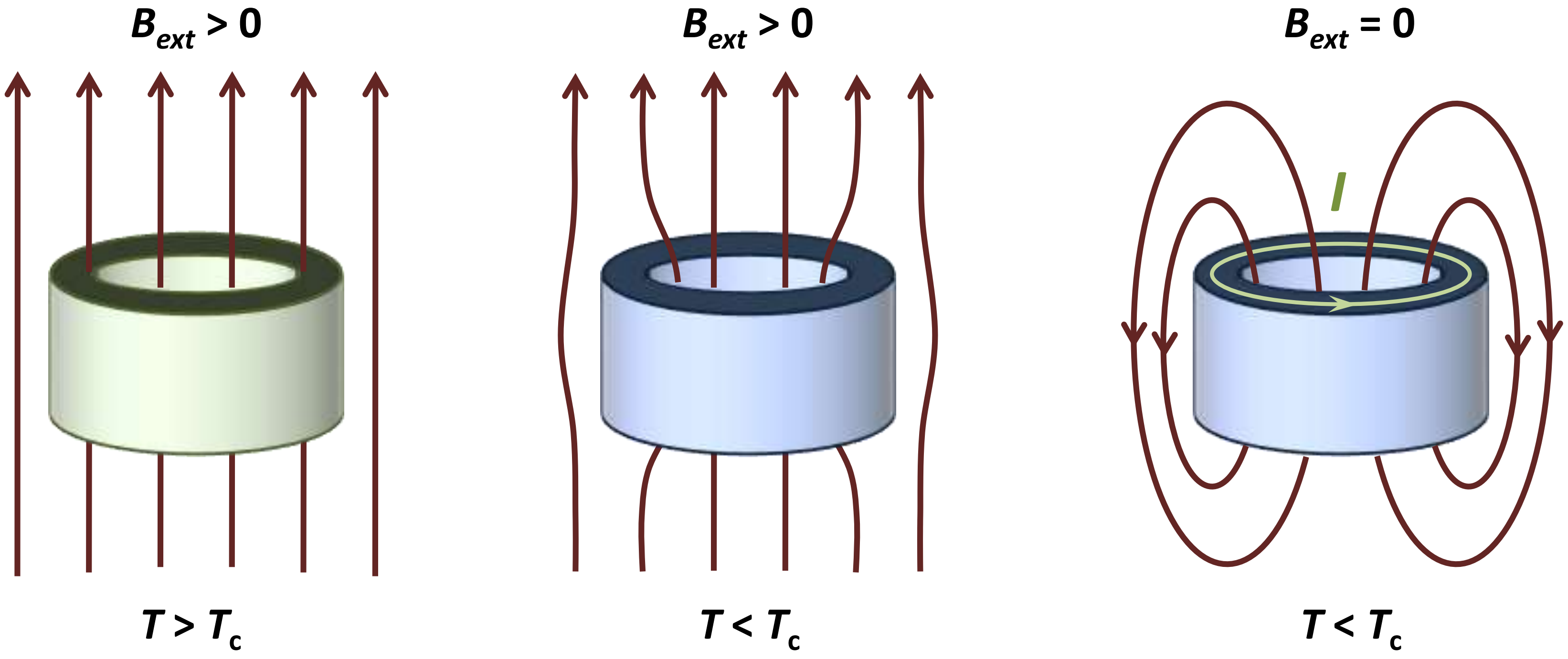
flux trapping: ***Faraday's law:*** $-\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{E}$

$$-\frac{\partial}{\partial t}\int_A \mathbf{B}\cdot\hat{\mathbf{n}}\; dS = -\frac{\partial}{\partial t}\Phi = \int_A (\nabla \times \mathbf{E})\cdot\hat{\mathbf{n}}\; dS = \oint_\Gamma \mathbf{E}\cdot d\ell = 0$$

in superconductor: $E = 0 \quad \Rightarrow \quad \dot{\mathbf{\Phi}} = \mathbf{0} \;\; \text{or} \;\; \dot{\mathbf{B}} = \mathbf{0}$

1.2 Perfect Conductivity

improvement of resistance mesurement by study of decay of persistent current



→ *measure decay of magnetic moment generated by frozen in persistent current*

loop with inductance L and resistance R:

$$RI + L\,dI/dt = 0$$

$$\Rightarrow \boldsymbol{I(t) = I_0 \exp\left(-\frac{R}{L}t\right)}$$

example: 10% decay in 1 year observed
@ L = 1 nH
➔ $\boldsymbol{R < 10^{-17}\Omega}$

Superconductivity and Low Temperature Physics I

Lecture No. 2
28 October 2021

R. Gross

Summary of Lecture No. 1 (1)

- **information on contents and structure of the lectures on superconductivity and low temperature physics I & II**

  related lectures and seminars

- **general introduction into the field of low temperature physics**

  important research fields, related Nobel prizes

  information on related research at WMI

- **A brief history of superconductivity and low temperature physics**

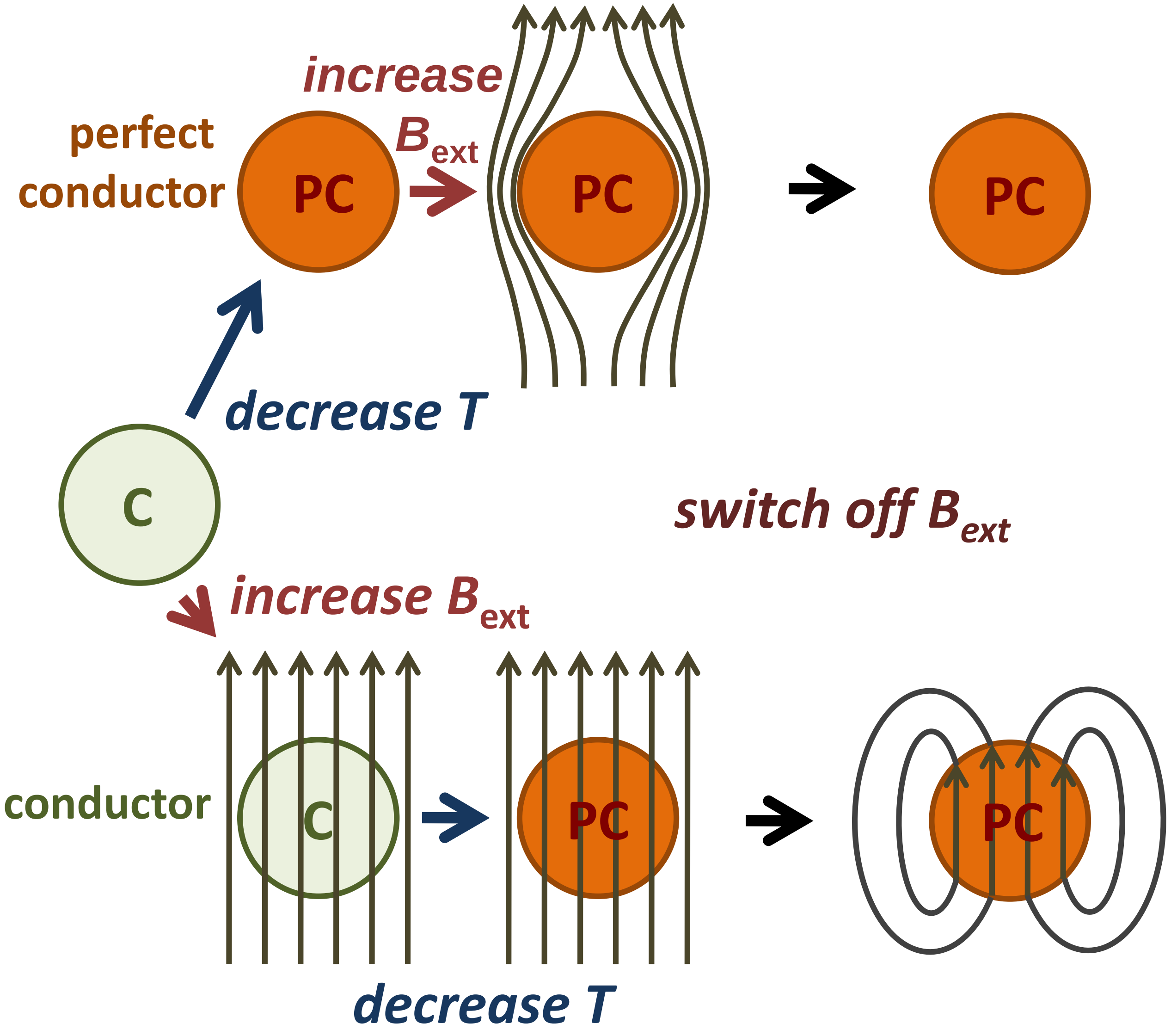
  important discoveries, key researchers, ….

Chapter 1

1. Basic Properties of Superconductors

1.3 Perfect Diamagnetism

perfect conductor in magnetic field



path dependent final state of the perfect conductor

1.3 Perfect Diamagnetism

variation of applied magnetic field for a perfect conductor

Faraday's law:

$$-\frac{\partial \mathbf{B}}{\partial t} = \boldsymbol{\nabla} \times \mathbf{E}$$

Ohm's law:

$$\mathbf{J} = \sigma \mathbf{E} \quad \Rightarrow \quad \mathbf{E} = \frac{\mathbf{J}}{\sigma} = \rho \mathbf{J} = 0$$

= 0 in superconductor

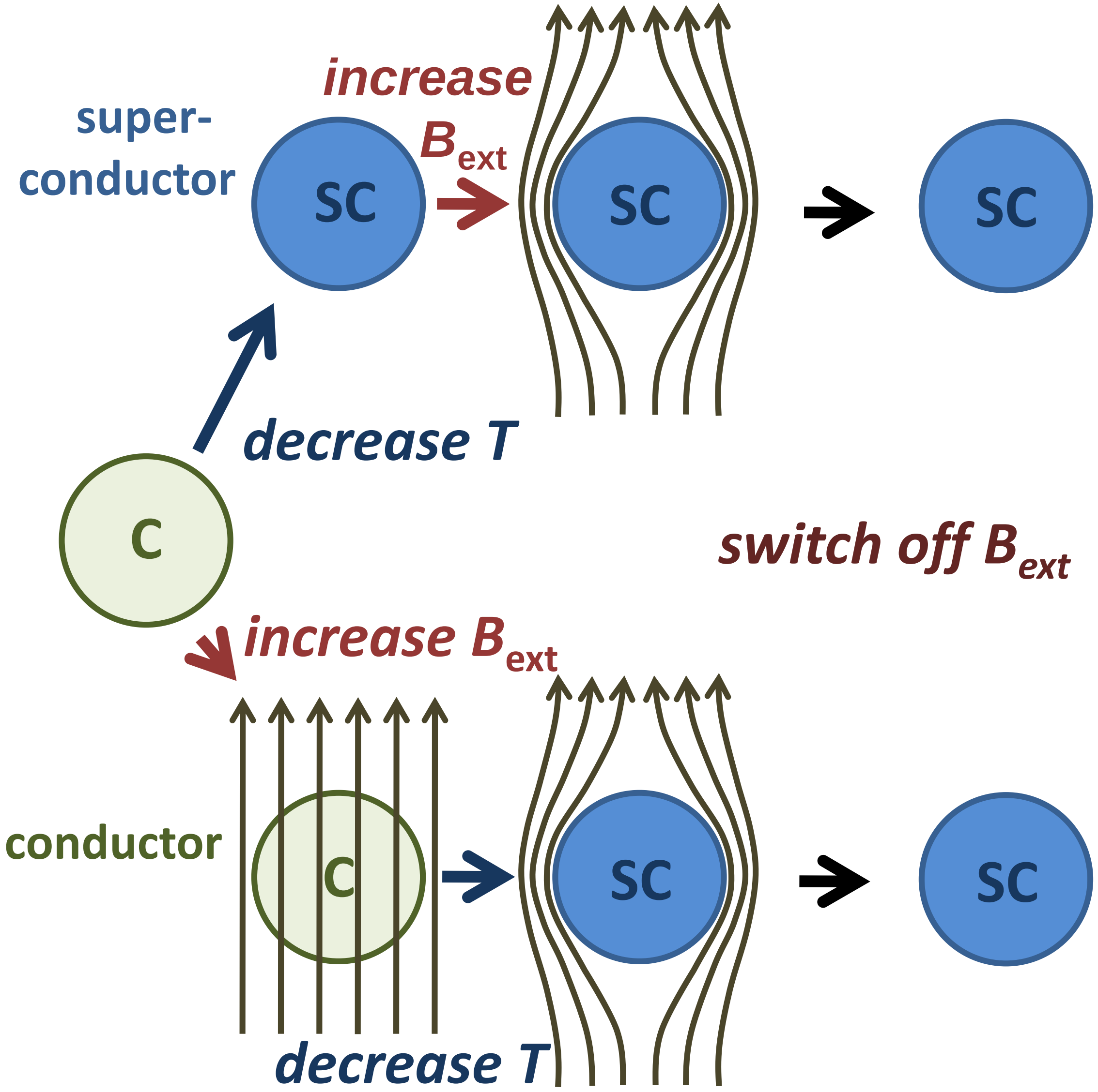
$$\Rightarrow \quad \frac{\partial \mathbf{B}}{\partial t} = 0$$

➔ $B_i = const.$ *inside a perfect conductor*

- *field variation → screening currents → shielding of temporal variation of flux density*
- *screening current do not decay* ➔ $B_i = const.$ *forever*
- *e.g. flux trapping in ring when swithching off external field*

1.3 Perfect Diamagnetism

superconductor in magnetic field



path **independent**
final state of the
superconductor

⇩

superconducting state is a thermodynamic phase

Meißner-Ochsenfeld-Effect

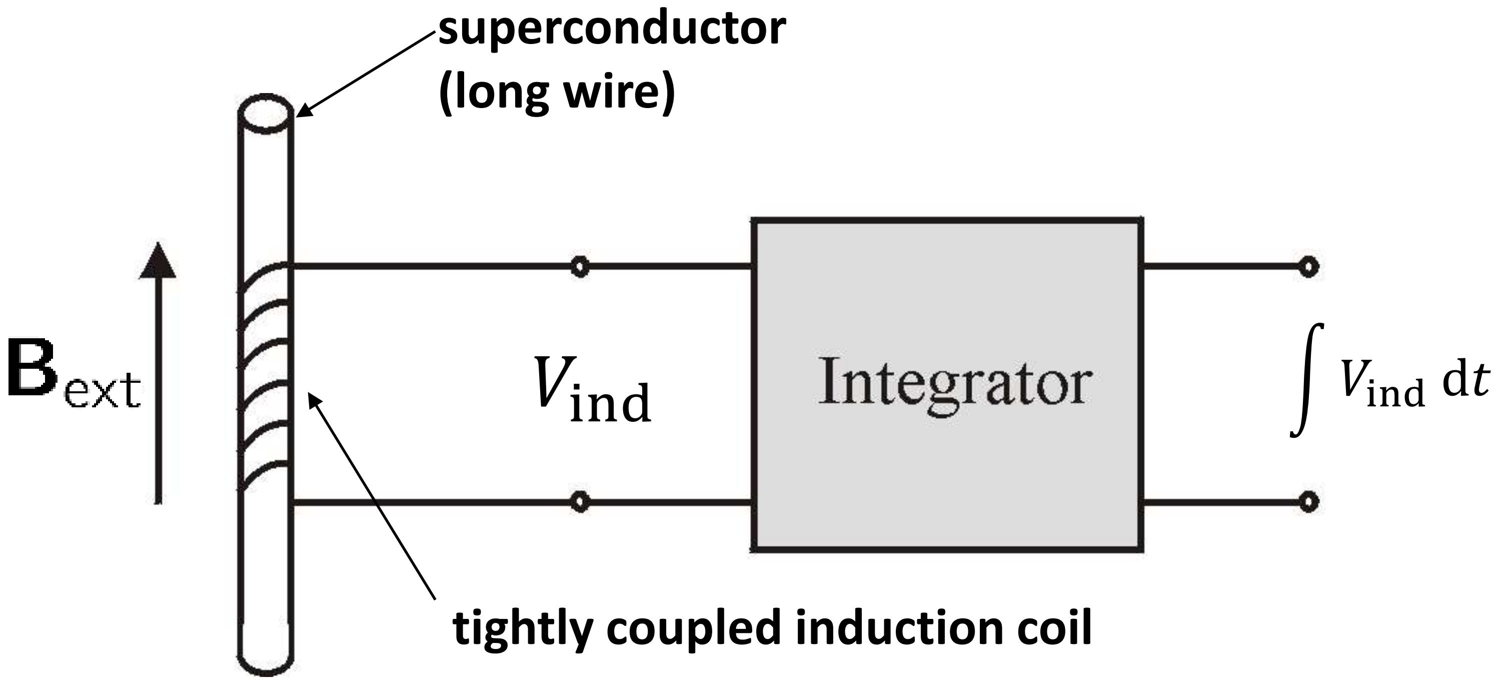
or

perfect diamagnetism

R. Gross and A. Marx , © Walther-Meißner-Institut (2004 - 2021)

1.3 Perfect Diamagnetism

simple experimental technique for determination of B_i:

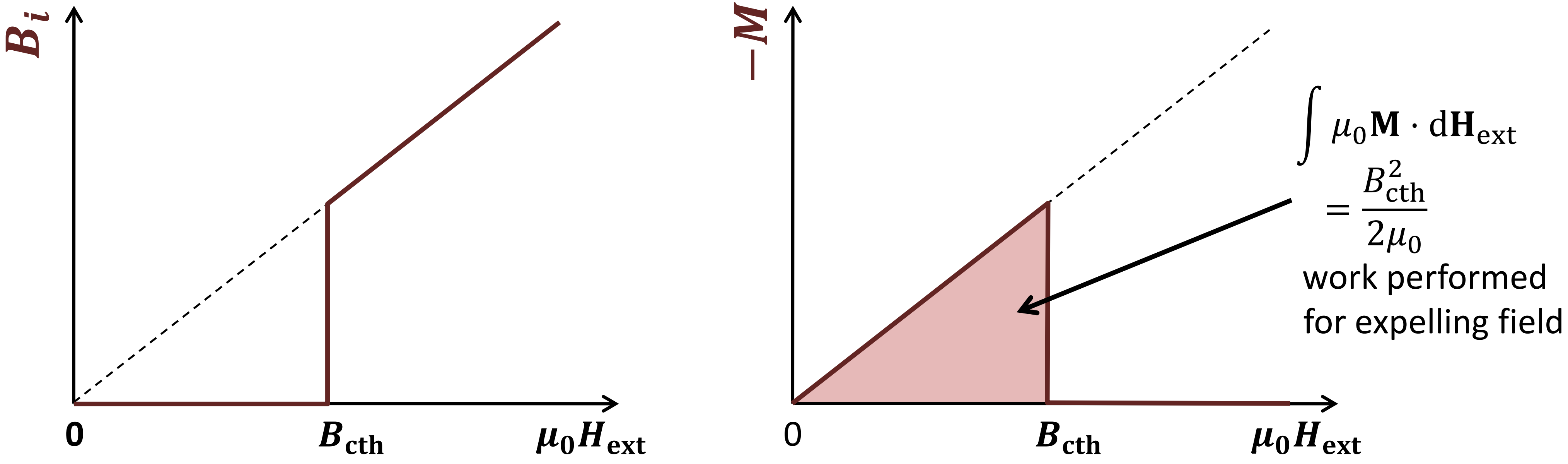


$$V_{\mathrm{ind}} = -\frac{\partial \Phi}{\partial t} \propto -\frac{\partial B_{\mathrm{i}}}{\partial t}$$

$$\Rightarrow \int V_{\mathrm{ind}}\,\mathrm{d}t \propto B_{\mathrm{i}}$$

1.3 Perfect Diamagnetism

inner magnetic field B_i and magnetization M of superconductors



$\mathbf{B}_i = \mu_0(\mathbf{H}_{\mathrm{ext}} + \mathbf{M})$

$\chi = -1$

$\mathbf{M} = \mathbf{B}_i/\mu_0 - \mathbf{H}_{\mathrm{ext}}$

$\mathbf{M} = \chi\, \mathbf{H}_{\mathrm{ext}}$

perfect diamagnetism survives only up to T-dependent critical field $B_{\mathrm{cth}}(T)$

→ *finite energy available for expelling magnetic field*

→ *condensation energy* (discussed later)

1.3 Perfect Diamagnetism

observation: **perfect diamagnetism survives only up to T - dependent critical field $B_{\mathrm{cth}}(T)$**

interpretation:

superconductor has only finite amount of energy available for expelling field

$$\frac{B_{\mathrm{cth}}^2(T)}{2\mu_0} = g_n(T) - g_s(T)$$

condensation energy

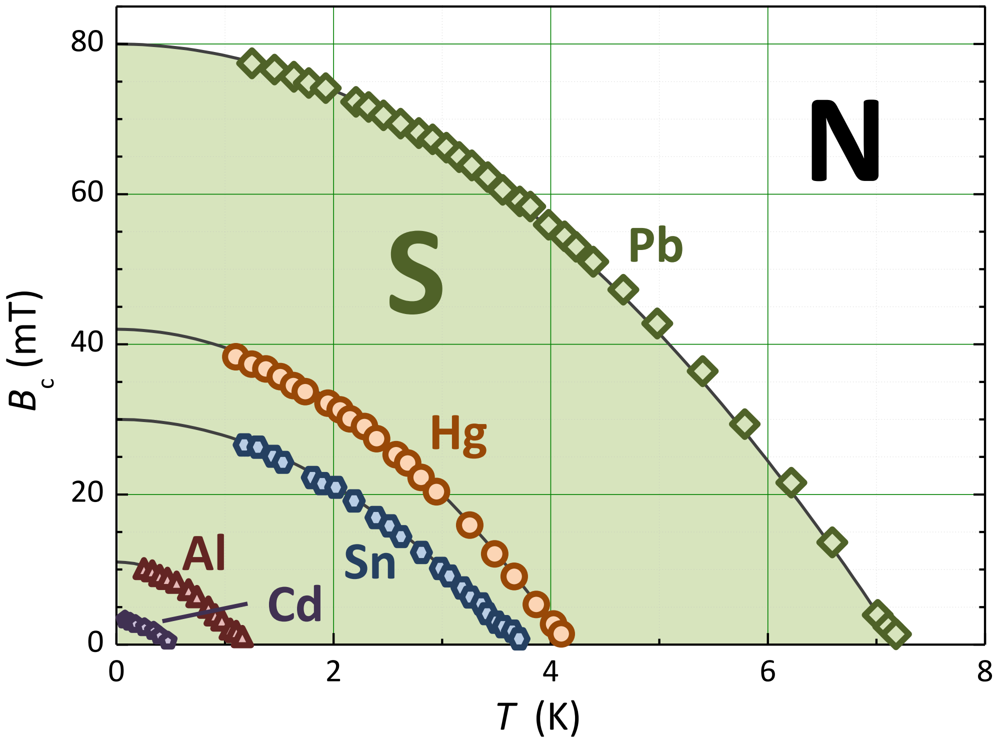
free enthalpy difference of N and S state

temperature dependence of B_{cth}:

$$B_{\mathrm{cth}}(T) = B_{\mathrm{cth}}(0)\left[1 - \left(\frac{T}{T_c}\right)^2\right]$$

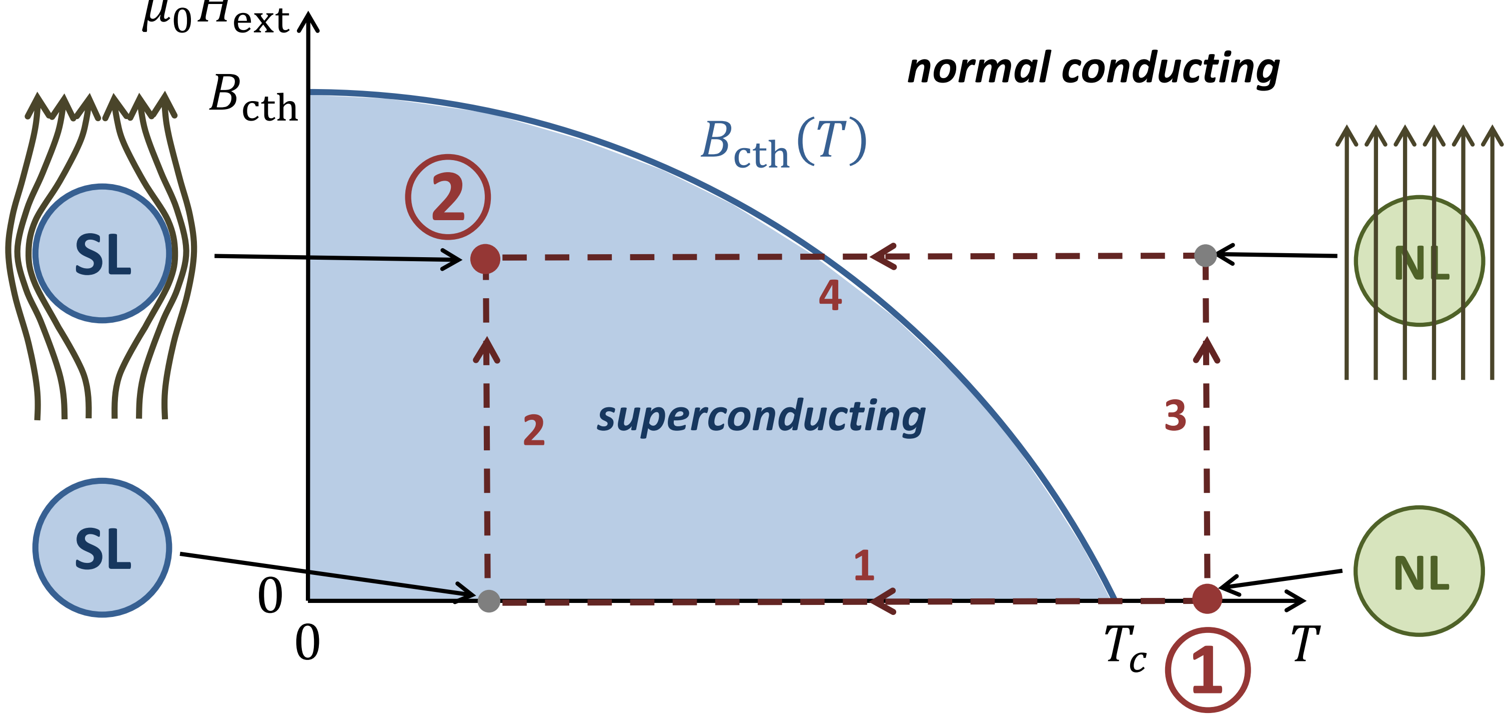
empirical relation, good approximation to exact result of BCS theory

phase diagram



1.3 Perfect Diamagnetism

superconductor: $\mathrm{B}_i = 0$ independent of path to position ②



$$\mathbf{B}_i = \mu_0(\mathbf{H}_{\mathrm{ext}} + \mathbf{M}) = \mu_0(\mathbf{H}_{\mathrm{ext}} + \chi \mathbf{H}_{\mathrm{ext}}) = \mu_0 \mathbf{H}_{\mathrm{ext}}(1+\chi) = 0$$

➔ **perfect diamagnetim: χ = - 1**

➔ **superconducting state is *thermodynamic phase***

1.3 Perfect Diamagnetism

Meißner effect:

path-independent complete exclusion of magnetic flux from the interior of a bulk superconductor

important remaining questions

- How does the magnetic induction B change at the surface? Step-like change?
- How do the screening currents set-off if not according to Faraday’s law?
- Can the magnetic flux penetrates partially to reduce the magnetic energy?
- What happens in a superconductor that is not simply connected (e.g. superconductor with hole such as a cylinder)?

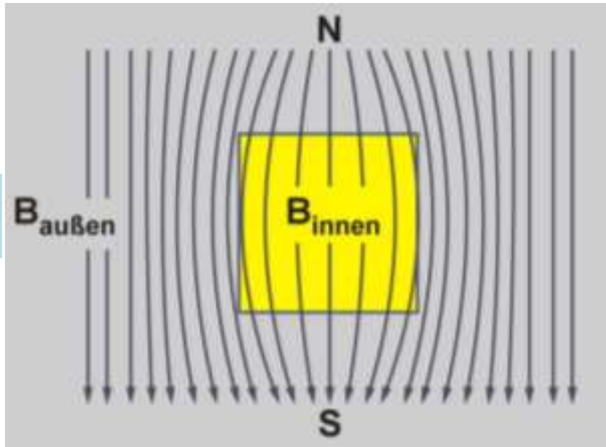
1.3 Perfect Diamagnetism

levitation of diamagnetic materials

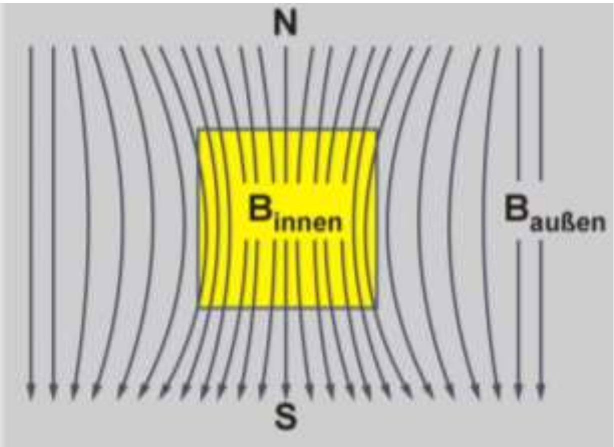
diamagnetic materials

para- or ferromagnetiv materials

$\chi < 0$

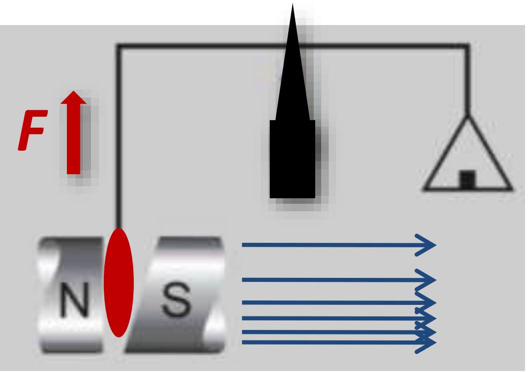


$\chi > 0$

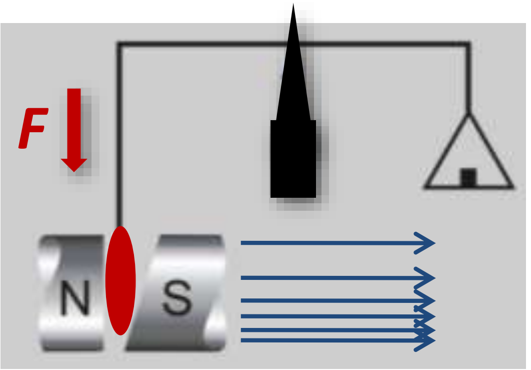


$$\mathbf{B}_i = (1+\chi)\,\mu_0\mathbf{H}_{\text{ext}}$$

(χ = magnetic susceptibility)



Faraday balance



material becomes „lighter“

material becomes „heavier“

R. Gross and A. Marx , © Walther-Meißner-Institut (2004 - 2021)

1.3 Perfect Diamagnetism

levitation of diamagnetic materials

$$\mathbf{F}_{\text{buoyancy}} = \frac{\chi}{2\mu_0}\,\mathbf{B}\cdot\nabla\mathbf{B}$$

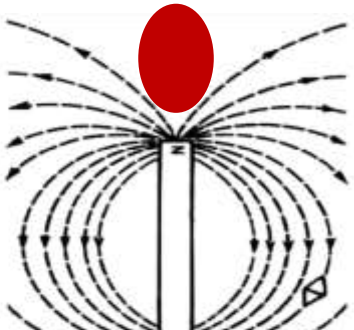
magnetic field *gradient of magnet field*

buoyancy = gravity

$$\mathbf{F}_{\text{gravity}} = \rho\ g$$

mass density *acceleration of gravity: 9.8 m/s²*

$$\boxed{\mathbf{B}\cdot\nabla\mathbf{B}\left[\frac{\mathrm{T}^2}{\mathrm{m}}\right] \approx \mathbf{0.02}\cdot\frac{\boldsymbol{\rho}[\mathrm{g/cm^3}]}{\boldsymbol{\chi}}}$$



- *organic materials:*

$\rho \simeq 1$ *g/cm³*, $\chi \simeq -1\cdot 10^{-5}$

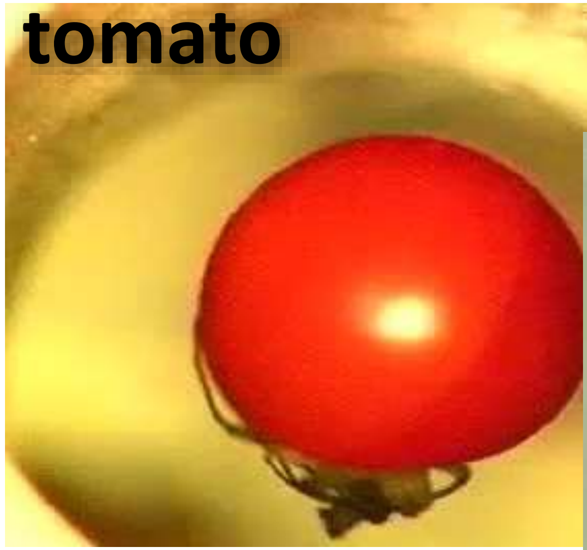
⇒ $\mathbf{B}\cdot\nabla\mathbf{B} \simeq 1\,000\left[\frac{\mathrm{T}^2}{\mathrm{m}}\right]$

can be achieved with strong magnet:
B = 20 Tesla, grad B = 100 T/m

10 cm

Levitated tomatos, strawberries, ...

source: http://www.hfml.ru.nl/



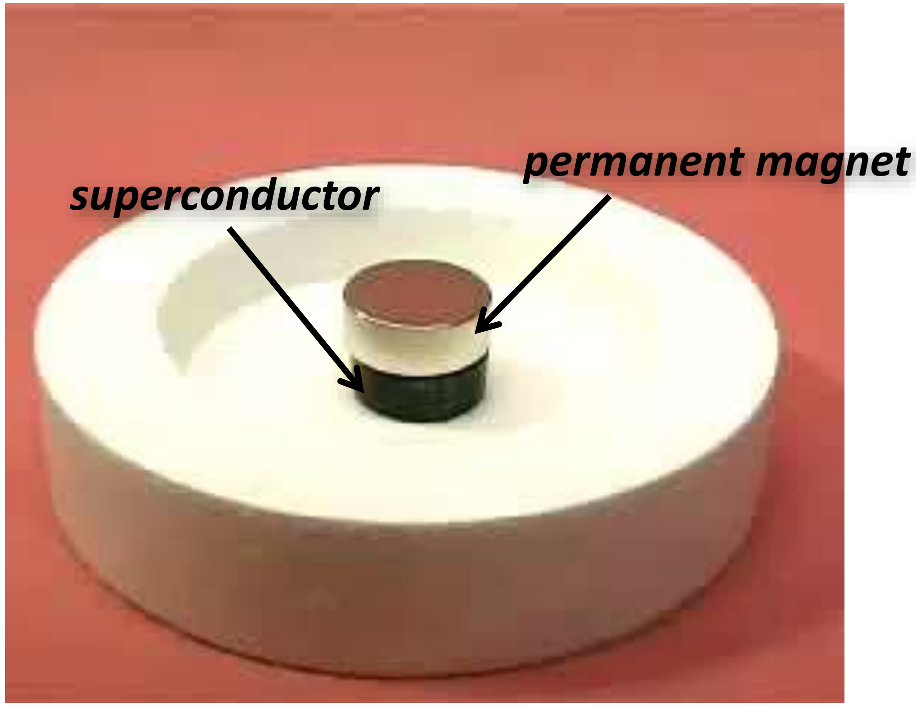
1.3 Perfect Diamagnetism

- *organic materials:* $\rho \simeq 1$ g/cm³, $\chi \simeq -1 \cdot 10^{-5}$

  ⇨ $\mathbf{B} \cdot \nabla \mathbf{B} \simeq 1\,000 \left[\frac{\mathrm{T}^2}{\mathrm{m}}\right]$

- *superconductors:* $\rho \simeq$ a few g/cm³, $\chi \simeq -1$

  ⇨ $\mathbf{B} \cdot \nabla \mathbf{B} \simeq 0.01 \left[\frac{\mathrm{T}^2}{\mathrm{m}}\right]$



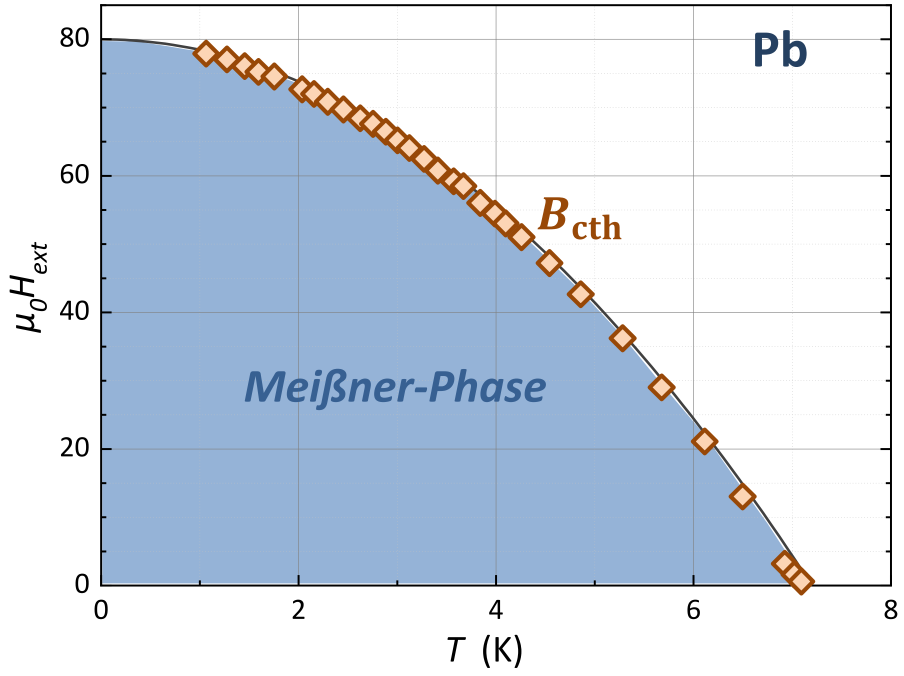
Superconductors:

ideal materials for magnetic levitation

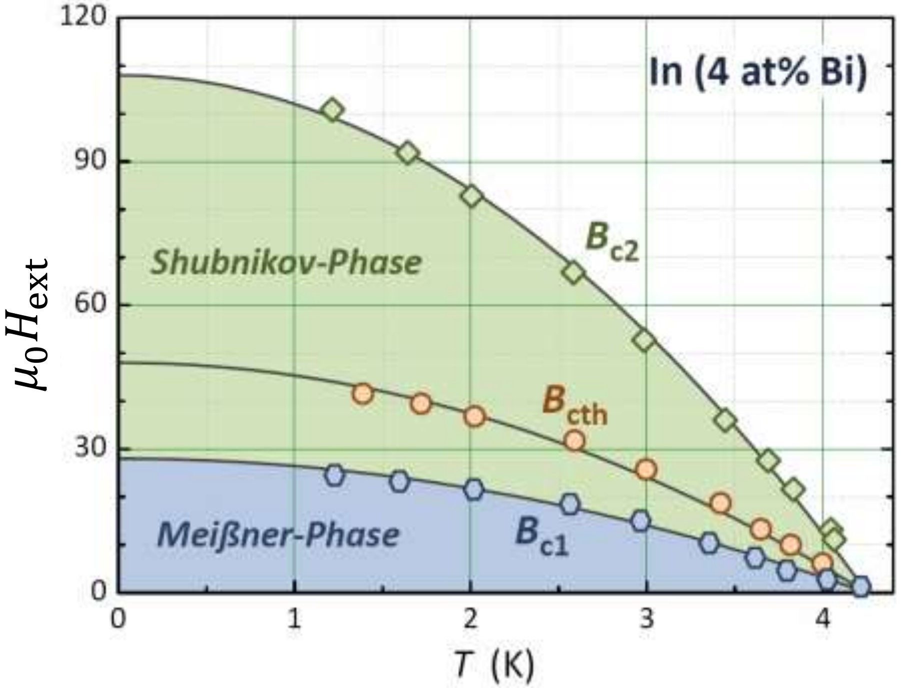
1. Basic Properties of Superconductors

1.4 Type-I and Type-II Superconductors

Type-I Superconductor



Type-II Superconductor



- **Meißner-Phase** for $B_{ext} < B_{cth}$
- **no Shubnikov-Phase**

- **Meißner-Phase** for $B_{ext} < B_{c1}$
- **Shubnikov-Phase** for $B_{c1} < B_{ext} < B_{c2}$

$$B_{c1} < B_{cth} < B_{c2}$$

Chapter 1

1. Basic Properties of Superconductors

1.1 History of Superconductivity
1.2 Perfect Conductivity
1.3 Perfect Diamagnetism
1.4 Type-I and Type-II Superconductors
⇨ 1.5 Flux Quantization
1.6 Superconducting Materials
1.7 Transition Temperatures

1.4 Flux Quantization

- discoverd 1961 by
  - ***Robert Doll*** and ***Martin Näbauer*** (WMI)
  - ***B.S. Deaver*** and ***W.M. Fairbanks*** (Stanford University)

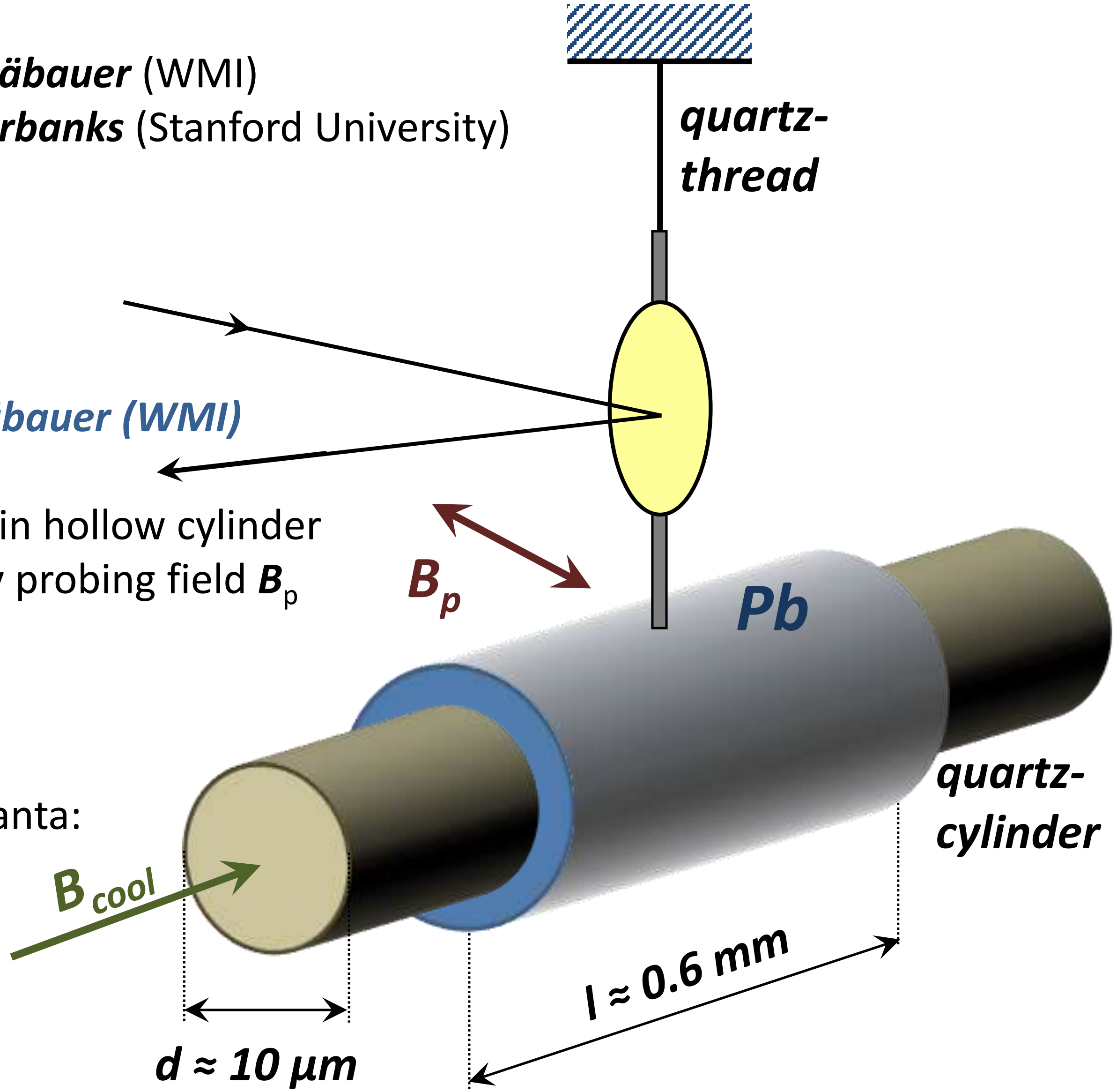
- *experiment by Doll and Näbauer (WMI)*

  - trapping of magnetic flux in hollow cylinder
  - apply torque **D** = **μ** x **B**$_p$ by probing field ***B***$_p$
  - increase sensitivity by resonance technique

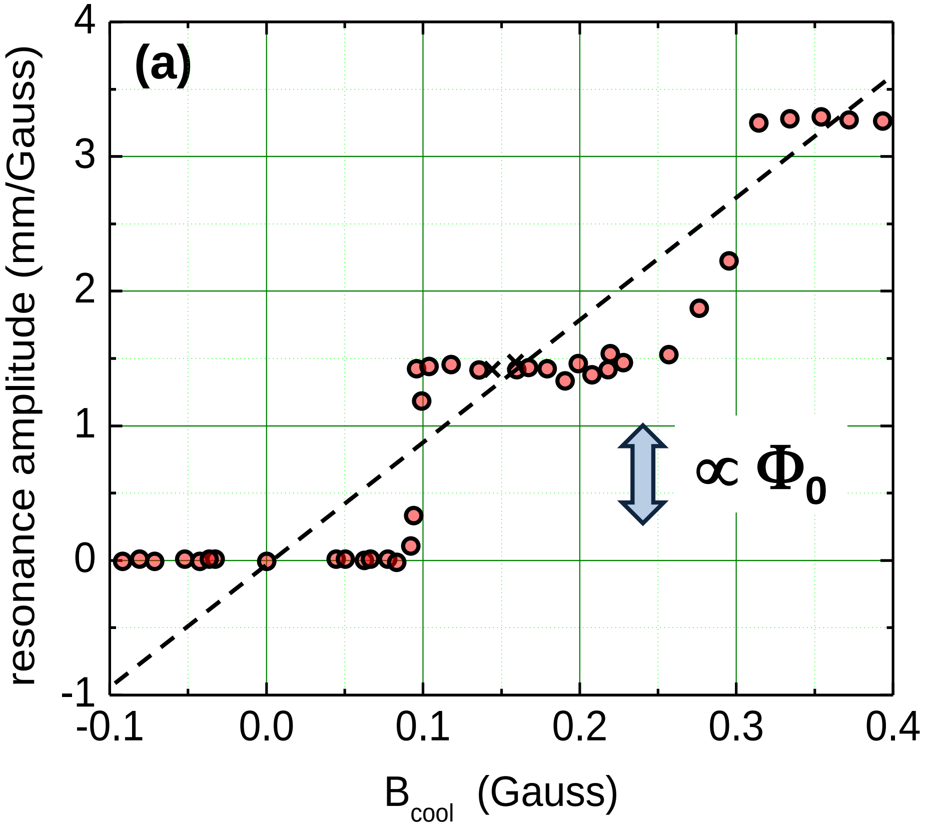
- number of trapped flux quanta:

$$N = B_{\text{cool}}\,\pi(d/2)^2$$

$N \simeq 1$
$@\, B_{\text{cool}} = 10^{-5}\,\text{T}, d = 10\,\mu\text{m}$

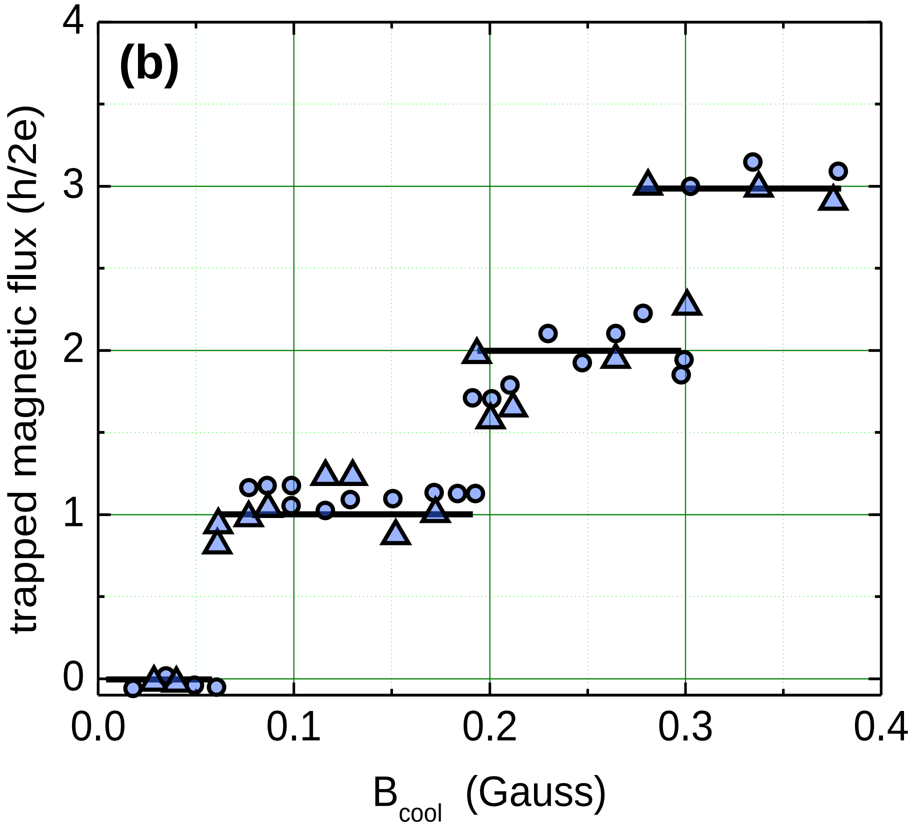


1.4 Flux Quantization



R. Doll, M. Näbauer

Phys. Rev. Lett. **7**, 51 (1961)



B.S. Deaver, W.M. Fairbank

Phys. Rev. Lett. **7**, 43 (1961)

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

prediction by F. London: h/e

→ ***experimental proof for existence of Cooper pairs***

Paarweise im Fluss

D. Einzel, R. Gross, Physik Journal 10, No. 6, 45-48 (2011)

Chapter 1

1. Basic Properties of Superconductors

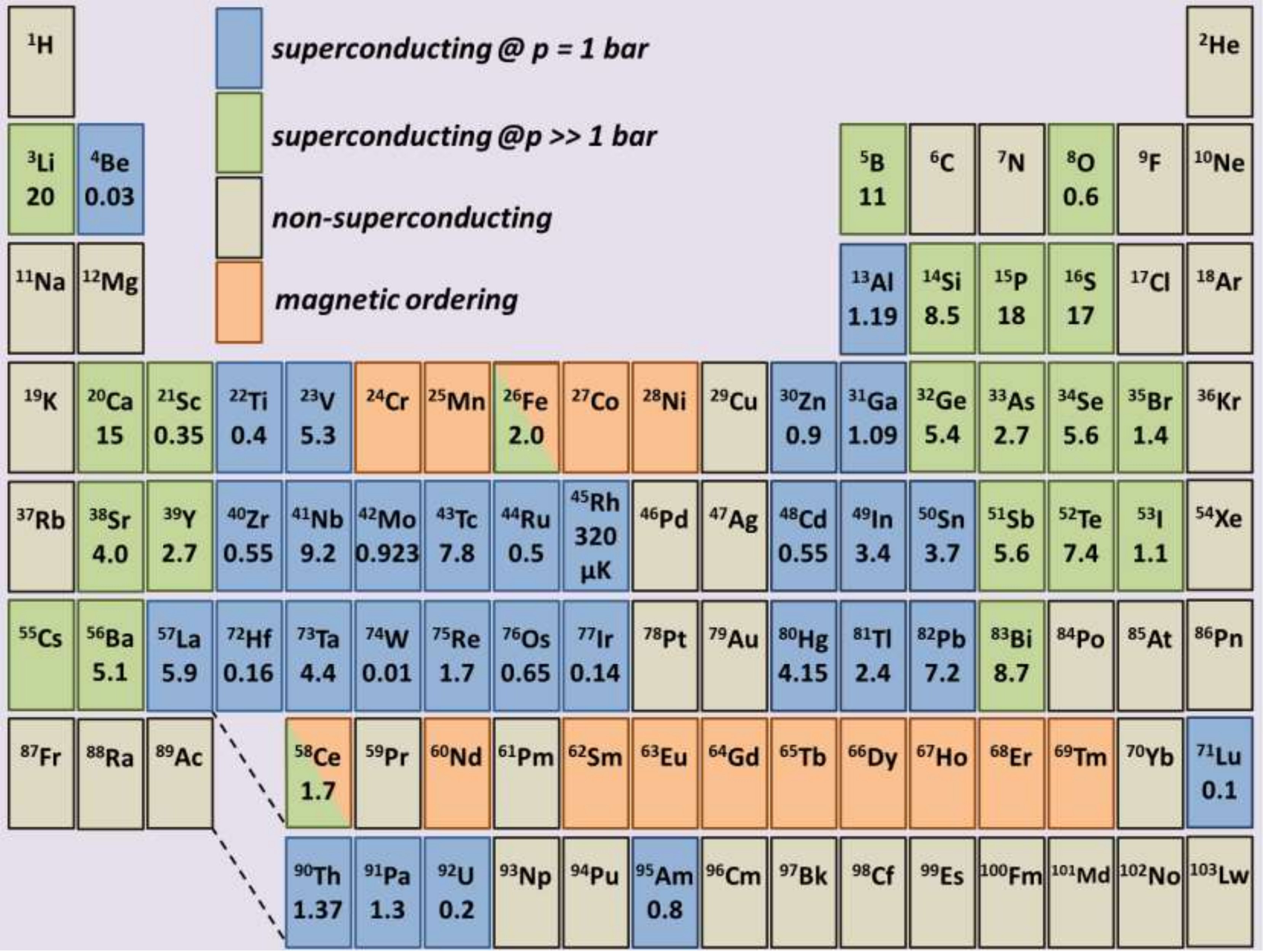
1.6 Superconducting Materials

- discovery of superconductivity in chemical element Hg
- since then thousands of further superconducting compounds found
- classification into families:

1. elemental superconductors (Hg, 1911)
2. alloys and intermtellic compounds
3. heavy Fermion superconductors (1979)
4. organic superconductors (1981)
5. fullerides (1991)
6. oxides superconductors , cuprates (1986)
7. iron pnictides (2006)

MgB_2 (2001)

1.6 Superconducting Materials



🟦 *superconducting @ p = 1 bar*

🟩 *superconducting @p >> 1 bar*

⬜ *non-superconducting*

🟧 *magnetic ordering*

^{1}H																	^{2}He
^{3}Li 20	^{4}Be 0.03											^{5}B 11	^{6}C	^{7}N	^{8}O 0.6	^{9}F	^{10}Ne
^{11}Na	^{12}Mg											^{13}Al 1.19	^{14}Si 8.5	^{15}P 18	^{16}S 17	^{17}Cl	^{18}Ar
^{19}K	^{20}Ca 15	^{21}Sc 0.35	^{22}Ti 0.4	^{23}V 5.3	^{24}Cr	^{25}Mn	^{26}Fe 2.0	^{27}Co	^{28}Ni	^{29}Cu	^{30}Zn 0.9	^{31}Ga 1.09	^{32}Ge 5.4	^{33}As 2.7	^{34}Se 5.6	^{35}Br 1.4	^{36}Kr
^{37}Rb	^{38}Sr 4.0	^{39}Y 2.7	^{40}Zr 0.55	^{41}Nb 9.2	^{42}Mo 0.923	^{43}Tc 7.8	^{44}Ru 0.5	^{45}Rh 320 μK	^{46}Pd	^{47}Ag	^{48}Cd 0.55	^{49}In 3.4	^{50}Sn 3.7	^{51}Sb 5.6	^{52}Te 7.4	^{53}I 1.1	^{54}Xe
^{55}Cs	^{56}Ba 5.1	^{57}La 5.9	^{72}Hf 0.16	^{73}Ta 4.4	^{74}W 0.01	^{75}Re 1.7	^{76}Os 0.65	^{77}Ir 0.14	^{78}Pt	^{79}Au	^{80}Hg 4.15	^{81}Tl 2.4	^{82}Pb 7.2	^{83}Bi 8.7	^{84}Po	^{85}At	^{86}Pn
^{87}Fr	^{88}Ra	^{89}Ac															
				^{58}Ce 1.7	^{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 0.1
				^{90}Th 1.37	^{91}Pa 1.3	^{92}U 0.2	^{93}Np	^{94}Pu	^{95}Am 0.8	^{96}Cm	^{97}Bk	^{98}Cf	^{99}Es	^{100}Fm	^{101}Md	^{102}No	^{103}Lw

elemental superconductors

1.6 Superconducting Materials

- ***elemental superconductors***

  - highest T_c: Nb, 9.2 K

  - lowest T_c: Rh, 0.32 mK

  - many elements become superconducting under pressure
    e.g. Li: T_c almost 20 K @ $p = 0.5$ Mbar
    non-magnetic high pressure Fe phase: $T_c = 2$ K

- ***problem related to observation of superconductivity in materials with very low T_C:***

$$k_\mathrm{B} T_c = 1.38 \cdot 10^{-26}\,\mathrm{J} \quad @ \quad T_c = 1\,\mathrm{mK}$$

requires small pair breaking rate → very pure materials

$$\tau^{-1} \leq \frac{\hbar}{k_\mathrm{B} T_c} = 1.38 \cdot 10^{-26} \frac{\mathrm{J}}{\hbar} @ \quad T_c = 1\,\mathrm{mK} \Rightarrow \tau \geq 10^{-8}\,s$$

1.6 Superconducting Materials

material	T_c
@ 1 bar	
Ru	0.35 K
Al	1.2 K
In	3.4 K
Sn	3.7 K
Hg, Ta	4.2 K
Pb	7.2 K
Nb	9.2 K
@ > 120 kbar	
Si	6.7 K
Ge	5.4 K
S	17 K
Li	16 K

material	T_c	
amorphous:	Pt	0.6 .. 0.9 K
quenched condensed:	Ga	8.0 K (orthorhombic phase: 1.09 K)
	Bi	6.0 K (crystalline phase: semimetal, no SC)

1.6 Superconducting Materials

- ***alloys and intermetallic compounds***

  - more than 1000 systems found until today

  - some have high relevance for applications:

    e.g. A15 compounds (1953) with with β-tungsten structure
    Nb_3Ge: $T_c = 23.2$ K, Nb_3Sn: $T_c = 18$ K, V_3Si: $T_c = 17$ K

    e.g. NbTi: $T_c = 10 - 11$ K, NbN: $T_c = 13 - 16$ K

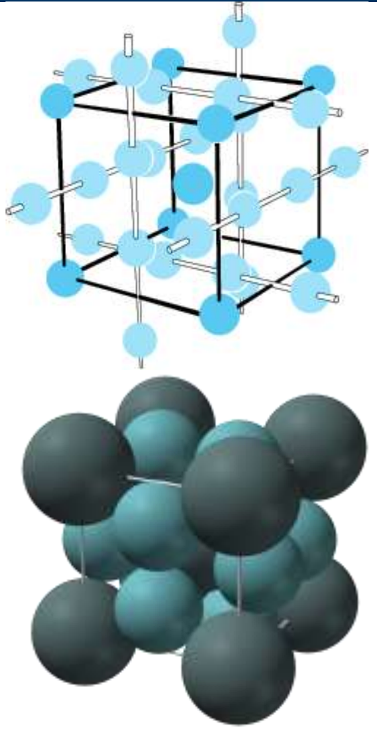
  - Chevrel phases: $M_xMo_6X_8$ M = Ca, Sr, Ba, Sn, Pb, Au, RE
    X = S, Se, Te (chalcogenides)

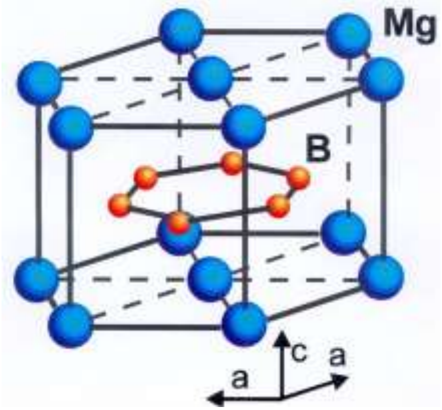
    e.g. $PbMo_6S_8$: $T_c = 15$ K

  - boron carbides: RM_2B_2C (1994) R = rare earth elem. (e.g. Tm, Er, Ho)
    M = Ni, Pd

    e.g. $(Lu/Y)Ni_2B_2C$: $T_c = 16$ K

  - MgB_2 (2001) T_c almost 40 K





1.6 Superconducting Materials

- ***heavy Fermion superconductors***

  - found by ***Frank Steglich*** *et al*. in 1979

    - $CeCu_2Si_2$ $T_c = 0.5$ K
    - today many systems known

  - electrons in these compounds have very large effective mass

    → heavy Fermions: $m^\star \sim 100 - 1000\ m_\mathrm{e}$

  - mechanism of superconductivity still under debate

1.6 Superconducting Materials

- ***organic superconductors***

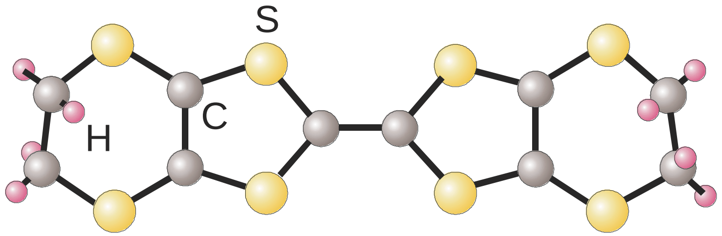
  - found by ***Jerome*** et al. in 1980

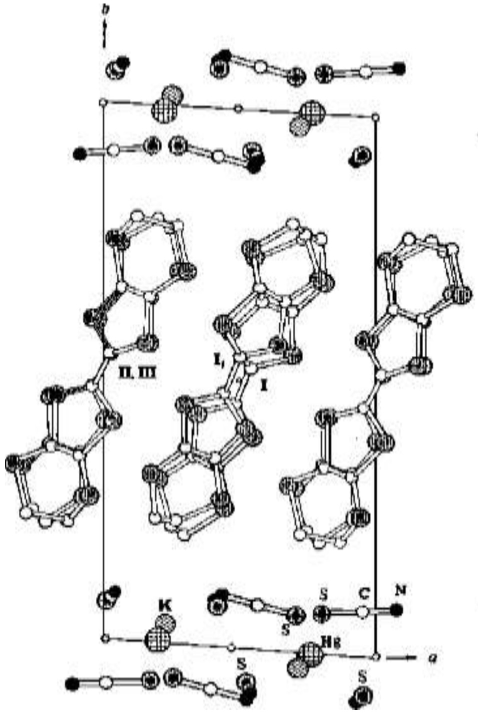
    - TMTSF (tetramethyl-tetraselenafulvalen) $T_c = 0.9$ K
    - today many systems known with T_c up to 12 K

    e.g. $(\text{BEDT-TTF})_2\text{Cu}[\text{N(CN)}_2]\text{Br}$ $T_c = 11.2$ K

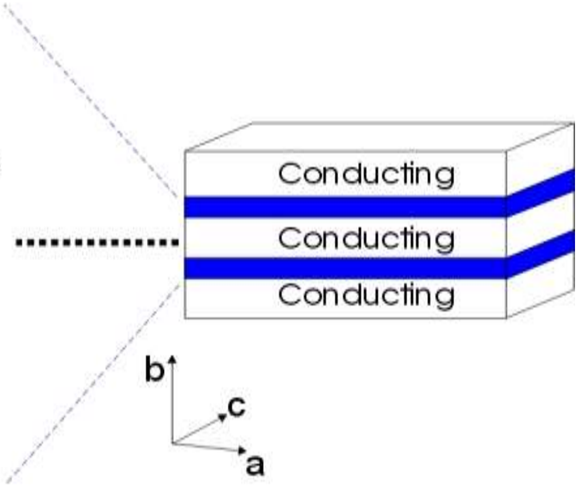
    bis(ethylenedithio)-tetrathiafulfalene

BEDT-TTF-molecule:





crystal structure:



- most systems are highly anisotropic

1.6 Superconducting Materials

- *fullerides*

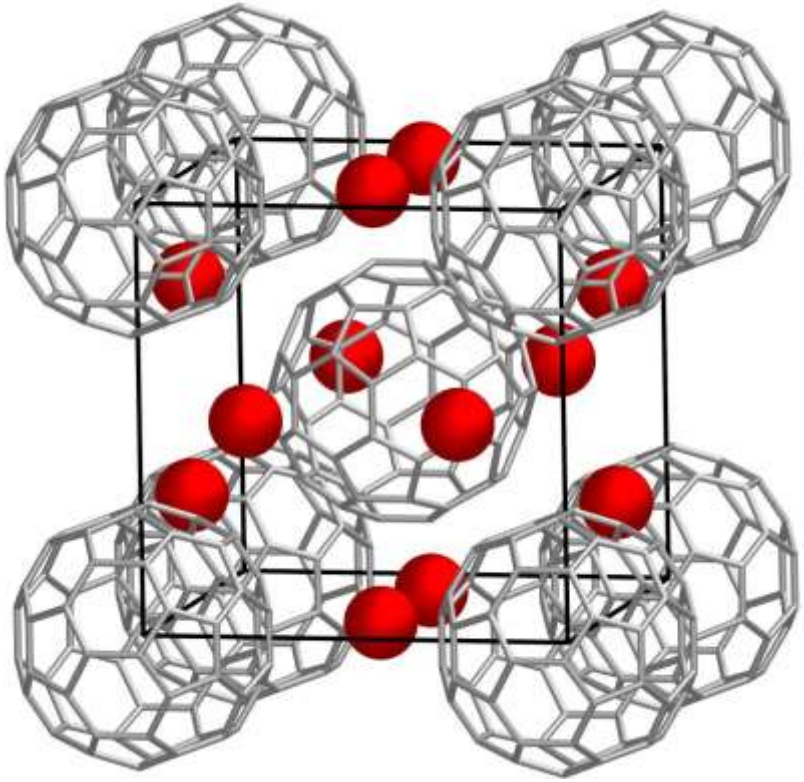
- doping of C_{60} molecules (fullerene), arrangement in regular structure → *fullerides*

- superconductivity found in 1991 by ***Robert Haddon*** at Bell Labs

K_3C_{60} with $T_c = 18$ K

- until today T_c up to 40 K found

Cs_2RbC_{60}	$T_c = 33$ K
Cs_3C_{60}	$T_c = 40$ K @ $p = 15$ kbar



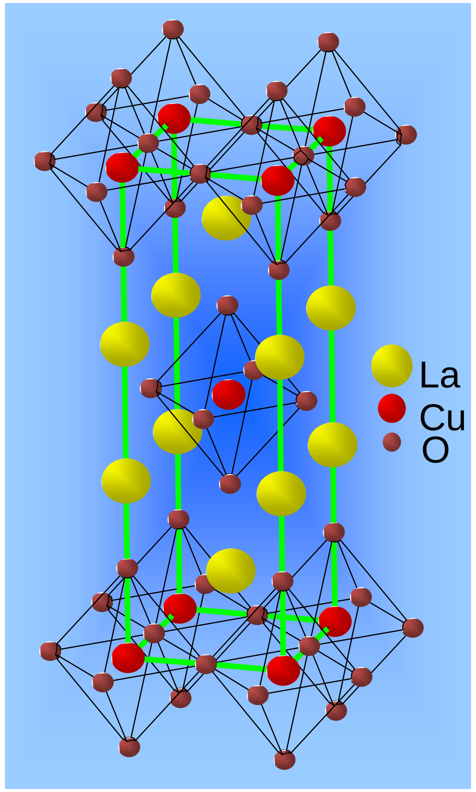
1.6 Superconducting Materials

- ***oxide superconductors***

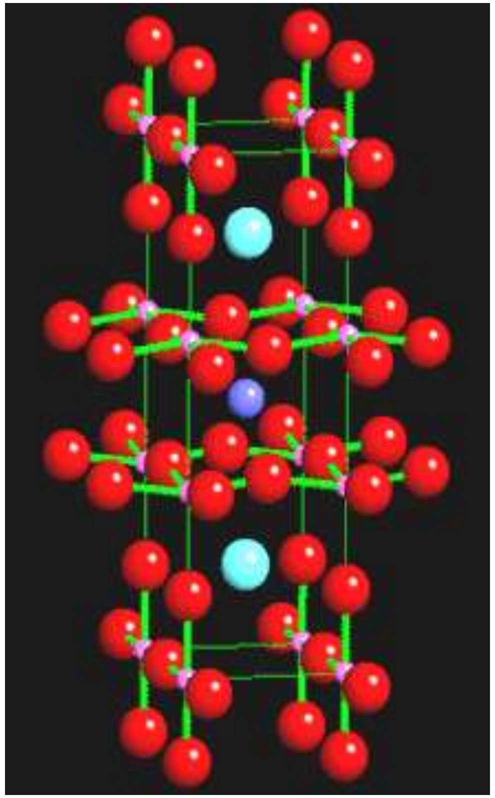
  - discovered by ***Georg Bednorz*** and ***Alex Müller*** in 1986 in $La_{2-x}Ba_xCuO_4$ (Zurich oxide)

  - until today several compounds found with T_c up to 135 K (165 K under pressure)

  - layered crystal structure formed by CuO_2 planes and charge reservoir layers



$La_{2-x}Sr_xCuO_4$



$YBa_2Cu_3O_7$

R. Gross and A. Marx , © Walther-Meißner-Institut (2004 - 2021)

1.6 Superconducting Materials

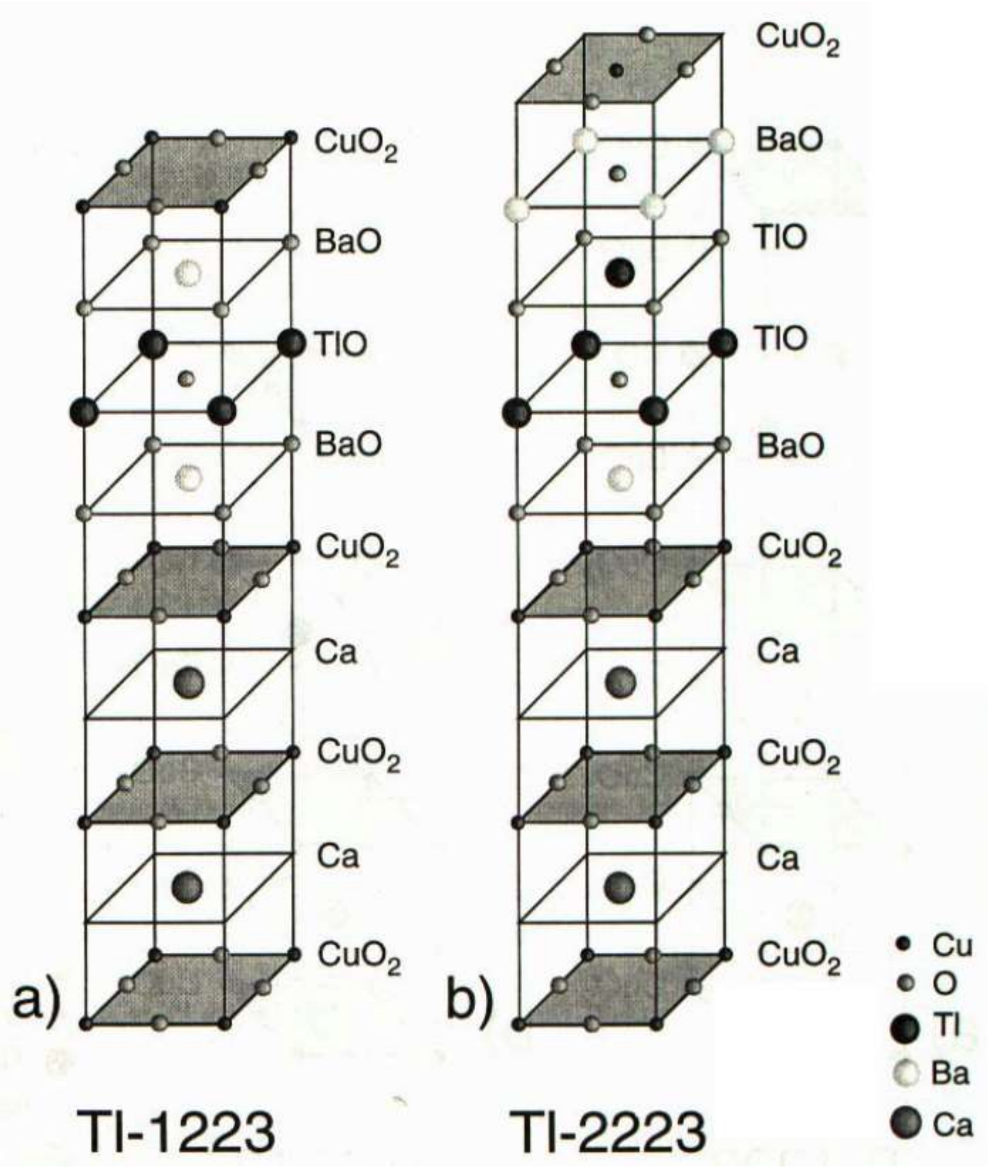
4 component systems

$$A_mB_2Ca_{n-1}Cu_nO_{2+m+2n}$$

Bi, Tl, Hg   Ba, Sr = alcaline earth metals

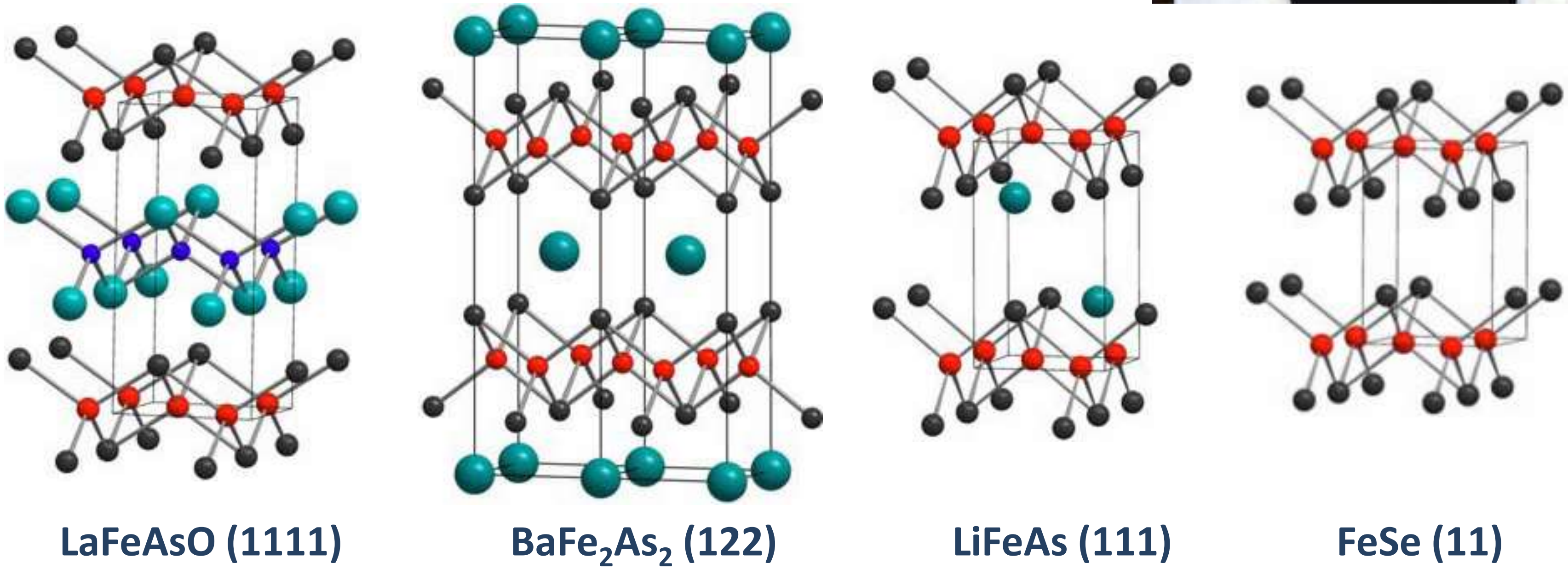
examples

$Bi_2Sr_2Ca_2Cu_3O_{10}$ = Bi-2223 (110 K)
$Tl_2Ba_2Ca_2Cu_3O_{10}$ = Tl-2223 (127 K)
$HgBa_2Ca_2Cu_3O_9$ = Hg-1223 (135 K)



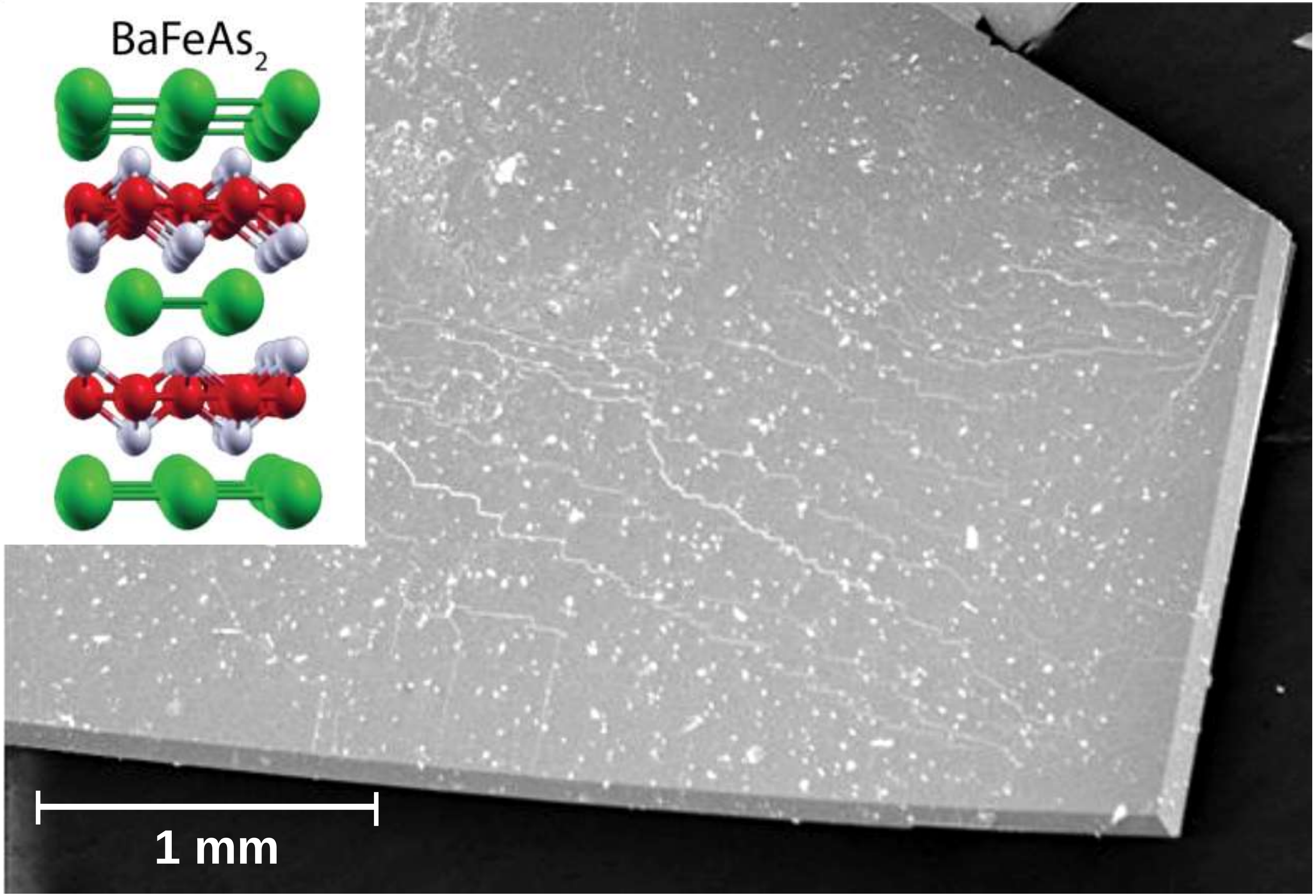
1.6 Superconducting Materials

- *iron pnictide superconductors*
  - discovered in 2006 by ***Hideo Hosono*** et al.
    in La[$O_{1-x}F_x$]FeAs, $T_c = 26$ K
  - until today several compounds/families found with T_c up to 55 K



Yoichi Kamihara, Hidenori Hiramatsu, Masahiro Hirano, Ryuto Kawamura, Hiroshi Yanagi, Toshio Kamiya, and Hideo Hosono "Iron-Based Layered Superconductor: LaOFeP". *J. Am. Chem. Soc.* **128** (31): 10012–10013 (2006).

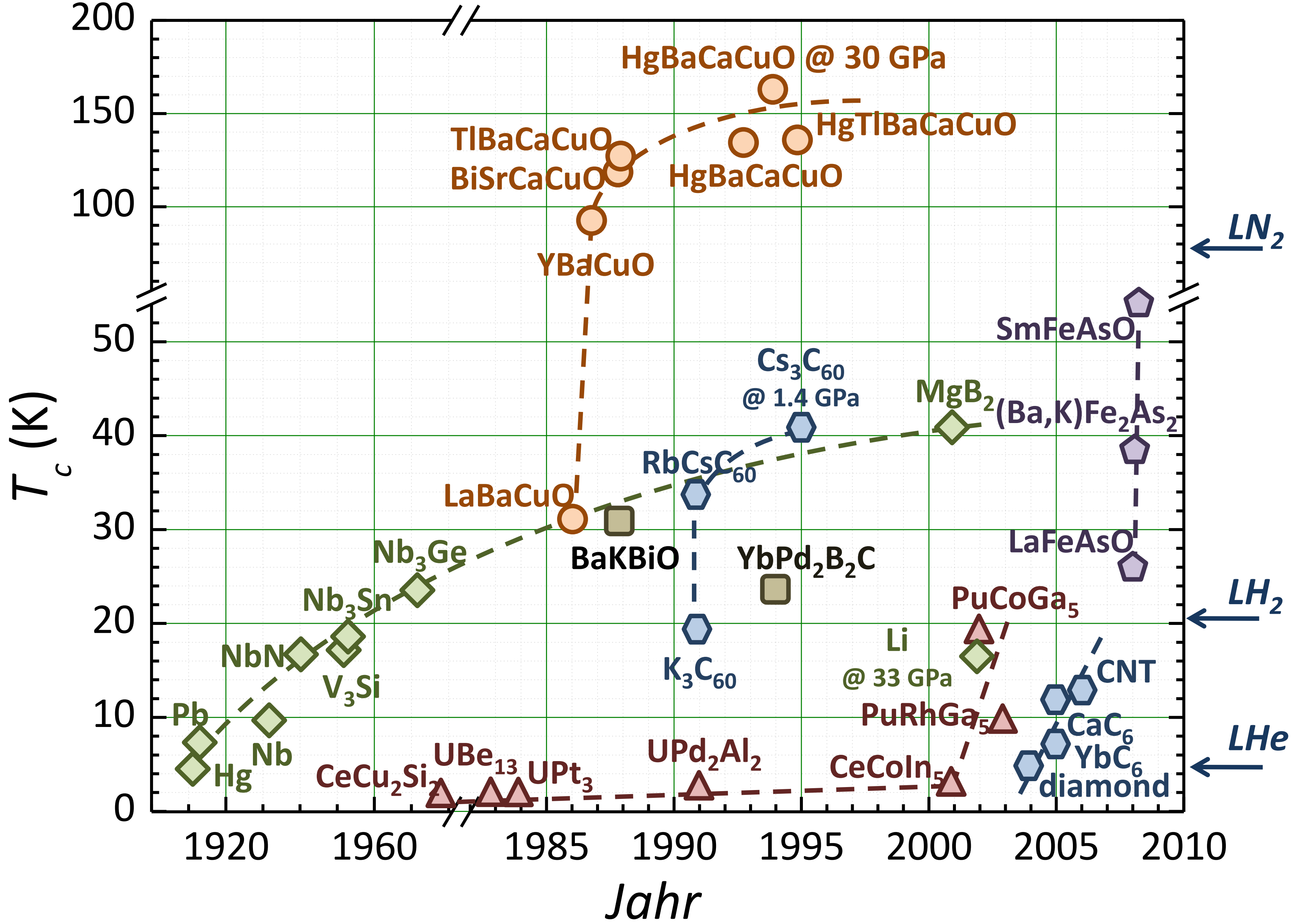
1.6 Superconducting Materials



Chapter 1

1. Basic Properties of Superconductors

1.7 Transition Temperatures



1.7 Transition Temperatures

- **recently discoverd materials with very high transition temperatures**

  – **2015**:
    Eremets and co-workers report that H_2S becomes a metallic conductors under high pressure (100–300 GPa) and shows a transition temperature of $T_c = -70°\mathrm{C}$ (203 K).

LETTER

doi:10.1038/nature14964

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]

  – **2019**:
    Eremets *et al*. measured for LaH_{10} under high pressure (170 GPa) a transition temperature of $T_c \simeq 250$ K (≈ −23 °C)

LETTER

https://doi.org/10.1038/s41586-019-1201-8

Superconductivity at 250 K in lanthanum hydride under high pressures

A. P. Drozdov[1,7], P. P. Kong[1,7], V. S. Minkov[1,7], S. P. Besedin[1,7], M. A. Kuzovnikov[1,6,7], S. Mozaffari[2], L. Balicas[2], F. F. Balakirev[3], D. E. Graf[2], V. B. Prakapenka[4], E. Greenberg[4], D. A. Knyazev[1], M. Tkacz[5] & M. I. Eremets[1*]

1.7 Transition Temperatures

- **recently discoverd materials with very high transition temperatures**

  – **2020**:
  Snider *et al*. measured for CH_8S under high pressure (267 GPa) a transition temperature of $T_c \simeq 288$ K (≈ 15 °C), Nature 586, 373 - 377 (2020)

Article

Room-temperature superconductivity in a carbonaceous sulfur hydride

https://doi.org/10.1038/s41586-020-2801-z
Received: 21 July 2020
Accepted: 8 September 2020
Published online: 14 October 2020

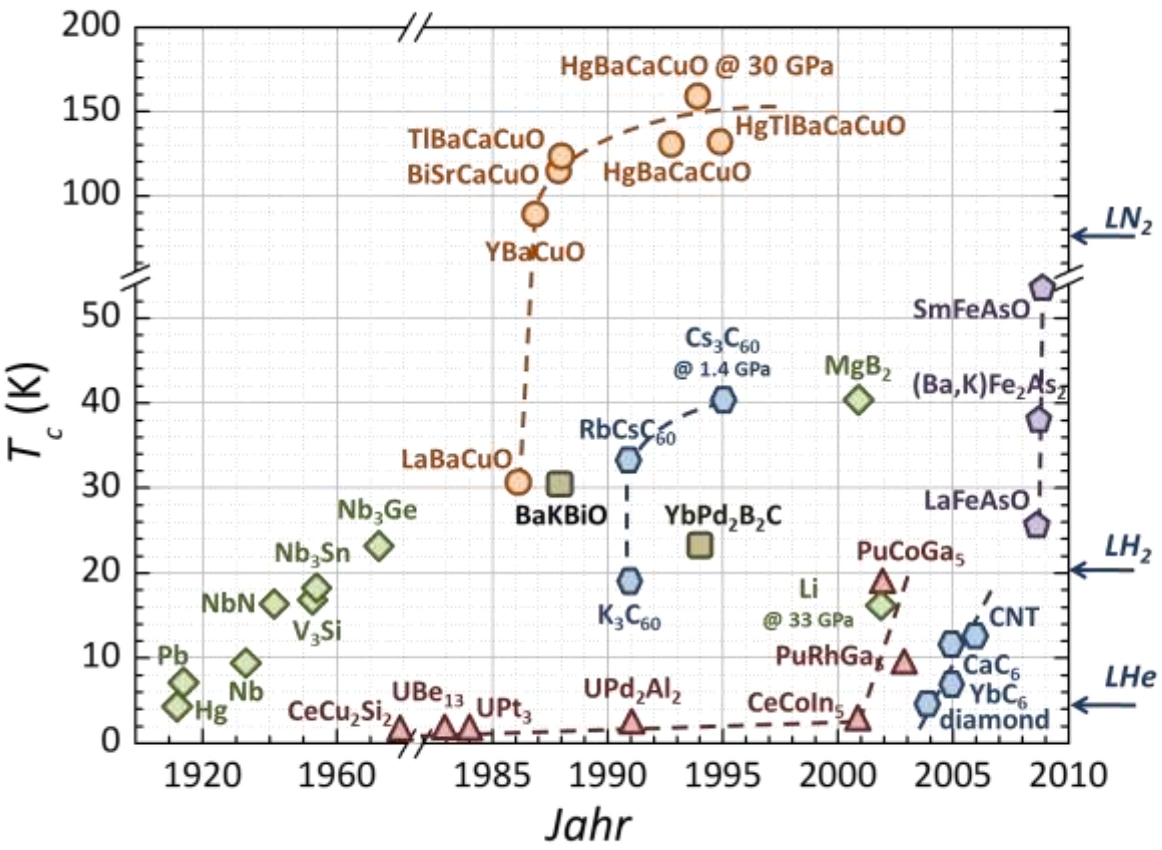
Check for updates

Elliot Snider[1,6], Nathan Dasenbrock-Gammon[2,6], Raymond McBride[1,6], Mathew Debessai[3], Hiranya Vindana[2], Kevin Vencatasamy[2], Keith V. Lawler[4], Ashkan Salamat[5] & Ranga P. Dias[1,2] ✉

One of the long-standing challenges in experimental physics is the observation of room-temperature superconductivity[1,2]. Recently, high-temperature conventional superconductivity in hydrogen-rich materials has been reported in several systems under high pressure[3–5]. An important discovery leading to room-temperature superconductivity is the pressure-driven disproportionation of hydrogen sulfide

➔ **material with the so far highest transition temperature**

1.7 Transition Temperatures



relevant material parameters for technical applications:

- high transition temperatures T_c
- high critical current densities J_c
- high critical magnetic fields B_c