Oslo International School for Master and PhD Students
Relativistic Heavy Ion Collisions
Cosmology and Dark Matter
Cancer Therapy

UiO : University of Oslo

UNIVERSITY OF BIRMINGHAM

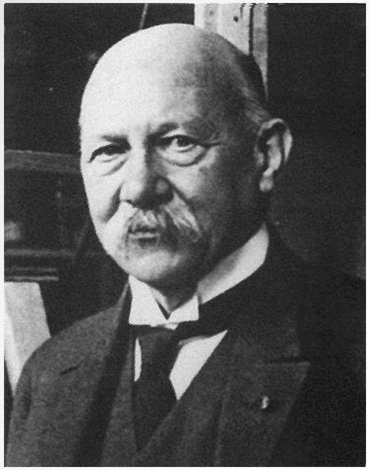
Introduction to superconductivity

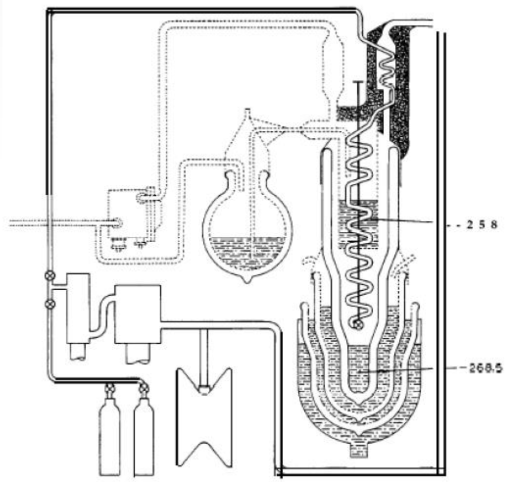
P. Mikheenko

Department of Physics, University of Oslo, P.O. Box 1048, Blindern, 0316 Oslo, Norway
University of Birmingham, Birmingham B15 2TT, UK

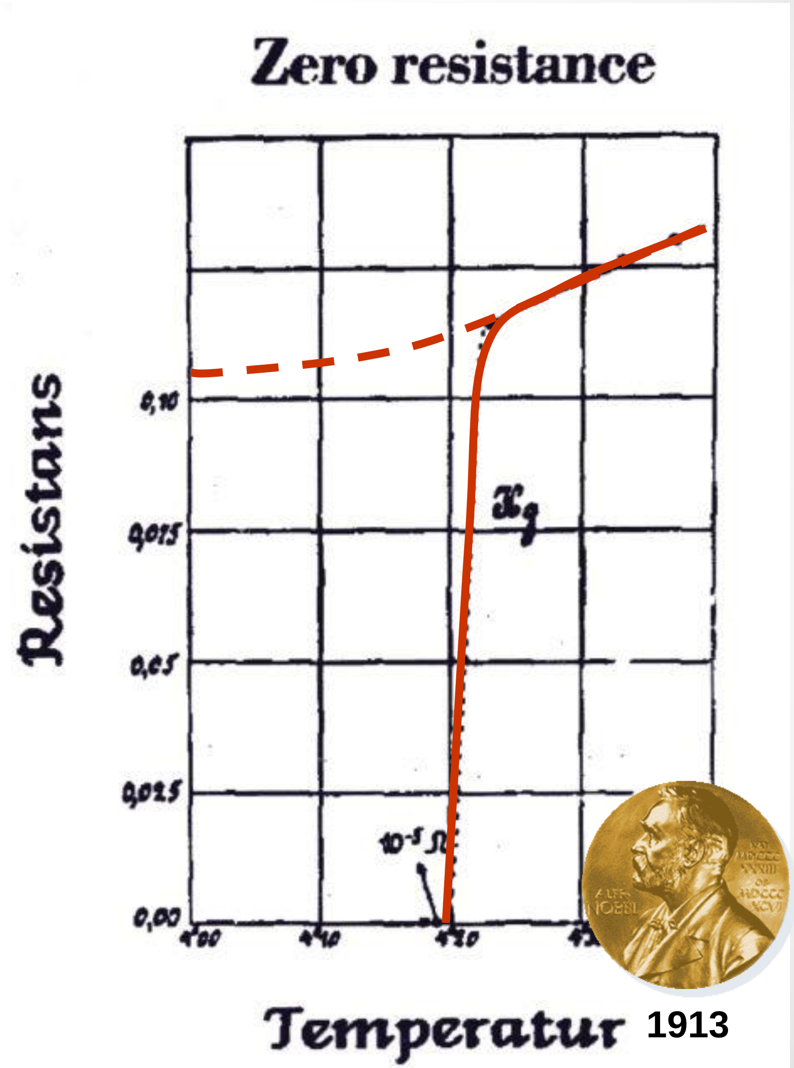
15-26 May 2017 Oslo, Norway

Discovery of Superconductivity



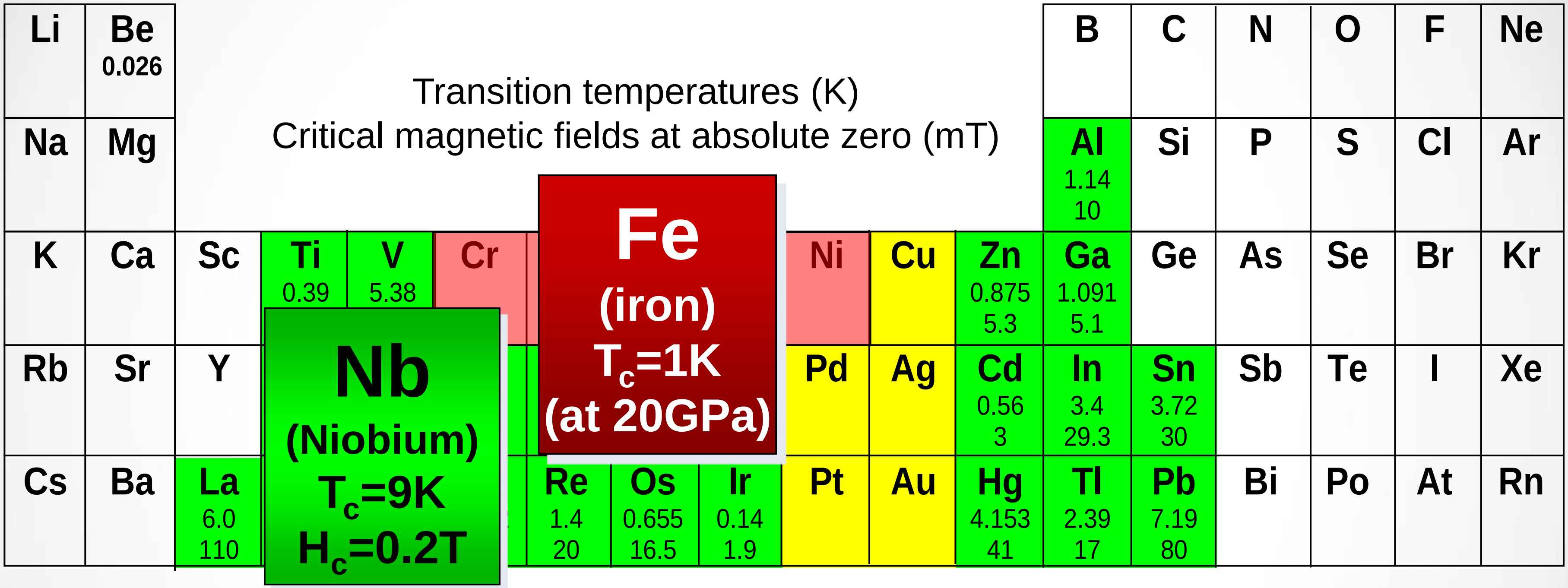


- Discovered by **Kamerlingh Onnes** in 1911 during first low temperature measurements to liquefy helium
- Whilst measuring the resistivity of “pure” Hg he noticed that the electrical resistance dropped to zero at 4.2K
- In 1912 he found that the resistive state is restored in a magnetic field or at high transport currents



The superconducting elements

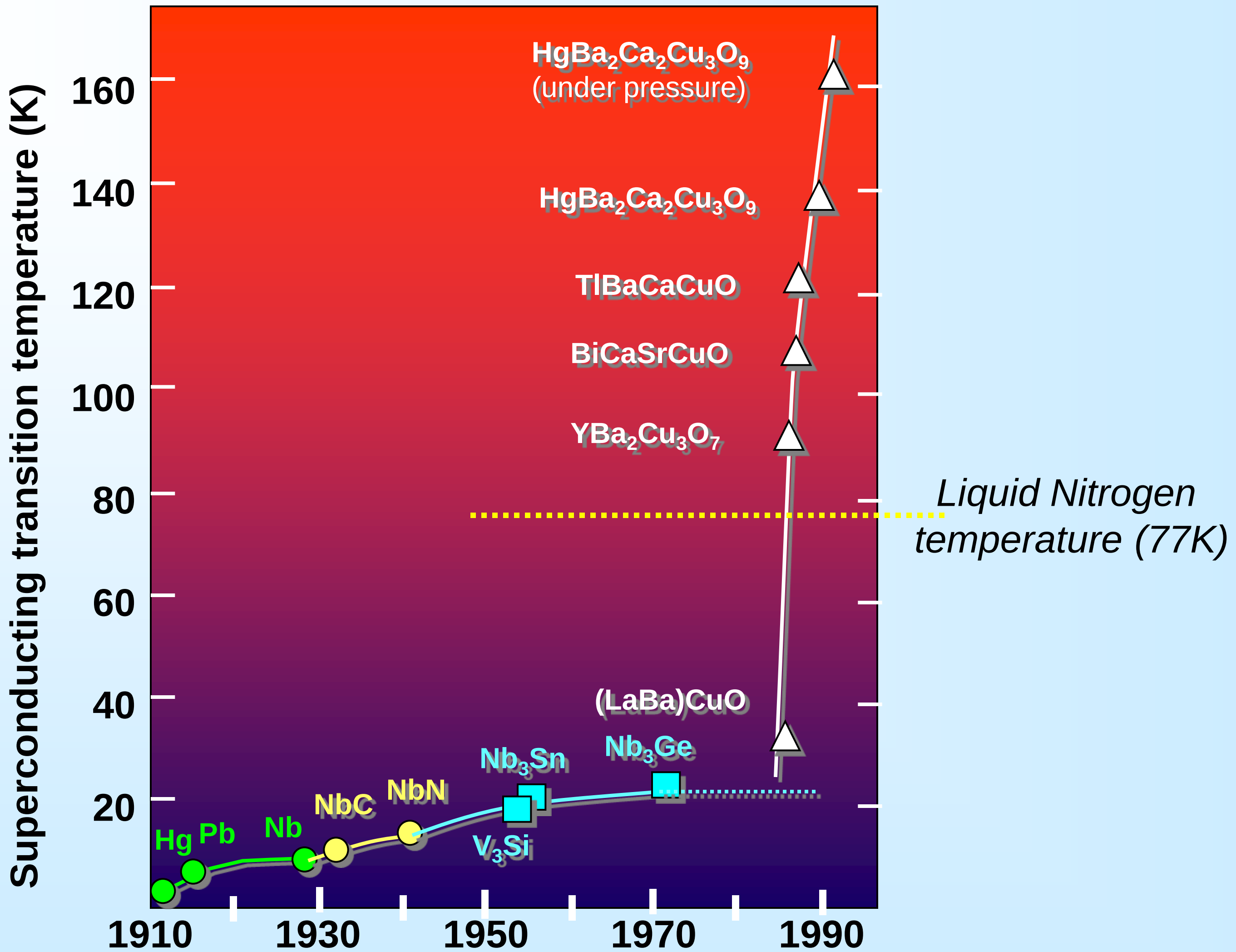
Transition temperatures (K)
Critical magnetic fields at absolute zero (mT)



- Transition temperatures (K) and critical fields are generally low
- Metals with the highest conductivities are not superconductors
- The magnetic 3d elements are not superconducting

...or so we thought until 2001

Superconductivity in alloys and oxides

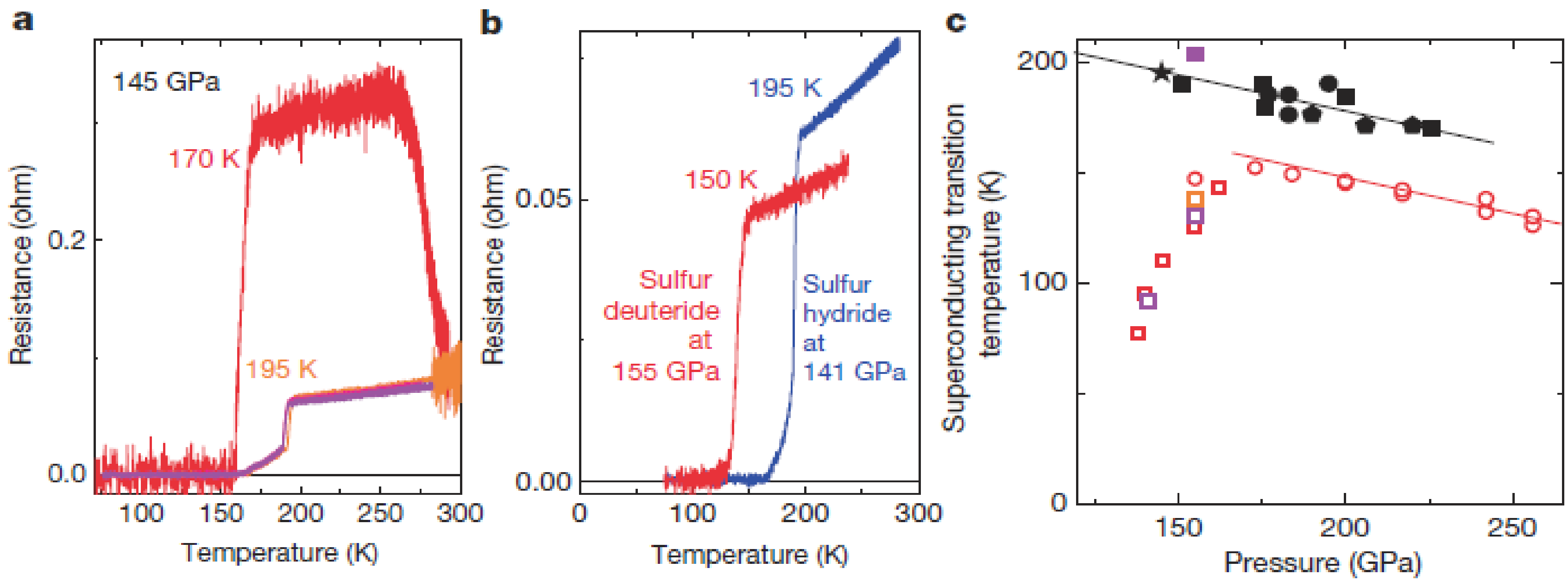


Conventional superconductivity at 203 kelvin at high pressures in the sulfur hydride system

doi:10.1038/nature14964 2015

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

[1]Max-Planck-Institut für Chemie, Hahn-Meitner-Weg 1, 55128 Mainz, Germany. [2]Institut für Anorganische Chemie und Analytische Chemie, Johannes Gutenberg-Universität Mainz, Staudingerweg 9, 55099 Mainz, Germany.

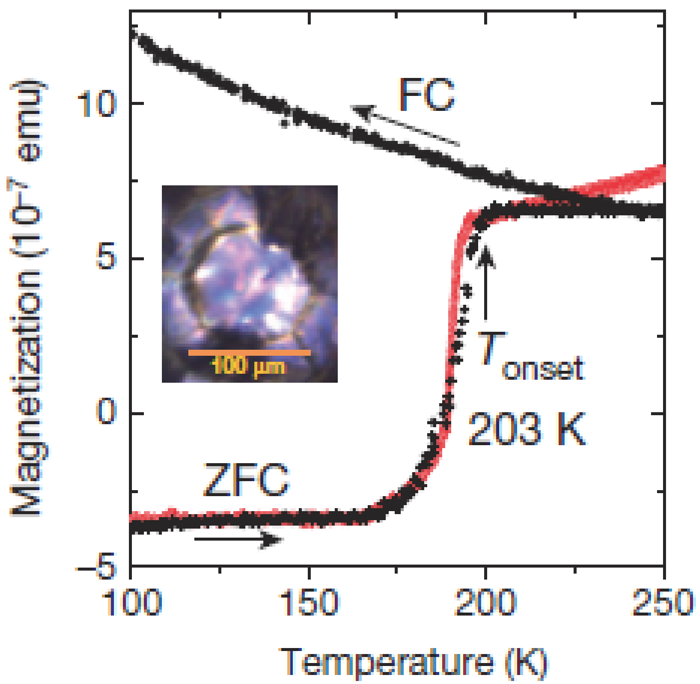


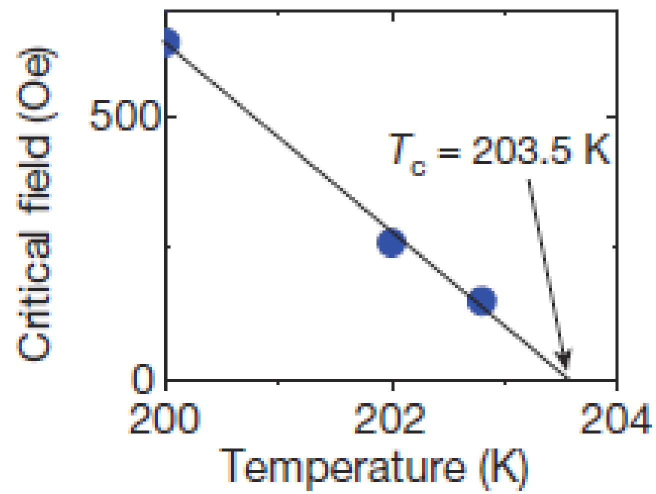
Conventional superconductivity at 203 kelvin at high pressures in the sulfur hydride system

doi:10.1038/nature14964 2015

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

[1]Max-Planck-Institut für Chemie, Hahn-Meitner-Weg 1, 55128 Mainz, Germany. [2]Institut für Anorganische Chemie und Analytische Chemie, Johannes Gutenberg-Universität Mainz, Staudingerweg 9, 55099 Mainz, Germany.





General properties

UiO : University of Oslo
UNIVERSITY OF BIRMINGHAM

- Zero resistance (*Kammerlingh-Onnes, 1911*) at $T < T_c$. The temperature T_c is called the *critical* one.

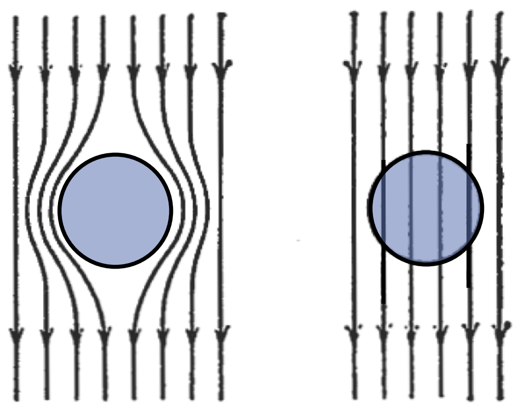
- Superconductivity can be destroyed also by an external magnetic field H_c which is also called the *critical* one (*Kammerlingh-Onnes, 1914*). Empirically,

$$H_c(T) = H_c(0)\left[1-(T/T_c)^2\right] .$$

- If the superconductivity is destroyed by a current the critical current is just the one which produces the field H_c at the surface (the *Silsby rule*).

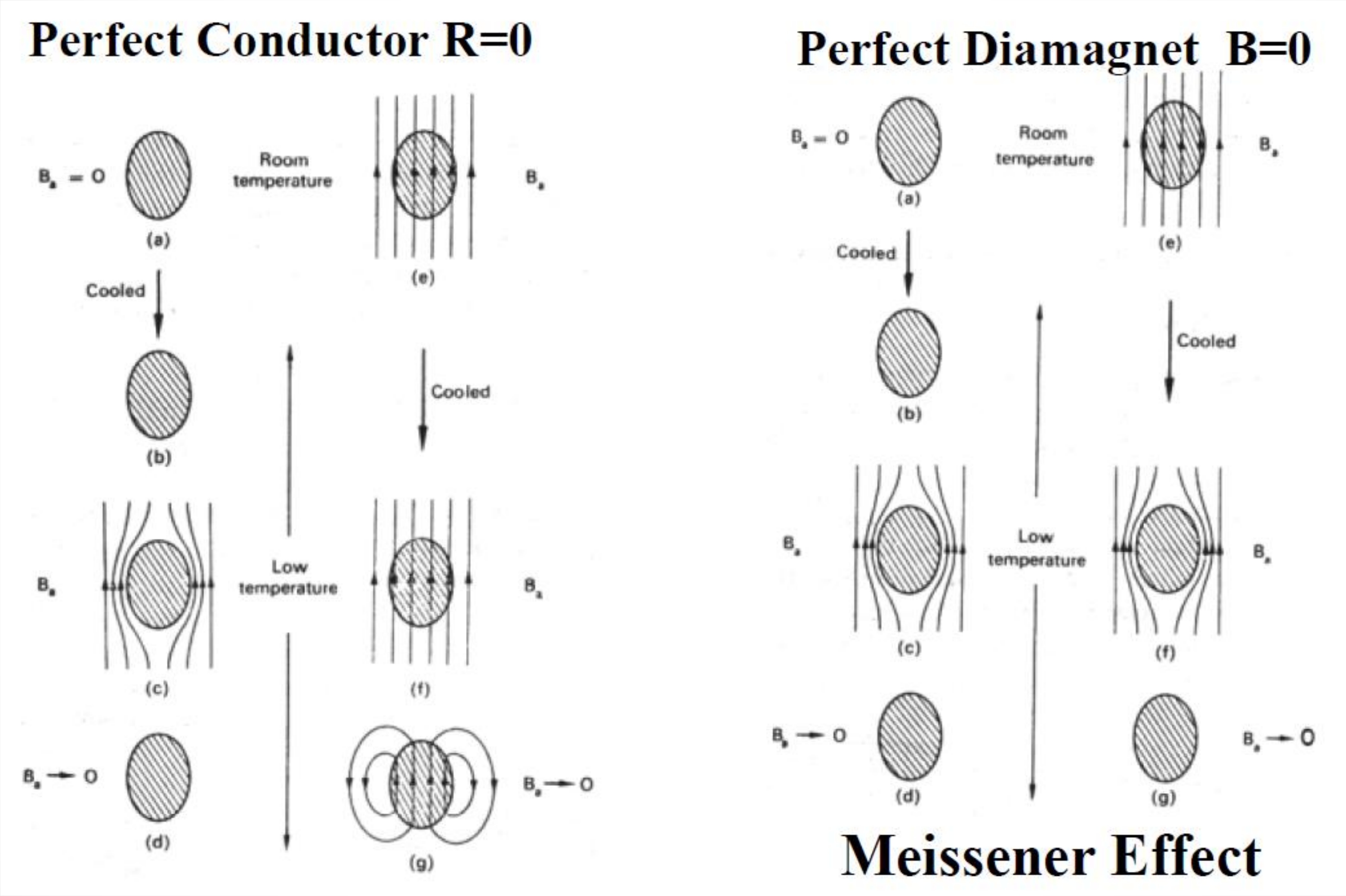
- The *Meissner-Ochsenfeld effect* (1933)

Magnetic field does not penetrate superconductor



Only for long samples!

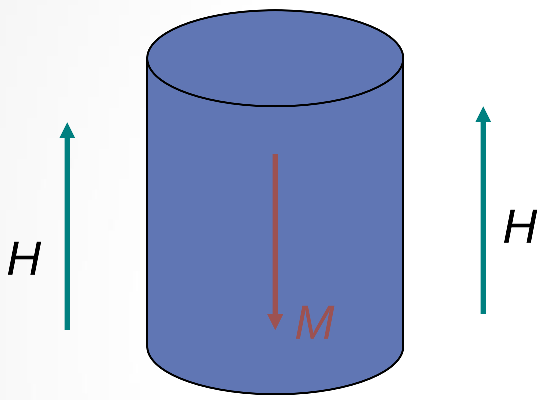
Meissner effect



Ideal conductor!

Ideal diamagnet!

Type I superconductors: Magnetization curve

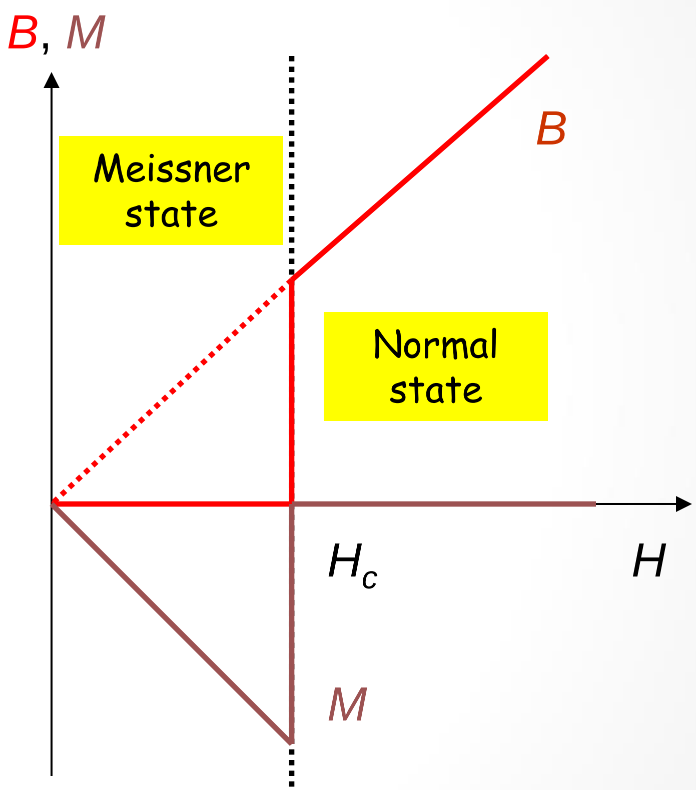


SI: $B/\mu_0 = H + M$

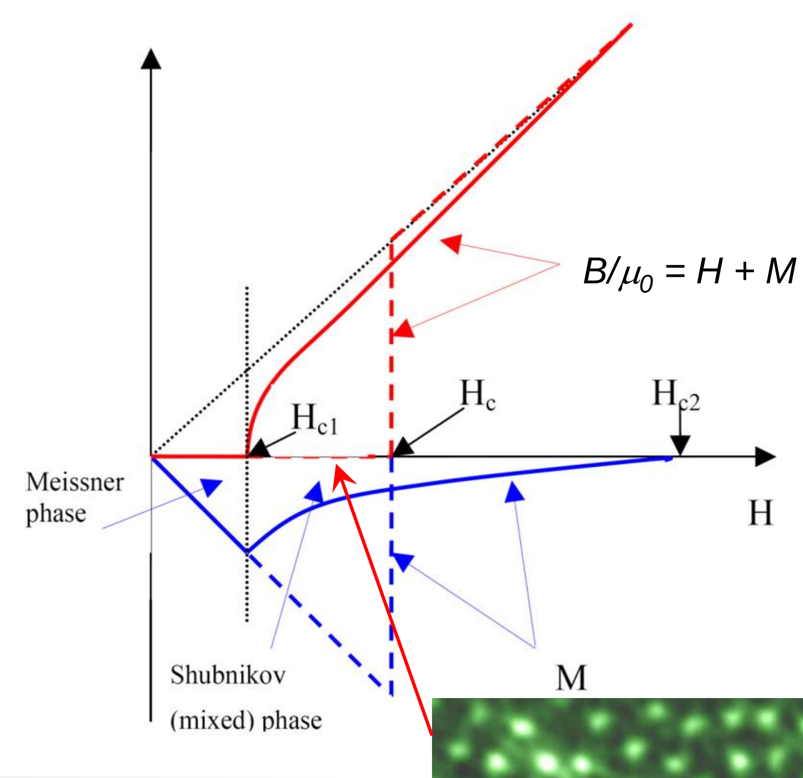
H – magnetic field strength

M – magnetization

B – magnetic induction



Type II superconductors



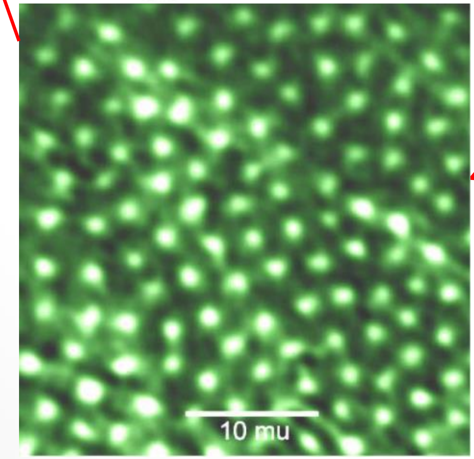
Dashed lines – type I superconductor

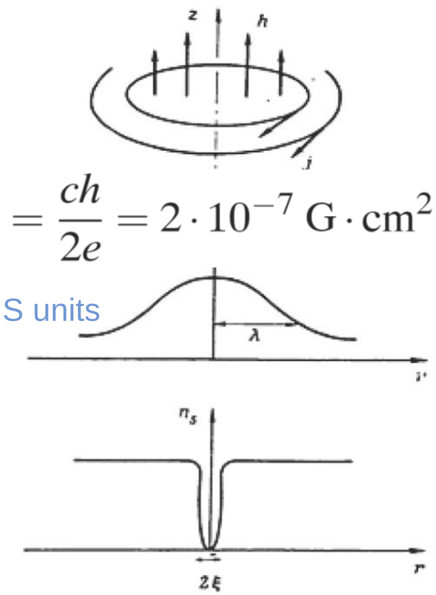
Solid lines – type II superconductor

In type II superconductors the Meissner effect in incomplete in the region

$H_{c1} < H < H_{c2}$

$\Phi_0 = h/(2e) \approx 2.067833758(46)\times10^{-15}$ Wb



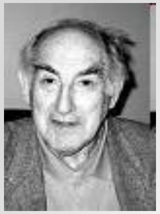


$$\Phi_0 = \frac{ch}{2e} = 2\cdot10^{-7}\ \mathrm{G}\cdot\mathrm{cm}^2.$$

Vortex lattice

A. A. Abrikosov

2003



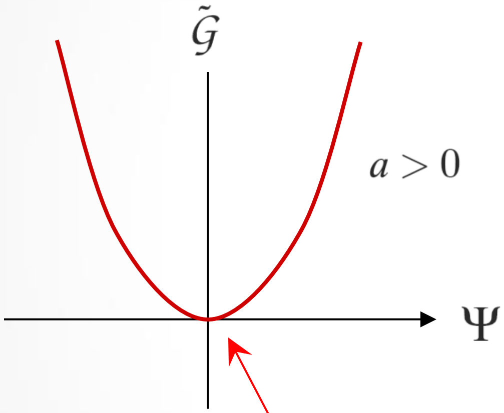
Ginzburg-Landau Theory (1950)

2003

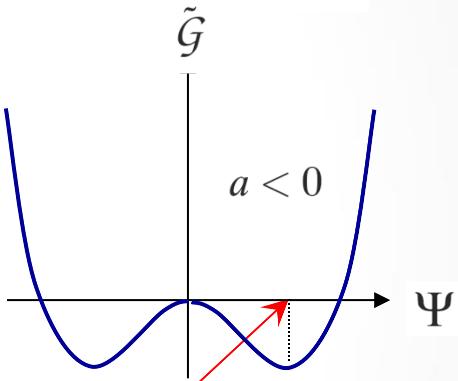
1962

Order parameter

$$|\Psi|^2 \ll 1 \quad \Rightarrow \quad \mathcal{G}_s = \mathcal{G}_n + a|\Psi|^2 + \frac{b}{2}|\Psi|^4 + \cdots .$$



$$\tilde{\mathcal{G}} \equiv \mathcal{G}_s - \mathcal{G}_n$$

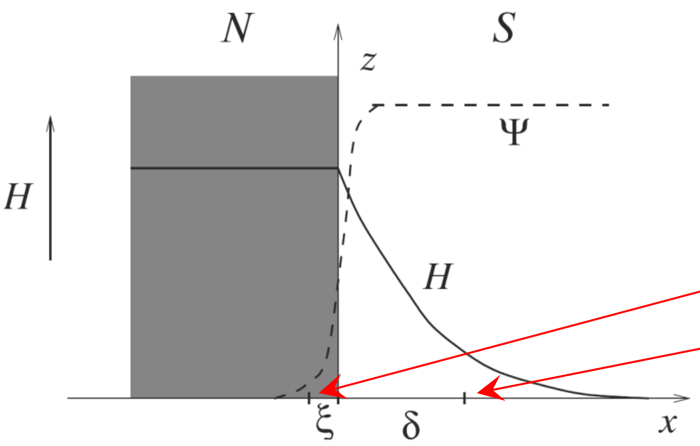


a should change the sign at the transition point

Introduce $\tau = \frac{T - T_c}{T_c}$. Near T_c, $|\tau| \ll 1$: $a = \alpha\tau$, $\alpha > 0$.

$$\begin{array}{ll} \Psi = 0 & \text{at} \quad T > T_c, \\ |\Psi|^2 = -(\alpha/b)\tau = |\Psi_0|^2 & \text{at} \quad T < T_c \end{array} .$$

N-S interface



$$\Psi = \tanh \frac{x}{\xi\sqrt{2}}$$

$\xi = \lambda/k$ ➡ *the coherence length.*

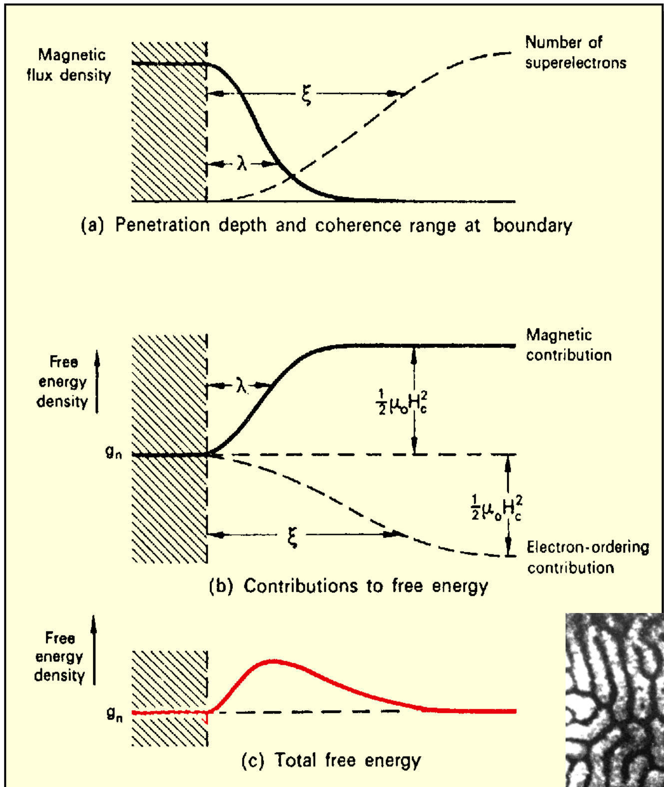
δ is just the London penetration depth near T_c.

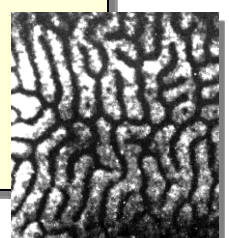
Surface energy:

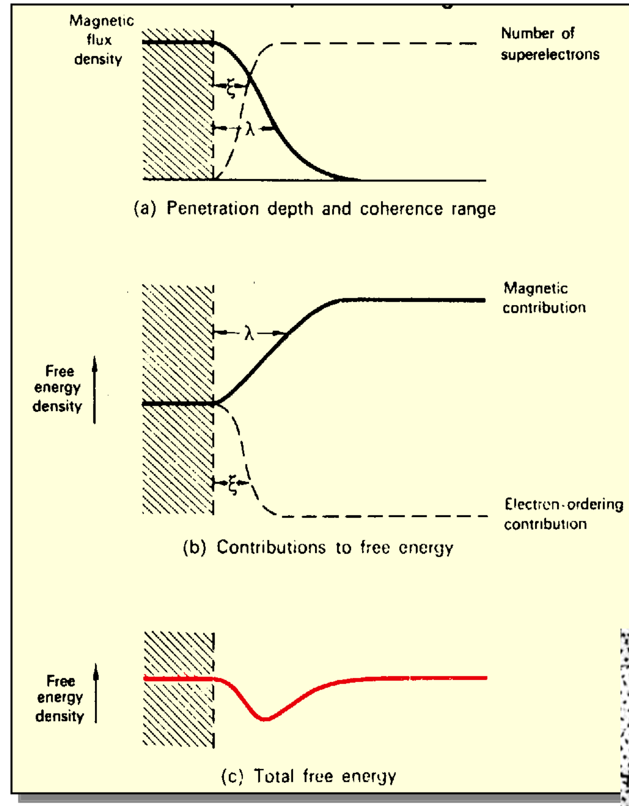
$$\sigma_{ns} = \begin{cases} > 0, & \kappa < 1/\sqrt{2} \\ = 0, & \kappa = 1/\sqrt{2} \\ < 0, & \kappa > 1/\sqrt{2}, \end{cases} \qquad \kappa = \frac{\lambda}{\xi}$$

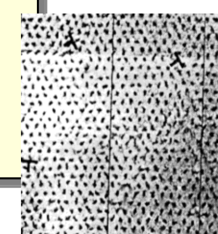
Depending on GL parameter k there is a tendency either to create, or not to create new surfaces

Two types of superconductors









(Abrikosov lattice, 1952)

Surface energy is positive:

Type I superconductivity

Surface energy is negative:

Type II superconductivity

Characteristic parameters of superconductors

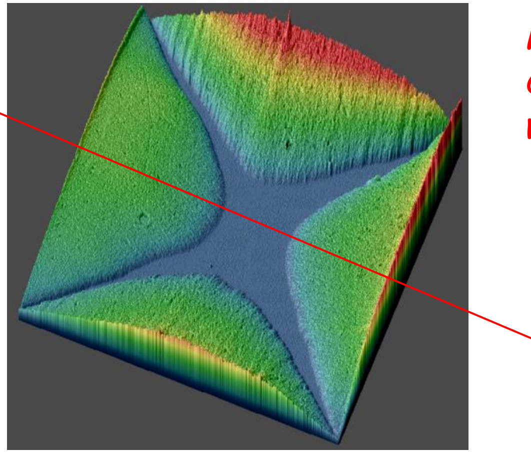
Superconductor	T_c (K)	$\lambda(0)$ (Å)	$\xi(0)$ (Å)	$H_{c2}(T)$
Nb	9.2	450	380	0.2
NbTi	9.5	1600	50	14
NbN	16	2000	50	16
Nb_3Sn	18.4	800	35	24
Nb_3Ge	23	-	35	38
$Ba_{0.6}K_{0.4}BiO_3$	31	2200	35	32
MgB_2	39	850	37	39
UPt_3	0.5	7800	200	2.8
UBe_{13}	0.9	3600	170	8
URu_2Si_2	1.2	-	130	8
$CeIrIn_5$	0.4	5300	250	1.0
$CeCoIn_5$	2.3	-	80	11.9
$TmNi_2B_2C$	11	800	150	10
$LuNi_2B_2C$	16	760	70	7
K_3C_{60}	19.5	~4800	35	~30
Rb_3C_{60}	30	~4200	30	~55
$YBa_2Cu_3O_7$	93	1450	13	150
$HgBa_2Ca_2Cu_3O_{10}$	135	1770	13	190

Critical temperature T_c, the penetration depth λ (0), the Cooper-pair size $\xi(0)$ and the upper critical magnetic field H_{c2} for type-II superconductors (for layered compounds, the in-plane values are given)

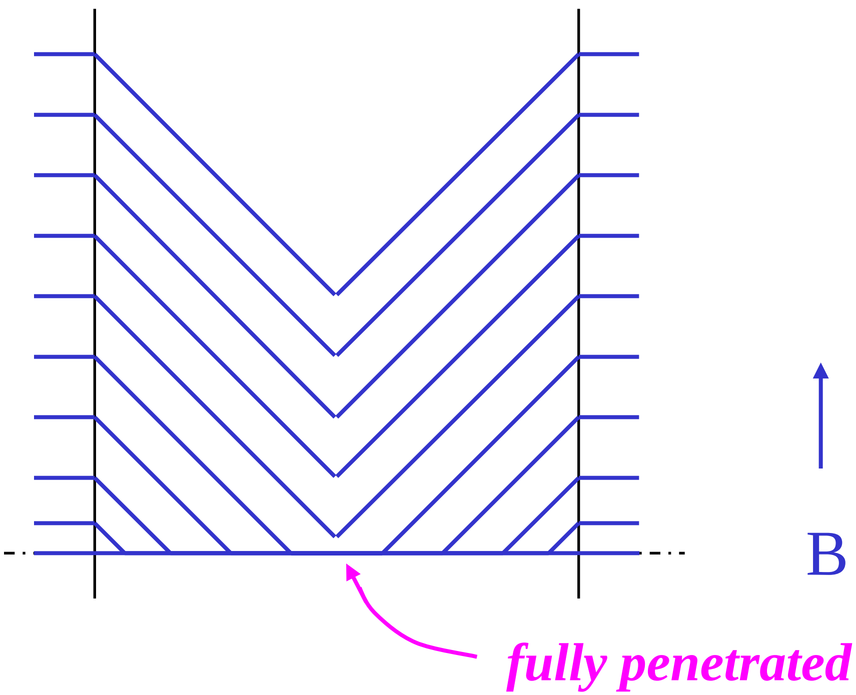
Bean critical state model

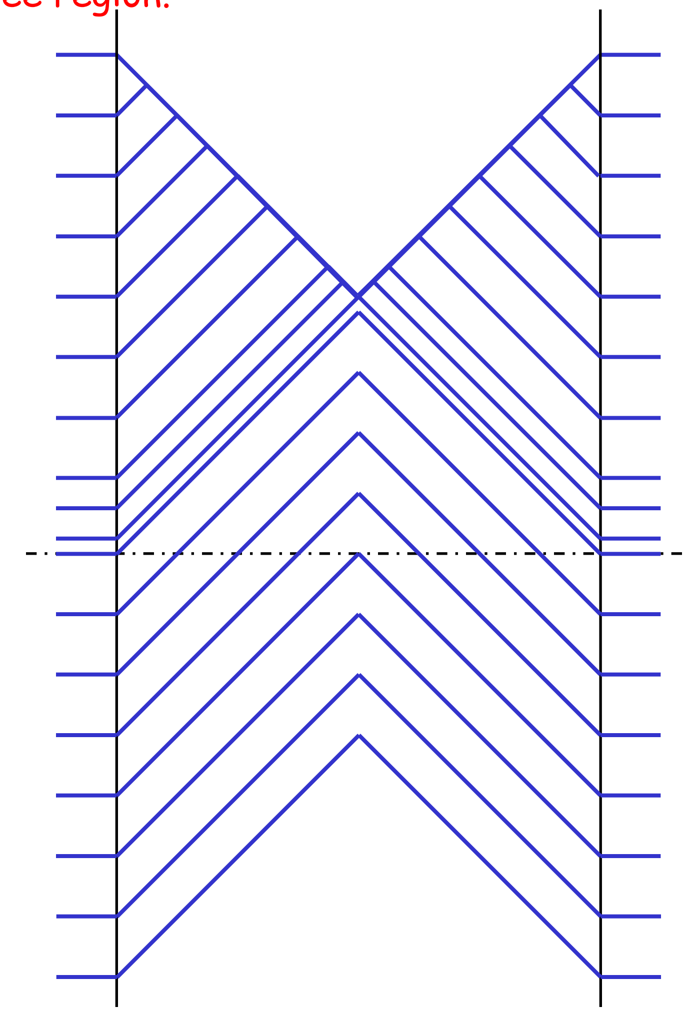
UiO : University of Oslo

UNIVERSITY OF BIRMINGHAM



Magnetic field penetrates to or 'exit' from the sample with constant gradient and current equal to critical current. There is no current in flux-free region.

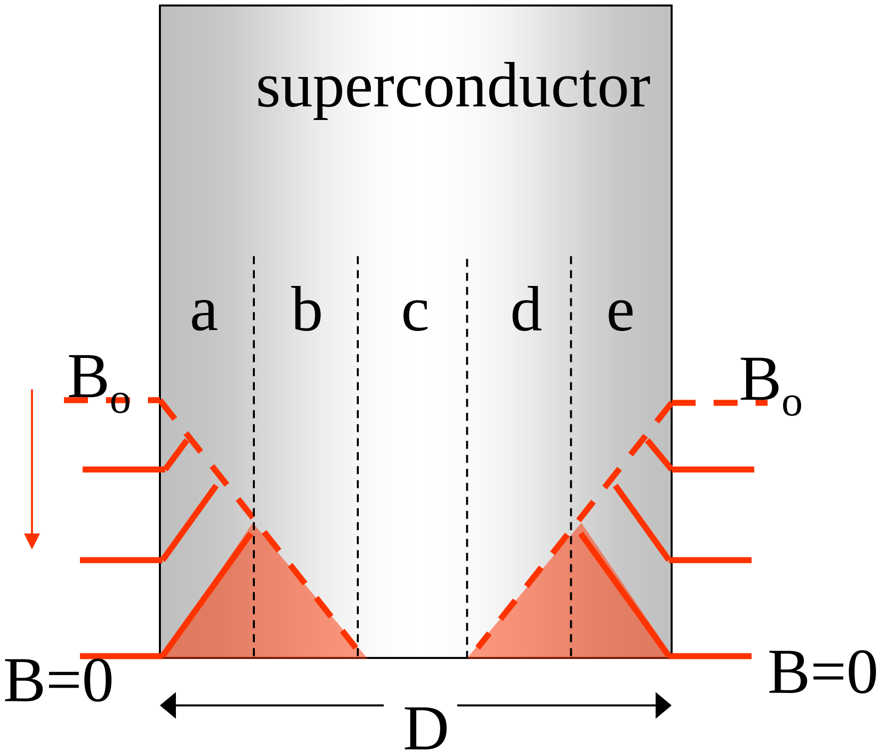


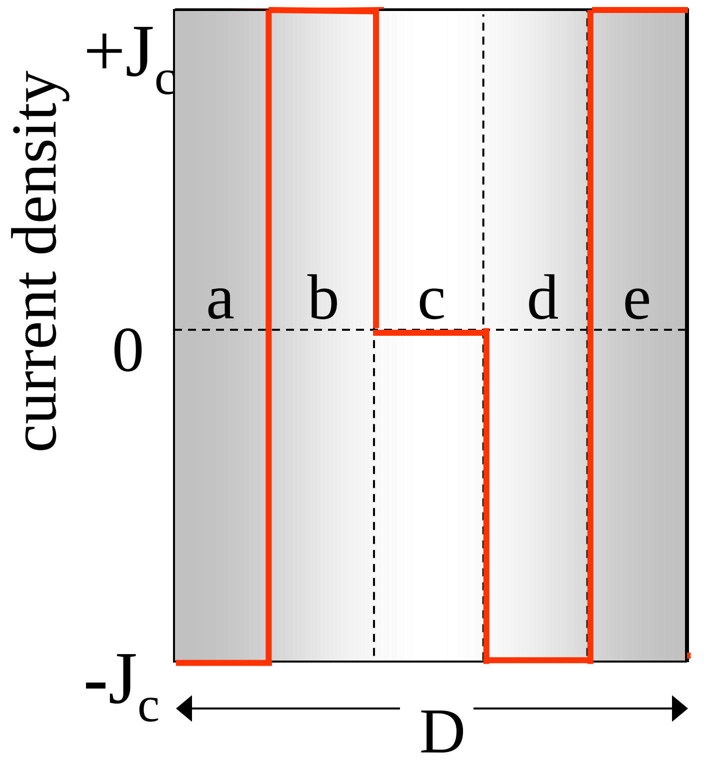


Meissner effect: field decrease

First increasing B to a value B_o then reducing B to zero again

Because the flux density gradient must remain constant, *flux is trapped* inside the superconducting sample, even at B=0





Bean critical state: thin films

UiO : University of Oslo

UNIVERSITY OF BIRMINGHAM

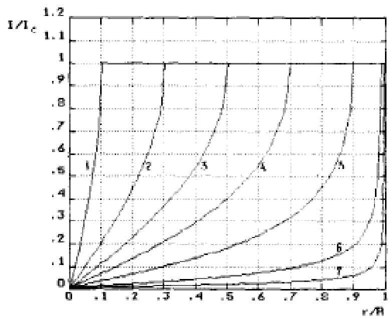
Inductance measurements of HTSC films with high critical currents

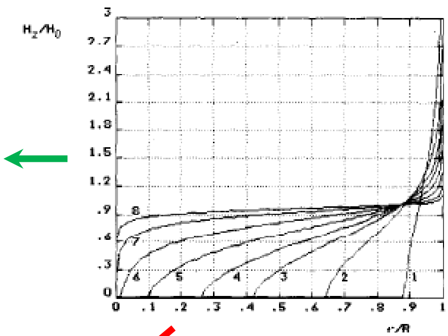
P.N. Mikheenko and Yu.E. Kuzovlev Physica C 204 (1993) 229–236 North-Holland

PHYSICAL REVIEW B VOLUME 50, NUMBER 13 1 OCTOBER 1994-I

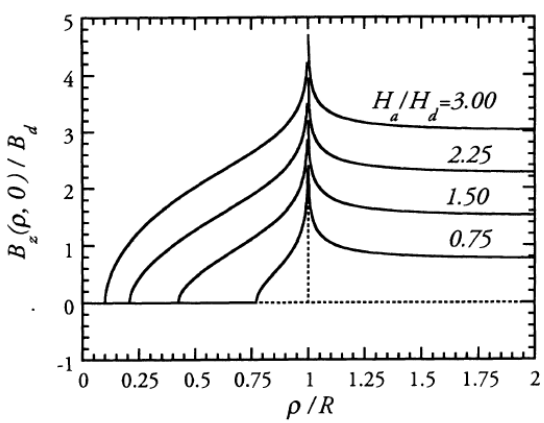
Hysteretic ac losses and susceptibility of thin superconducting disks

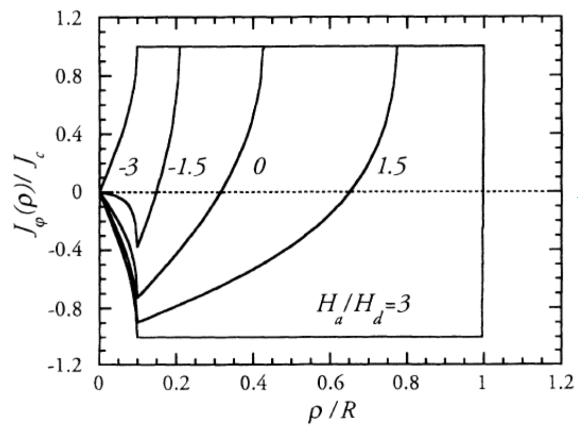
John R. Clem and Alvaro Sanchez

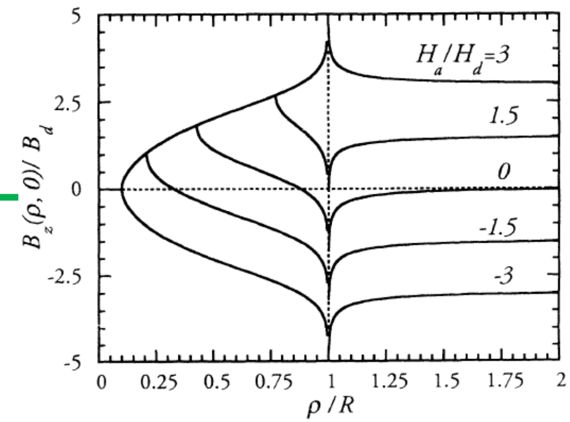




An important theoretical advance recently has been made by Mikheenko and Kuzovlev,[4] who showed how to apply the critical-state theory to thin superconducting disks. This work has been extended (and corrected) by Zhu *et al.*[5] The latter paper contains the basic information that is needed to calculate the hysteretic ac losses in a thin superconducting disk, as well as related properties such as the complex ac susceptibility.

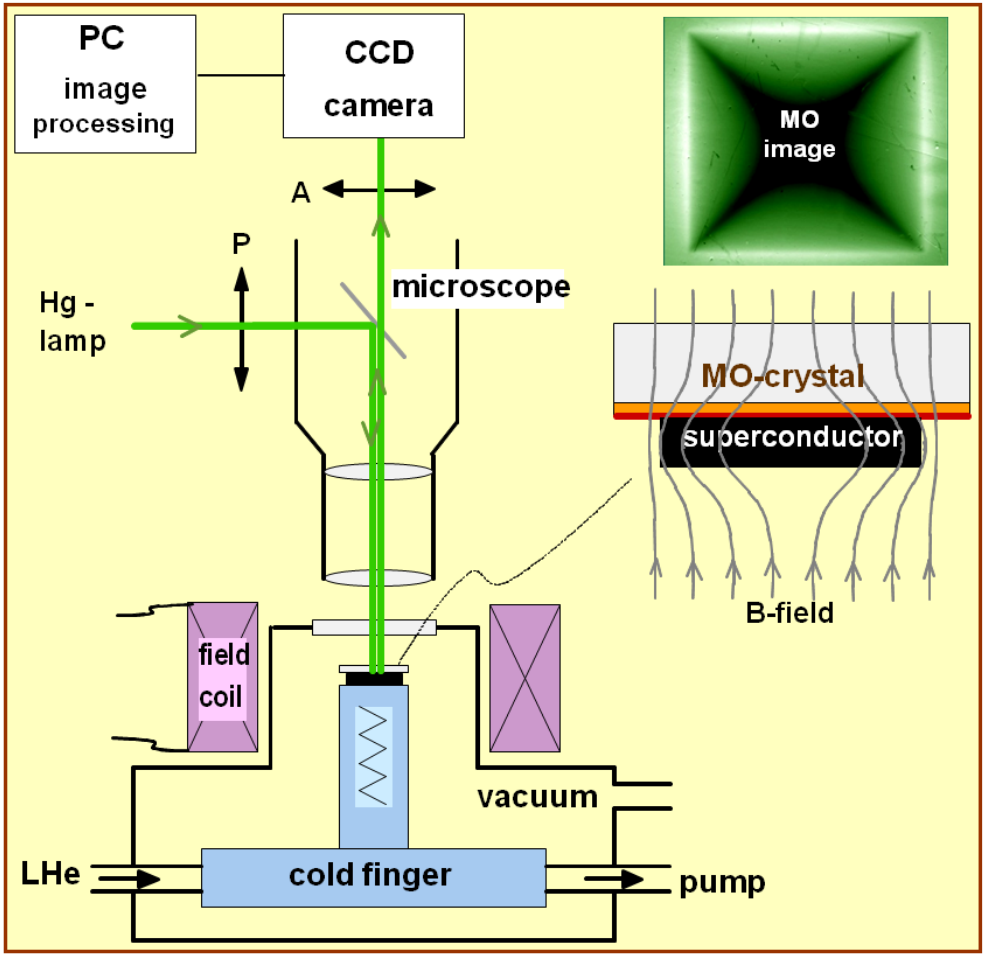


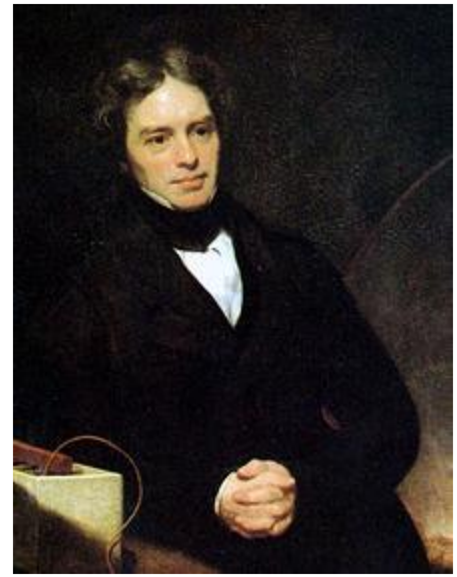




Magnetic field penetrates to or 'exit' from the sample with a varying gradient. Current is equal to critical current in region with magnetic flux. There is current in flux-free region.

Faraday effect and magneto-optical imaging

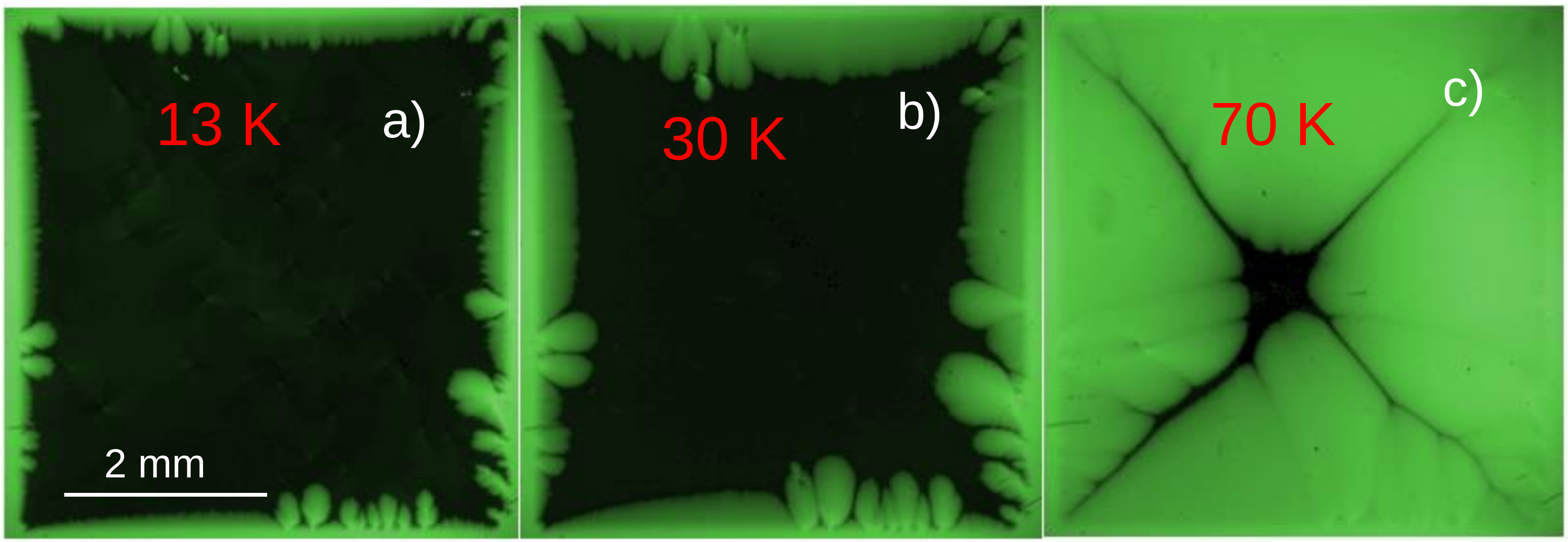




Michael Faraday, 1842, by Thomas Phillips

The Faraday effect is a rotation of the polarization of light in presence of magnetic field. The effect was discovered by Michael Faraday in 1845.

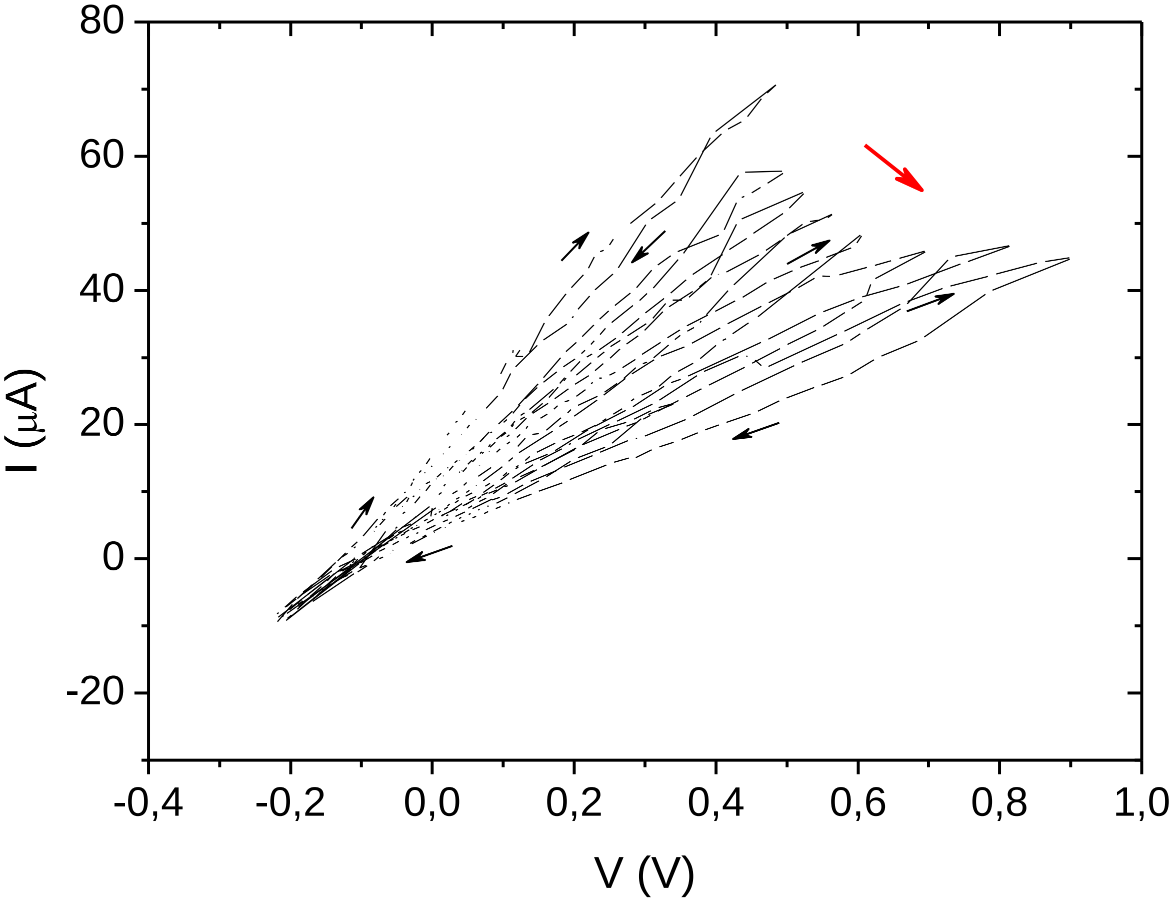
Magneto-optical imaging of $YBa_2Cu_3O_x$ thin films

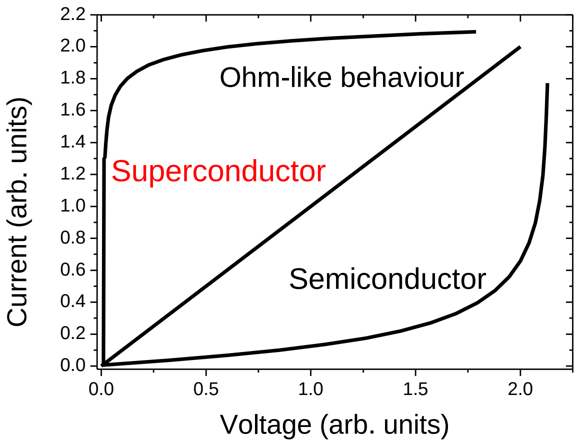


Magneto-optical image of an YBCO film at magnetic field of 85 mT and temperature of 13 K (a), 30 K (b) and 70 K (c).

P. Mikheenko, V-S Dang, Y Y Tse, M M Awang Kechik, P Paturi, H Huhtinen, Y Wang, A Sarkar, J S Abell and A Crisan, Supercond. Sci. Technol. **23**, 125007 (2010).

Transport measurements of muscles tissue

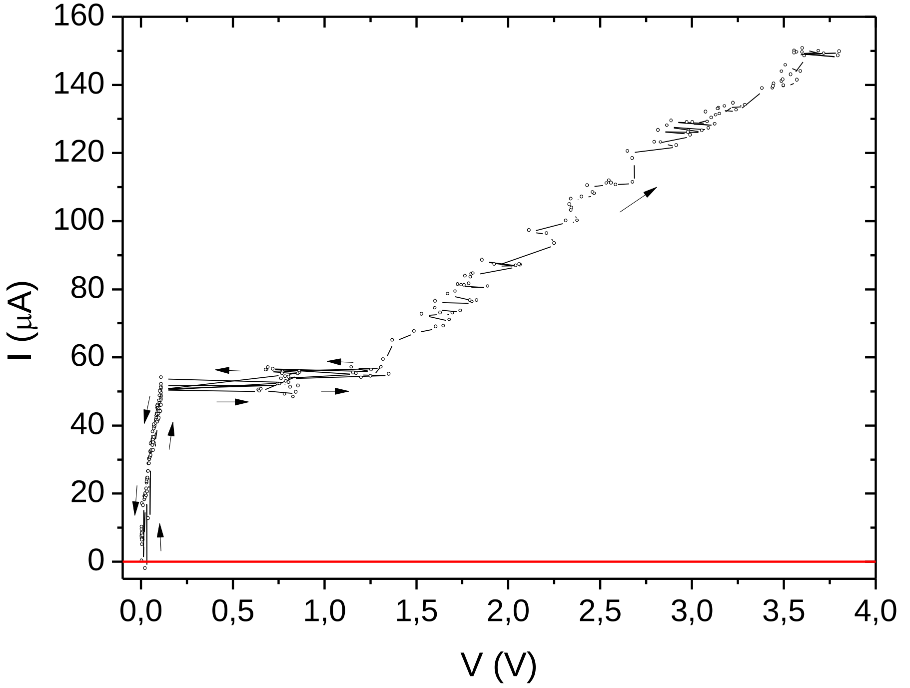




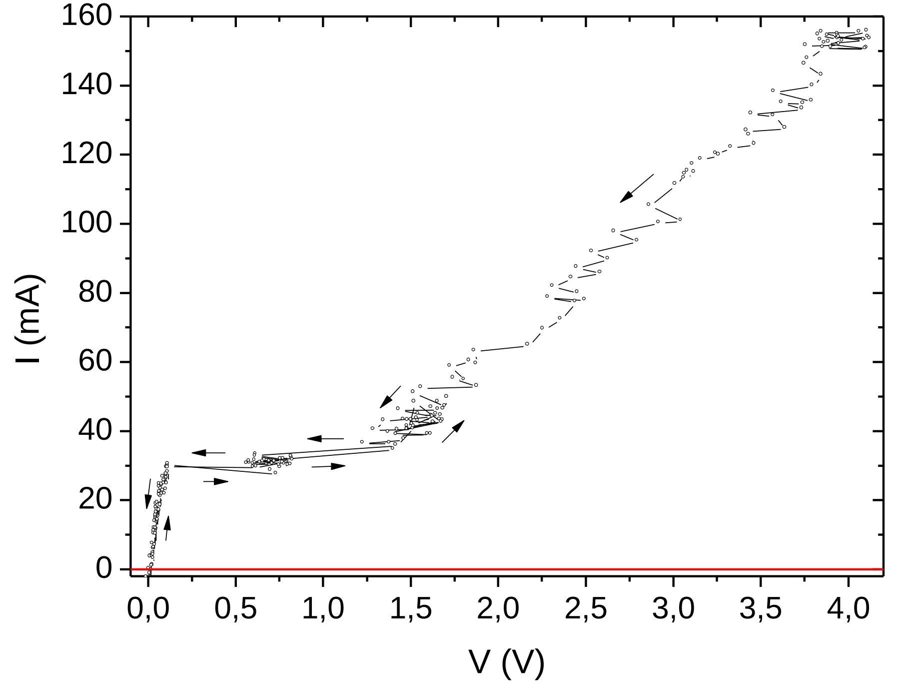
IV curves of the muscles tissue recorded in the process of the drying of the sample. Small black arrows show direction of the record. Large red arrow indicates increase of resistance in the process of measurement.

UiO : University of Oslo
UNIVERSITY OF BIRMINGHAM

Transport measurements of brain tissue



Current-voltage characteristic of the brain tissue measured in the four-probe configuration. Small black arrows show direction of the record.



Current-voltage characteristic of the brain slice shown in three-probe configuration with current leads 2 and 4, and potential leads 2 and 3.

Superconductivity in brain?

Advances in Cryogenic Engineering

VOLUME 17

A Collection of Invited Papers
and Contributed Papers Presented
at National Technical Meetings
During 1970 and 1971

K. D. TIMMERHAUS, *Editor*
Engineering Research Center
University of Colorado
Boulder, Colorado

SPRINGER SCIENCE+
BUSINESS MEDIA, LLC 1972

SPECULATIONS OF SUPERCONDUCTIVITY IN BIOLOGICAL AND ORGANIC SYSTEMS*†

E. H. Halpern and A. A. Wolf

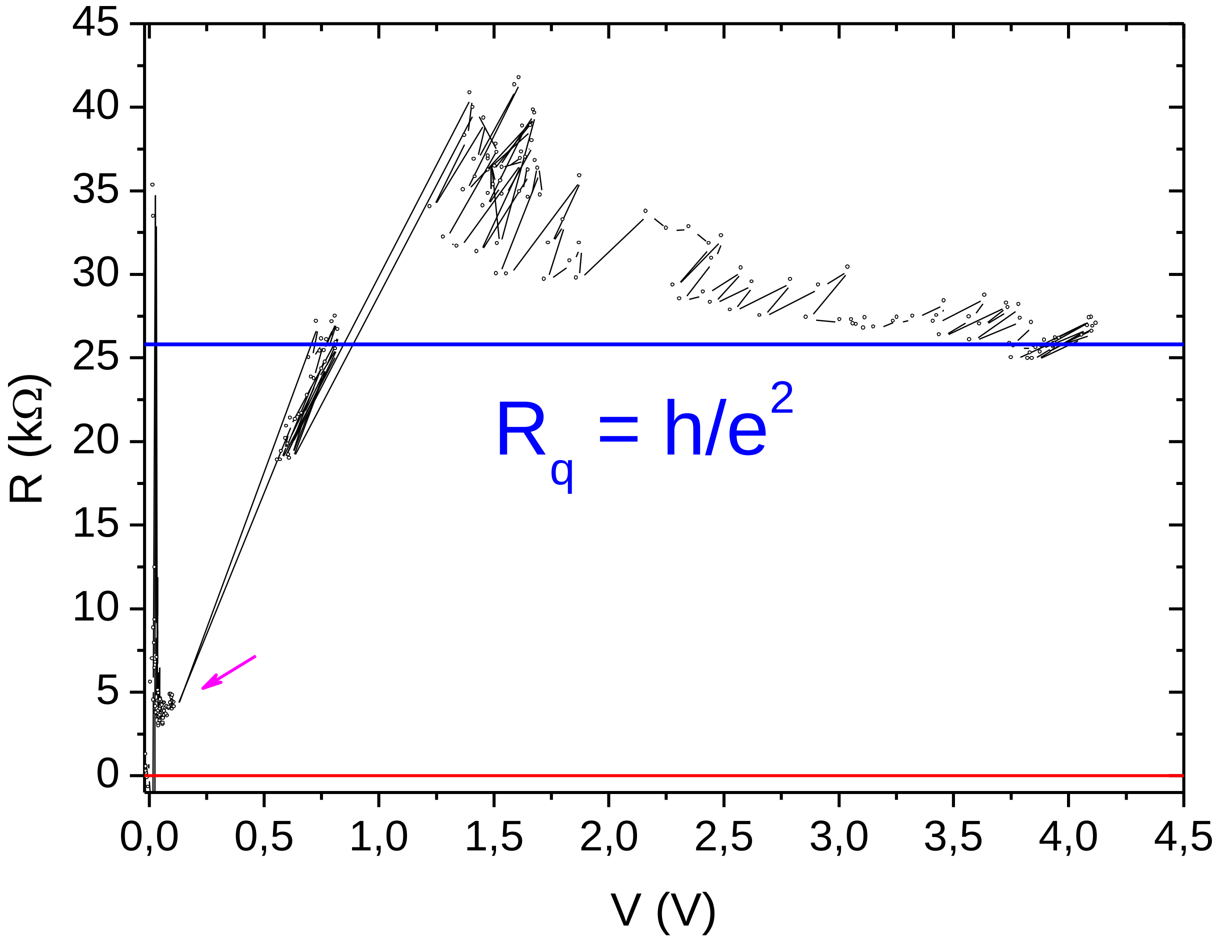
Naval Ship Research and Development Center
Annapolis, Maryland

SPECULATIONS AS TO WHERE SUPERCONDUCTIVITY CAN BE FOUND IN BIOLOGICAL SYSTEMS

It may be reasonable to expect superconductivity in regions of highest organization in biological systems. This would be found in the central nervous system and brain, where information is stored and processed, and where complex functions such as long-term memory and consciousness are centered. Consciousness is controlled by an energy flow through the brain, which is, in turn, controlled by blood flow bringing oxygen to the brain. This flow creates order in the molecular structure of various centers of the brain. John [12] described the mechanism of memory in terms of decreasing entropy with time in the higher-order centers of the brain.

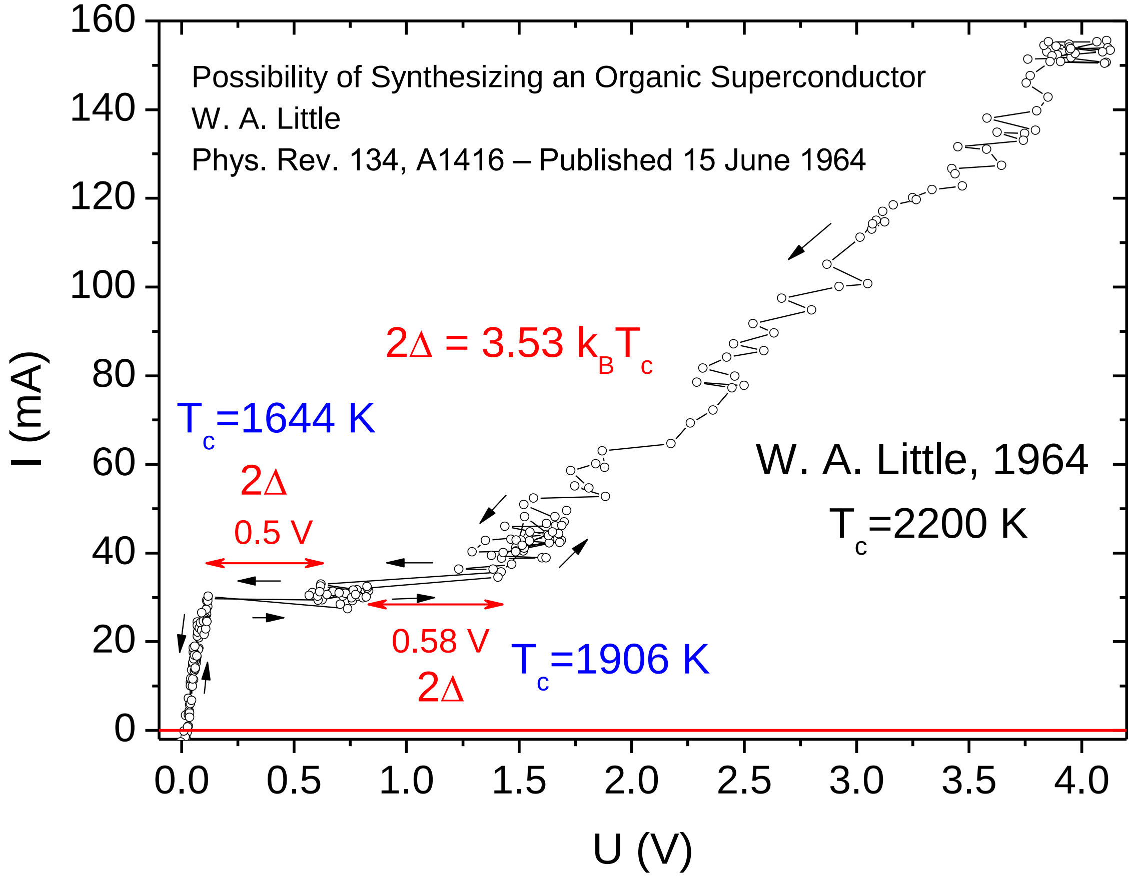
It is certainly conceivable to explain long-term memory (70 to 100 years lifetime of a person) in terms of persistent currents. That persistent currents exist seems to have been established by the response of living systems to strong magnetic fields. No theories of memory today seek to explain this phenomenon in terms of superconductivity. Certainly the work of Ladik *et al.* [5] on DNA as a room-temperature superconductor has bearing on the problem. DNA is critical to information storage and transfer of cell functions and reproduction of molecules.

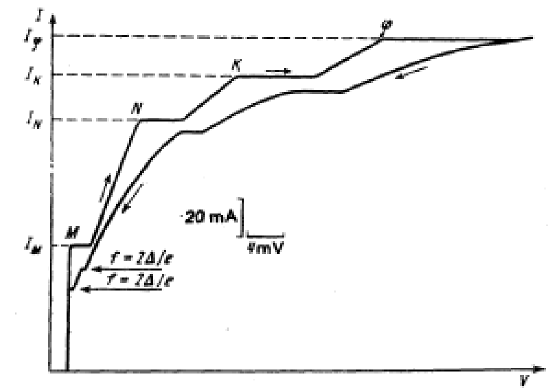
Quantum behaviour in brain



Current-voltage characteristic of the brain slice re-plotted as voltage dependence of the resistance.

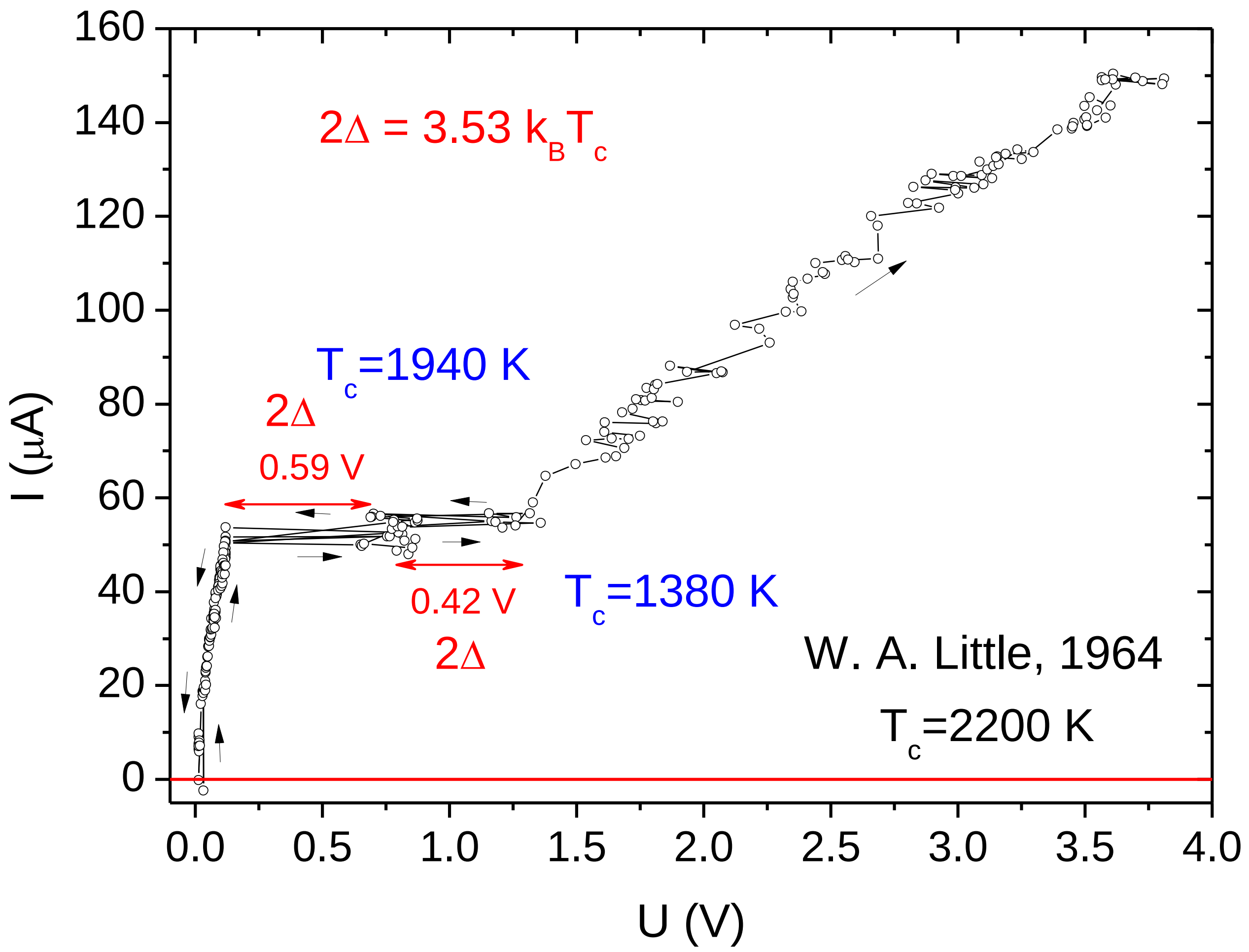
Link between energy gap and critical temperature





Yu.M.Ivanchenko, P.N.Mikheenko, V.F.Khirnyi, Kinetics of the destruction of superconductivity by the current in the thin films. Zhurnal eksperimentalnoi i teoreticheskoi fiziki, v.**80**, N 1, p.161-182 (1981).

Link between energy gap and critical temperature



Conclusions

- Superconductivity is important phenomenon in condensed matter physics.

- There is impressive progress in the synthesis of new superconducting materials and the search for superconductors with a higher critical temperature.