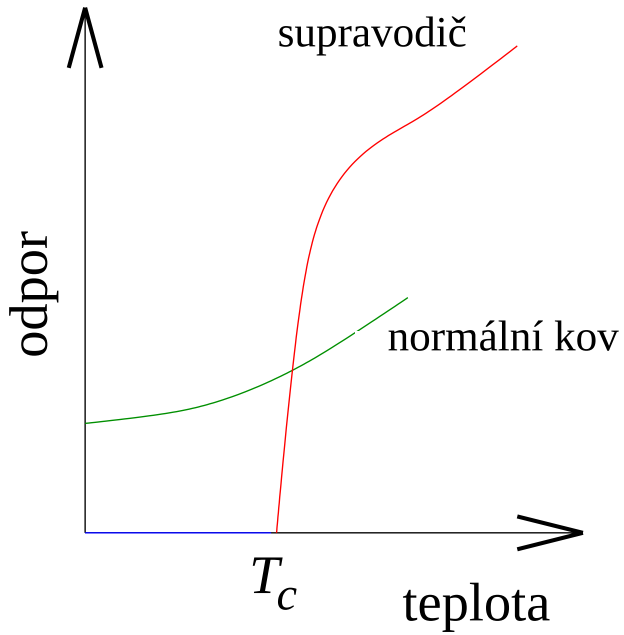
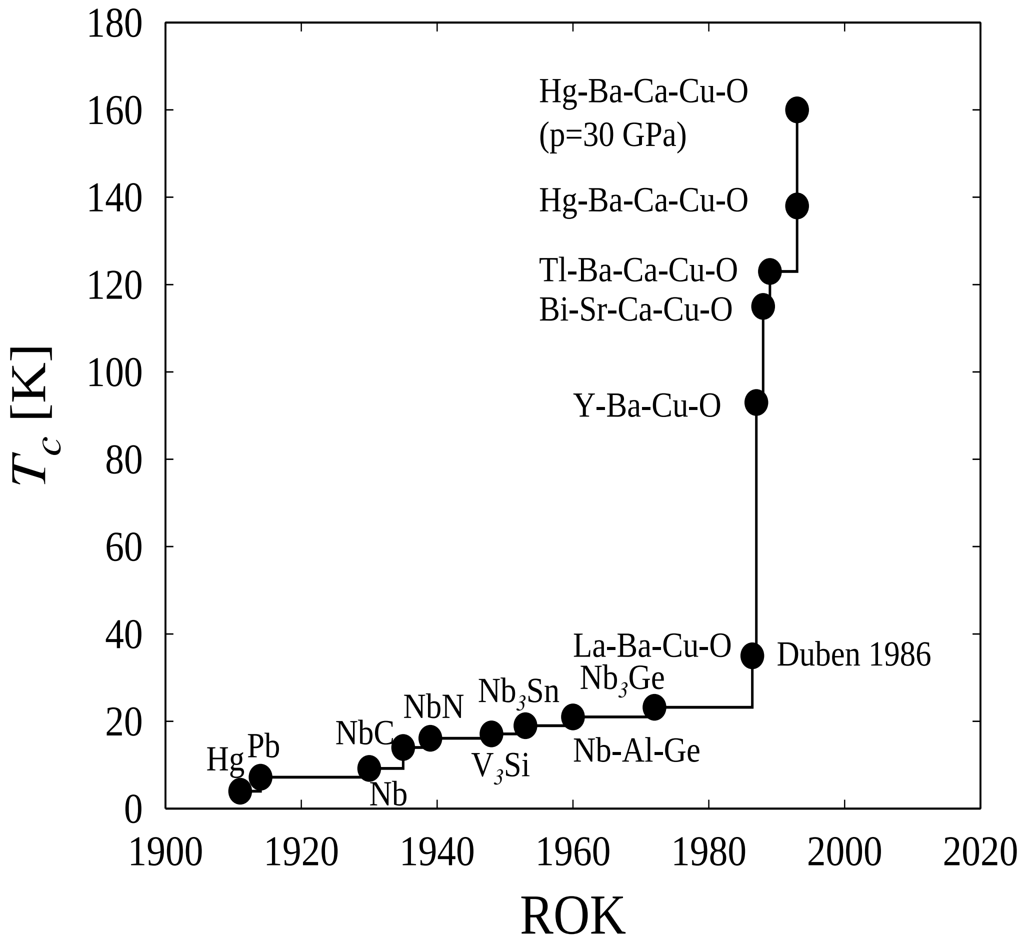
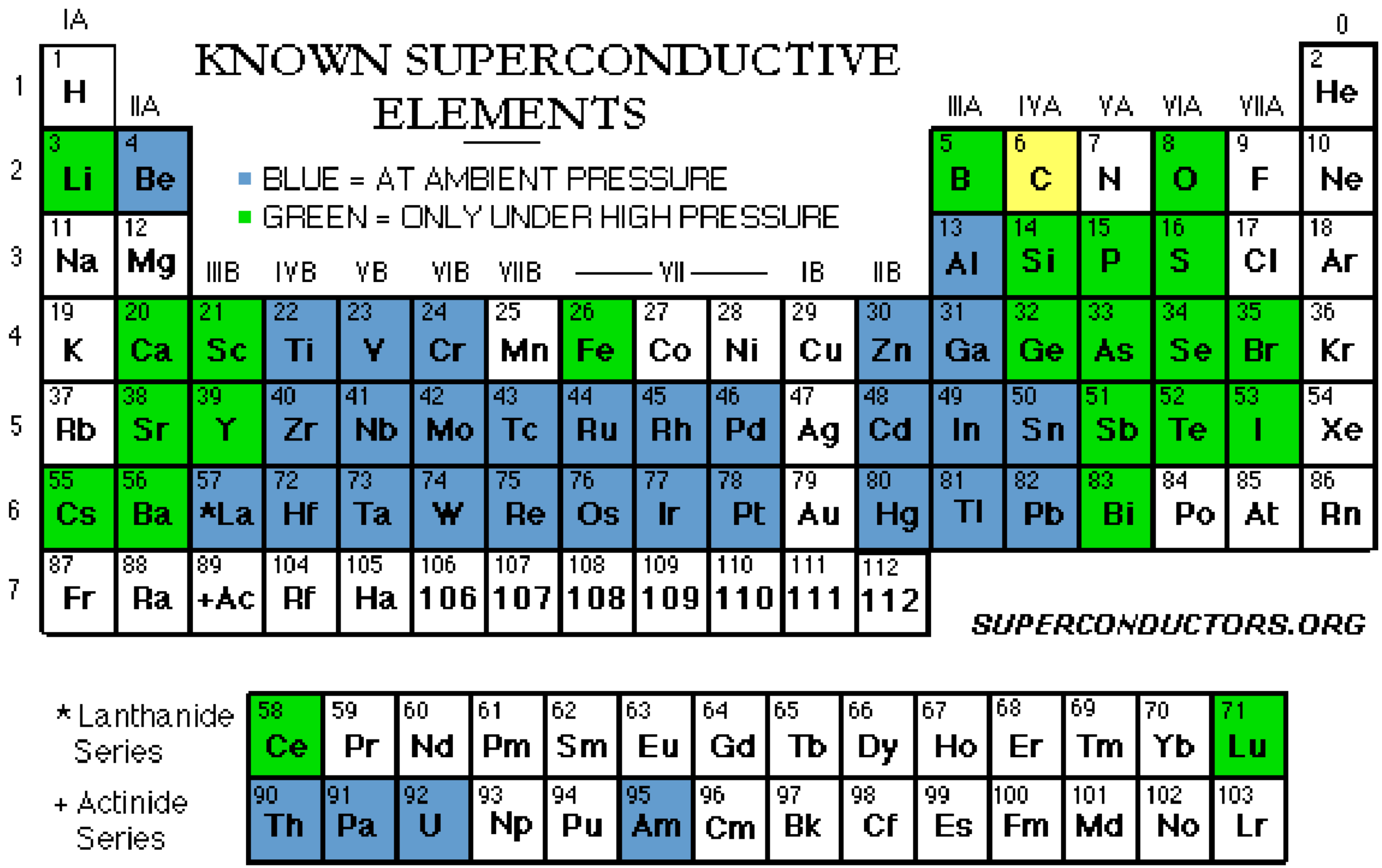
Supravodivost a vysokoteplotní supravodiče

1. Úvod a historie
2. Nekonečná stejnosměrná vodivost a Meissnerův jev
3. Základní prvky teorie supravodivosti
4. Magnetické vlastnosti supravodičů, supravodivé víry
5. Aplikace supravodivosti: Maglev a SQUID
6. Vysokoteplotní supravodiče


supravodič
odpor
normální kov
T_c
teplota


Hg-Ba-Ca-Cu-O
(p=30 GPa)
Hg-Ba-Ca-Cu-O
Tl-Ba-Ca-Cu-O
Bi-Sr-Ca-Cu-O
Y-Ba-Cu-O
La-Ba-Cu-O
Duben 1986
Nb_3Ge
Nb_3Sn
NbN
NbC
Hg
Pb
Nb
V_3Si
Nb-Al-Ge
T_c [K]
ROK
0
20
40
60
80
100
120
140
160
180
1900
1920
1940
1960
1980
2000
2020

Supravodivé prvky



The Nobel Prize in Physics 1913

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

Heike Kamerlingh Onnes

the Netherlands

Leiden University
Leiden, the Netherlands

b. 1853
d. 1926

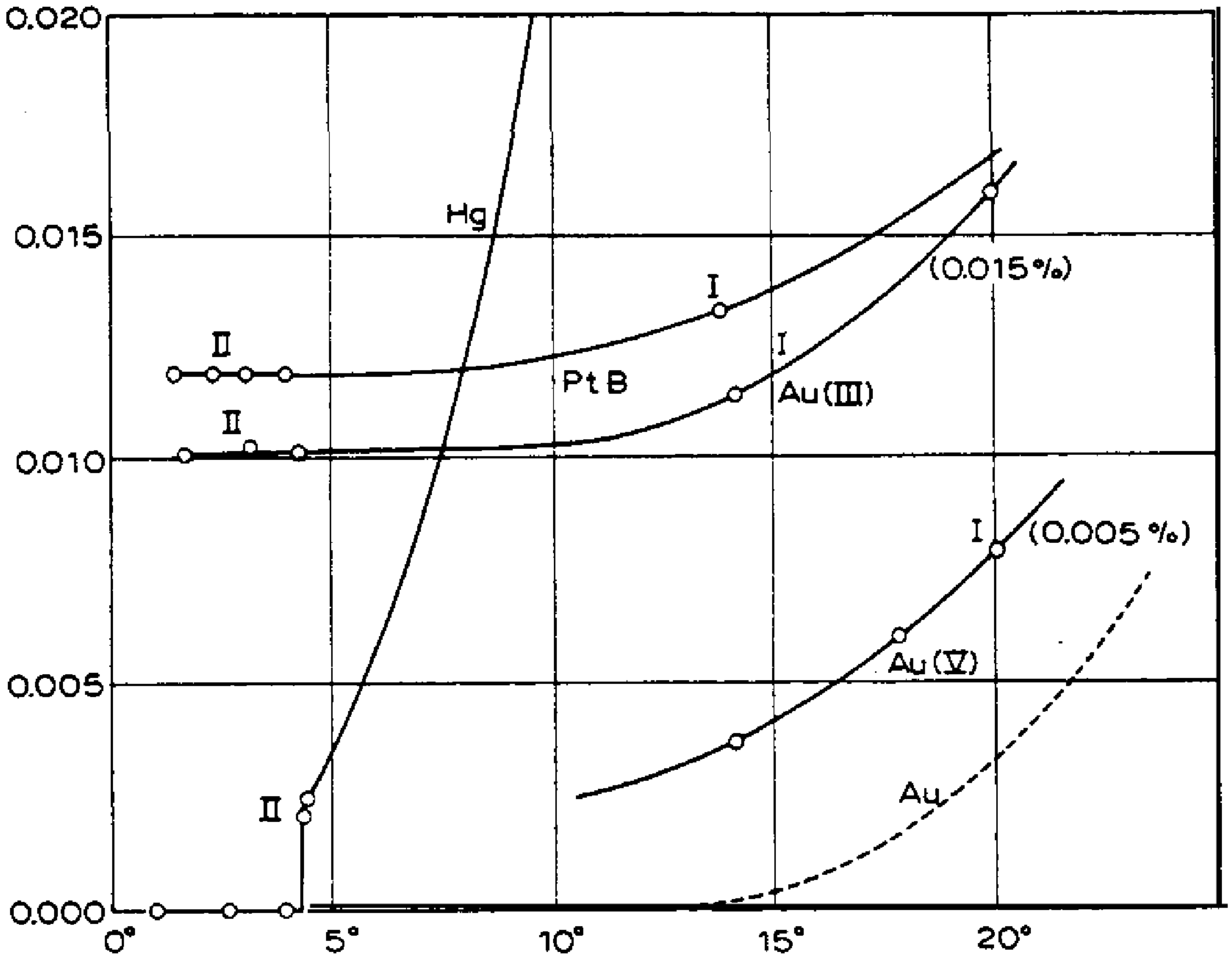
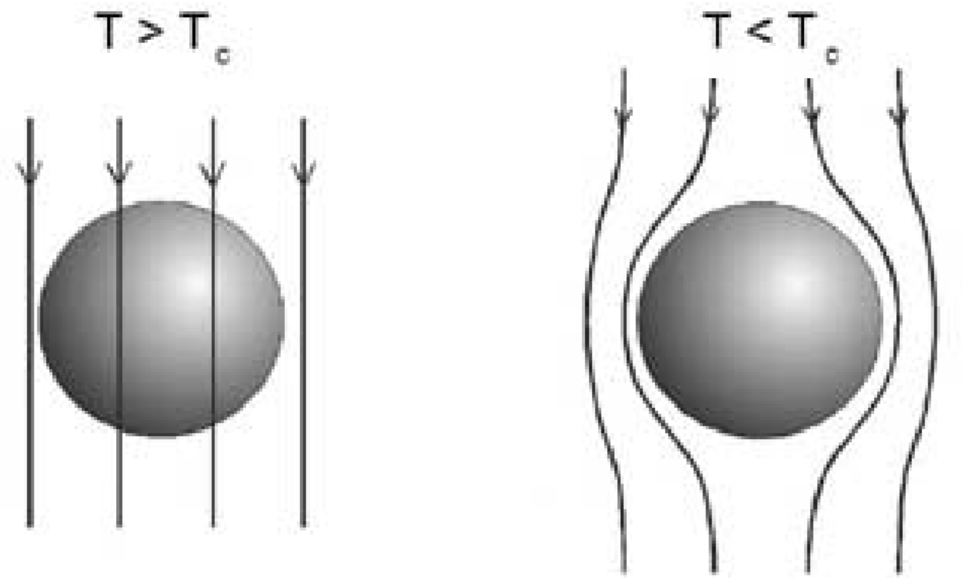
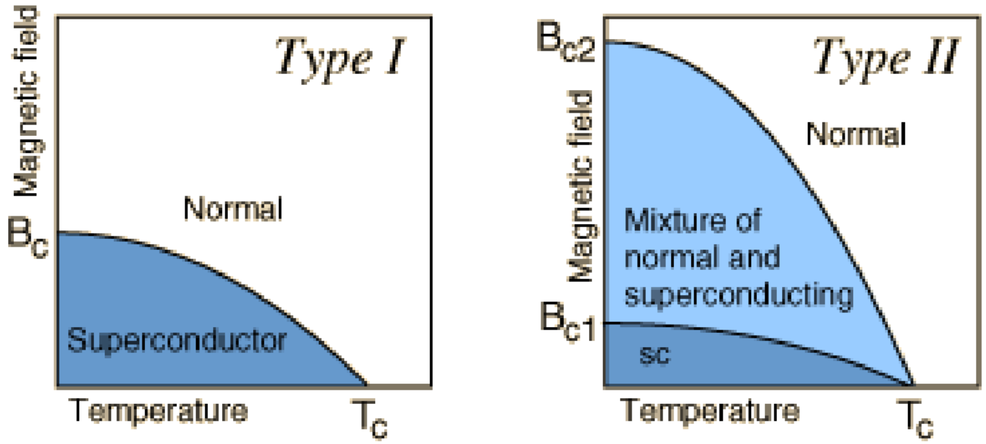

0.020
0.015
0.010
0.005
0.000
0°
5°
10°
15°
20°
Hg
Pt B
Au (III)
(0.015 %)
Au (V)
(0.005 %)
Au
I
II

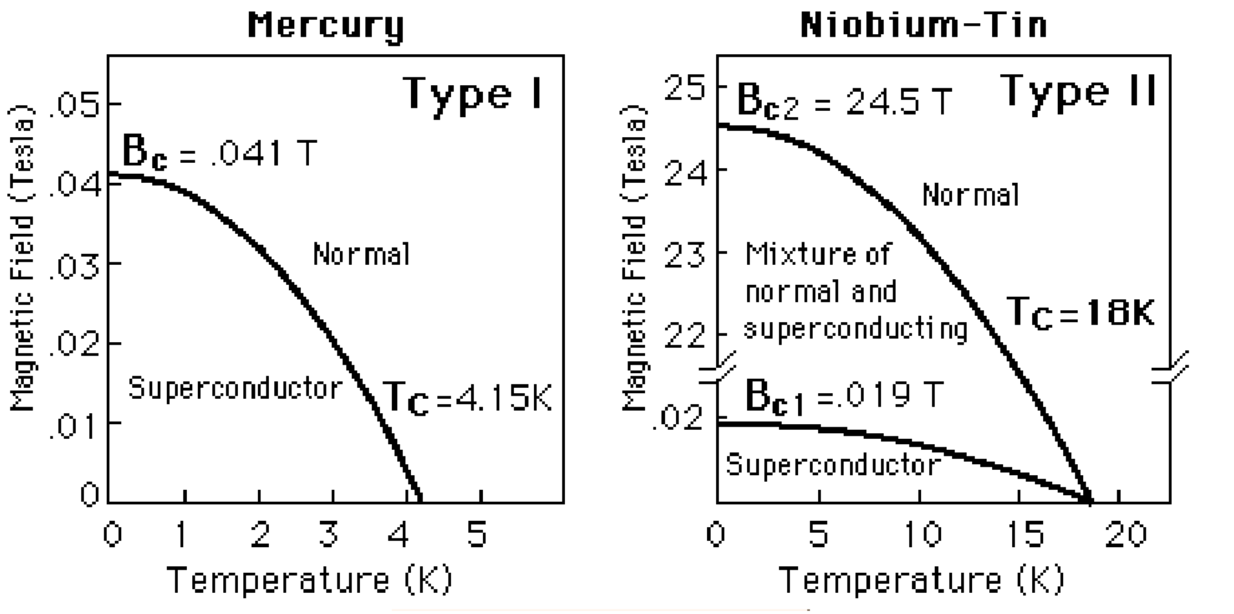
Fig. 14



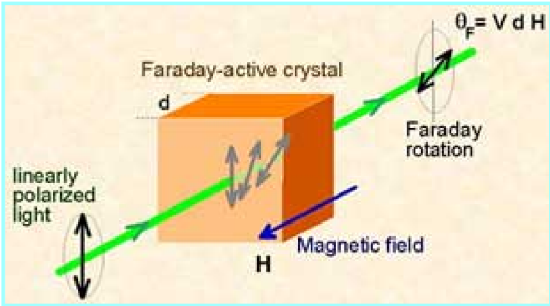
Meissner effect

When a superconductor is cooled down below the critical temperature, $\boldsymbol{T_c}$, its resistance to electrical current is known to disappear. The other fundamental property of superconductors is so-called Meissner effect, i.e., expulsion of magnetic field. An external field is entirely compensated by shielding currents which it induces in the superconductor, and which will flow forever due to absence of resistance.


Type I
Magnetic field
Normal
B_c
Superconductor
Temperature
T_c
Type II
B_c2
Magnetic field
Normal
Mixture of normal and superconducting
B_c1
sc
Temperature
T_c

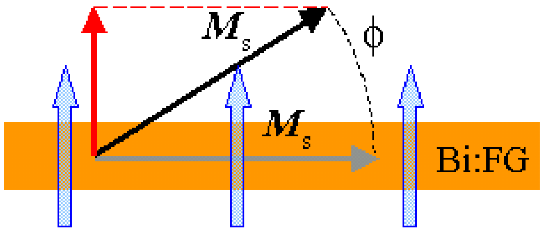

Mercury
Type I
Magnetic Field (Tesla)
.05
.04
.03
.02
.01
0
B_c = .041 T
Normal
Superconductor
T_c =4.15K
0 1 2 3 4 5
Temperature (K)
Niobium-Tin
Type II
Magnetic Field (Tesla)
25
24
23
22
.02
B_c2 = 24.5 T
Normal
Mixture of normal and superconducting
T_c =18K
B_c1 =.019 T
Superconductor
0 5 10 15 20
Temperature (K)

Fundamentals of magneto-optical imaging



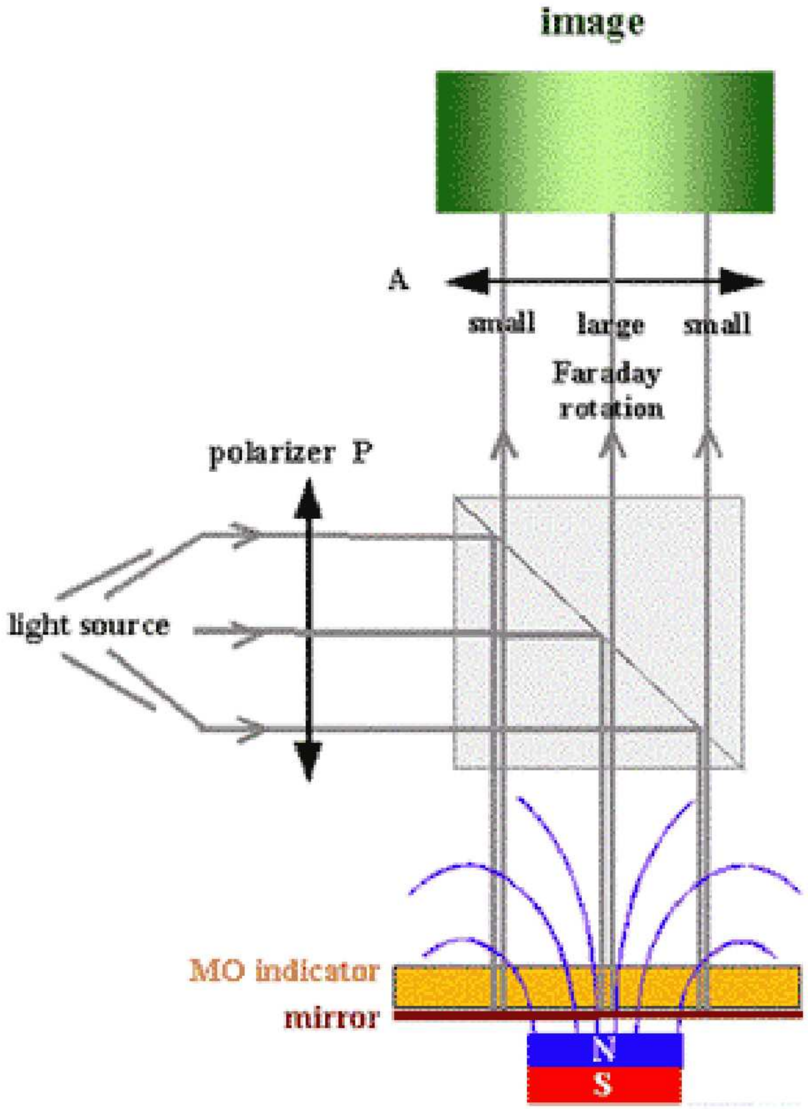
Physical principles

The physical idea behind the magneto-optical imaging is the Faraday effect, i.e., rotation of the light polarization induced by magnetic field. On 13 September, 1845, Michael Faraday wrote in his Diary *"...magnetic force and light were proved to have relation to each other. This fact will most likely prove exceedingly fertile and of great value in the investigation of both conditions of natural force"* .



Magneto-optical films

A number of different materials have been applied as indicators in MO imaging: cerous nitrate-glycerol, various europium compounds (EuS, EuSe) [H. Kirchner, Phys. Lett. 26A, 651 (1968)] and bismuth-substituted iron garnets [A.A. Polyanskii et al. Sov. Tech. Phys. Lett. 15, 872 (1989)]. Today, the most popular indicator is the ferri-magnetic Bi:YIG film with in-plane spontaneous magnetization. Application of a perpendicular magnetic field creates an out-of-plane component of the magnetization responsible for the Faraday rotation. A single-crystal film with typical thickness of a few microns can be grown by liquid-phase epitaxy on a gadolinium-gallium-garnet (GGG) substrate.



Magneto-optical setup

The MO indicator is placed in the light beam path between a polarizer and an analyzer crossed by 90 degrees. If a magnetic field is present perpendicularly to the film, the magnetization of the Bi:YIG will be tilted out of the plane. The perpendicular component of the magnetization will cause a Faraday rotation of the light. The rotation angle will be small where the magnetic field is small, and large in regions of high fields. After leaving the analyzer the light will therefore have an intensity distribution that reflects the magnitude of the field in the plane of the indicator film.

The Nobel Prize in Physics 1972

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

John Bardeen

1/3 of the prize

USA

University of Illinois
Urbana, IL, USA

b. 1908
d. 1991

Leon Neil Cooper

1/3 of the prize

USA

Brown University
Providence, RI, USA

b. 1930

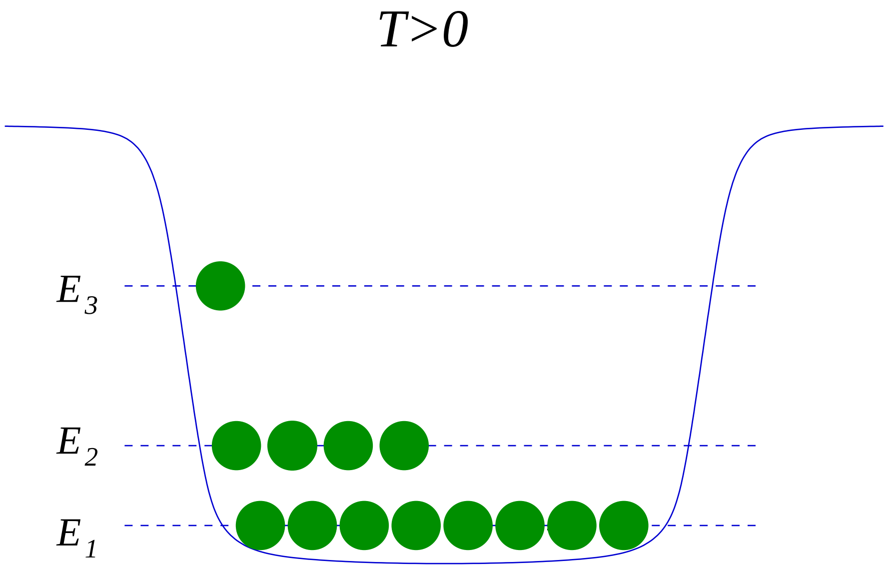
John Robert Schrieffer

1/3 of the prize

USA

University of Pennsylvania
Philadelphia, PA, USA

b. 1931



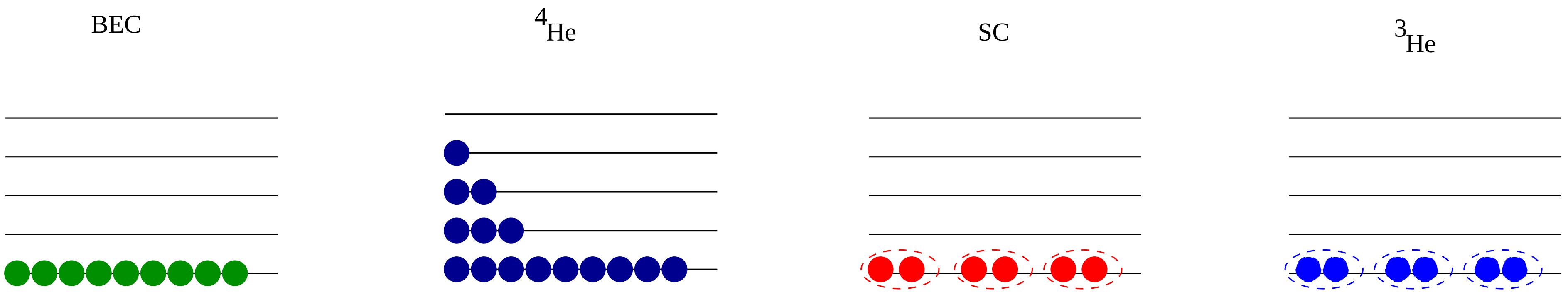
$$N_i = \frac{1}{e^{\frac{E_i - \mu}{kT}} - 1}$$

$$\lim_{N \to \infty} \frac{N_1}{N} = 0 \quad \text{pro} \quad T > T_B$$

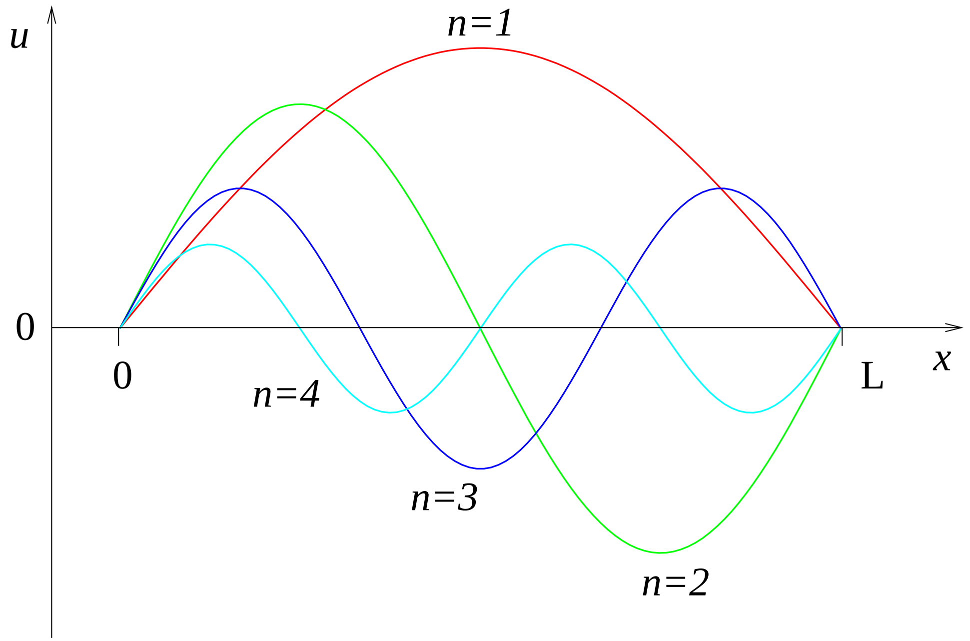
$$\lim_{N \to \infty} \frac{N_1}{N} > 0 \quad \text{pro} \quad T < T_B$$

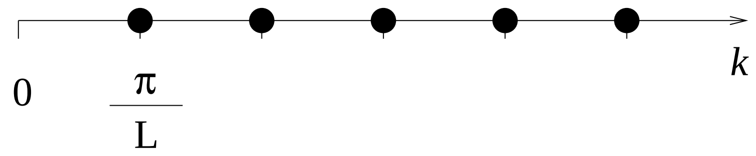
$$T_B \sim h^2$$

Schematické znázornění základních stavů kondenzátů



Kmity struny upevněné na koncích





$$\lambda_1 = 2L\,,\ \lambda_2 = 2L/2\,,\ \lambda_3 = 2L/3\,,\ \ldots\,,\ \lambda_n = 2L/n$$

$$\omega = \frac{2\pi c}{\lambda} \qquad \omega_n = \frac{2\pi c}{\lambda_n} = \frac{\pi c n}{L}$$

$$u_n(x,t) = \cos(\omega_n t + \varphi)\sin(\frac{2\pi}{\lambda_n}x) = \cos(\omega_n t + \varphi)\sin(k_n x)$$

$$k = \frac{2\pi}{\lambda} \qquad k_n = \frac{2\pi}{\lambda_n} = \frac{\pi n}{L}$$

Elektrony v jednorozměrném krystalu

Vlnové délky vln spojených s elektrony:

$$\lambda_1 = 2L\,,\ \lambda_2 = 2L/2\,,\ \lambda_3 = 2L/3\,,\ \ldots\,,\ \lambda_n = 2L/n\,;\ k_n = \frac{2\pi}{\lambda_n} = \frac{\pi n}{L}$$

$$E_n \ldots ?$$

Vztah mezi kinetickou energii a hybností:

$$E = \frac{p^2}{2m} \qquad E_n = \frac{p_n^2}{2m}$$

De-Broglieho relace:

$$p = \frac{h}{\lambda} \qquad p_n = \frac{h}{\lambda_n}$$

Výsledný vzorec pro energie elektronů:

$$E_n = \frac{h^2}{2m\lambda_n^2} = \frac{\hbar^2 k_n^2}{2m}$$

Elektrony v trojrozměrném krystalu

Vlnové chování ve všech třech směrech.

Vlnové délky:

$$\lambda_{x1} = 2L_x\,,\ \lambda_{x2} = 2L_x/2\,,\ \lambda_{x3} = 2L_x/3\,,\ \dots,\ \lambda_{xn} = 2L_x/n\,;\ k_{xn} = \frac{2\pi}{\lambda_{xn}} = \frac{\pi n}{L_x}$$

$$\lambda_{y1} = 2L_y\,,\ \lambda_{y2} = 2L_y/2\,,\ \lambda_{y3} = 2L_y/3\,,\ \dots,\ \lambda_{yn} = 2L_y/n\,;\ k_{yn} = \frac{2\pi}{\lambda_{yn}} = \frac{\pi n}{L_y}$$

$$\lambda_{z1} = 2L_z\,,\ \lambda_{z2} = 2L_z/2\,,\ \lambda_{z3} = 2L_z/3\,,\ \dots,\ \lambda_{zn} = 2L_z/n\,;\ k_{zn} = \frac{2\pi}{\lambda_{zn}} = \frac{\pi n}{L_z}$$

$$E_{n_x,n_y,n_z} \dots ?$$

Vztah mezi kinetickou energii a hybností:

$$E = \frac{\mathbf{p}^2}{2m} = \frac{p_x^2 + p_y^2 + p_z^2}{2m} \qquad E_{n_x,n_y,n_z} = \frac{p_{xn_x}^2 + p_{yn_y}^2 + p_{zn_z}^2}{2m} = \frac{\mathbf{p}_{n_x,n_y,n_z}^2}{2m}$$

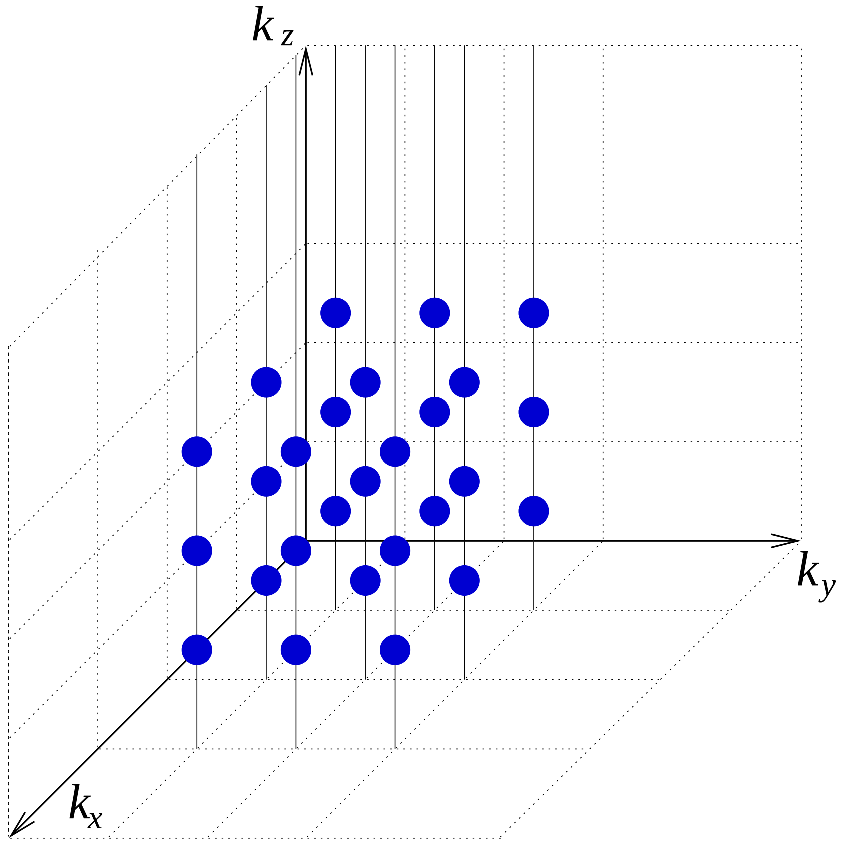
De-Broglieho relace:

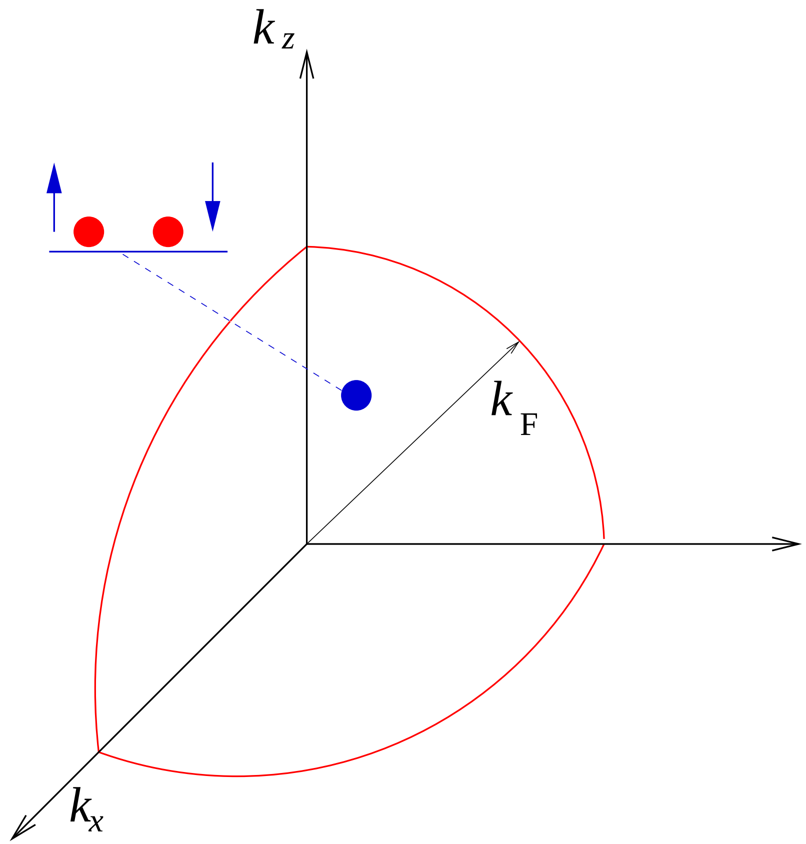
$$p_x = \frac{h}{\lambda_x}\,, \dots \qquad p_{xn} = \frac{h}{\lambda_{xn}}\,, \dots$$

Výsledný vzorec pro energie elektronů:

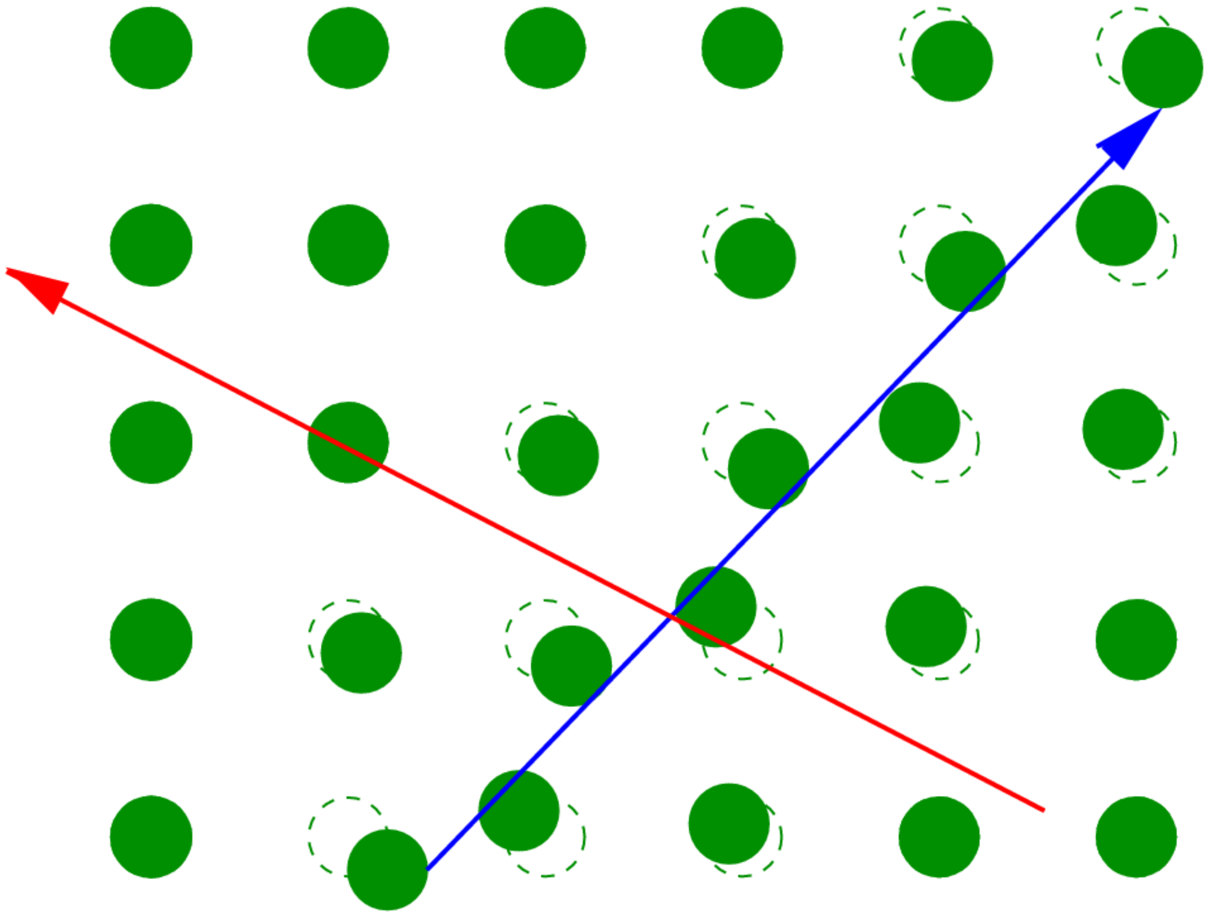
$$E_{n_x,n_y,n_z} = \frac{h^2}{2m}\left(\frac{1}{\lambda_{xn_x}^2} + \frac{1}{\lambda_{yn_y}^2} + \frac{1}{\lambda_{zn_z}^2}\right) = \frac{\hbar^2}{2m}\left(k_{xn_x}^2 + k_{xn_x}^2 + k_{xn_x}^2\right) = \frac{\hbar^2\mathbf{k}_{n_x,n_y,n_z}^2}{2m}$$

Mříž reprezentující množinu elektronových stavů, Fermiho plocha apod.

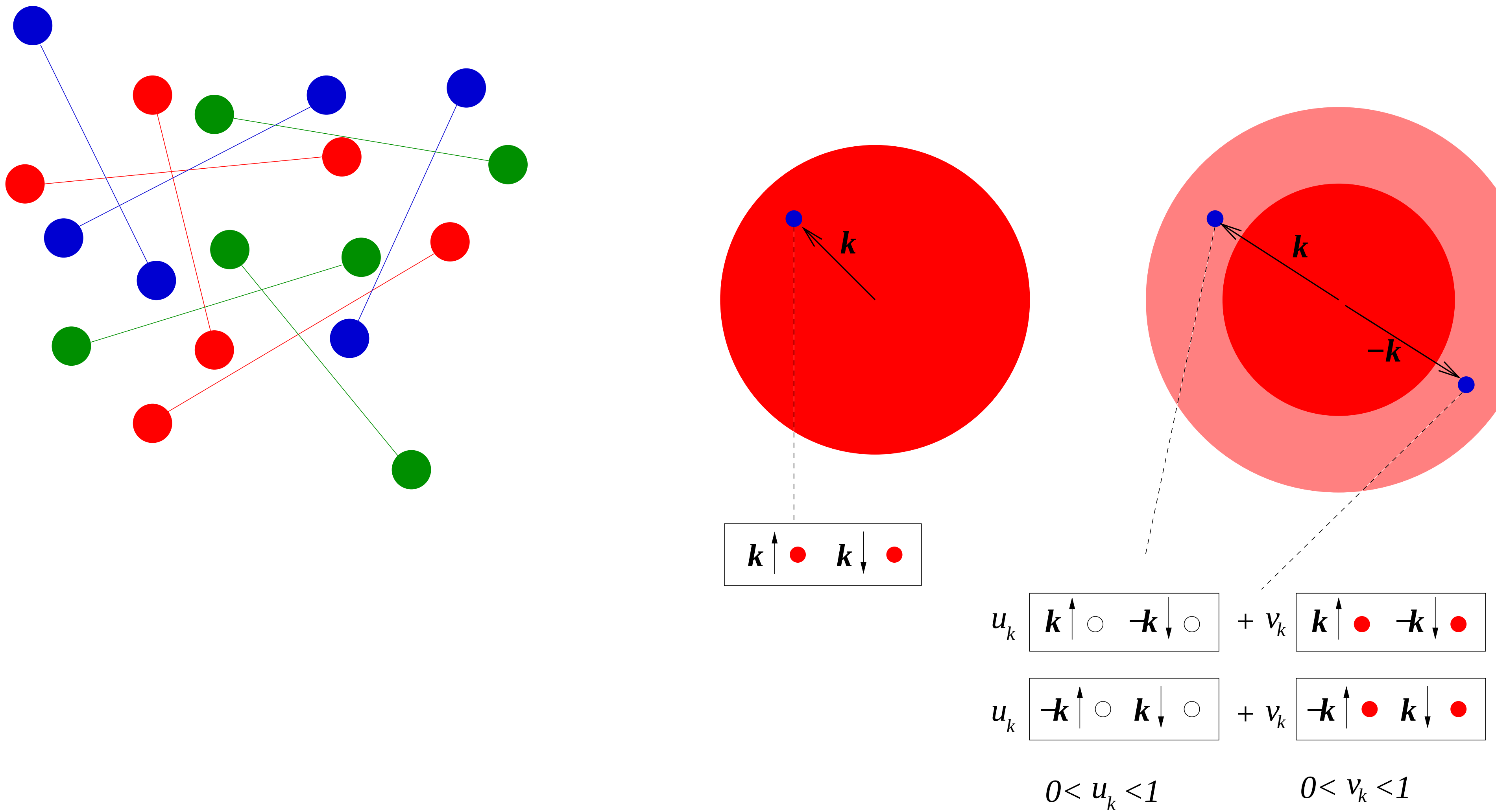




Schematické znázornění mechanismu přitažlivé elektron- elektronové interakce

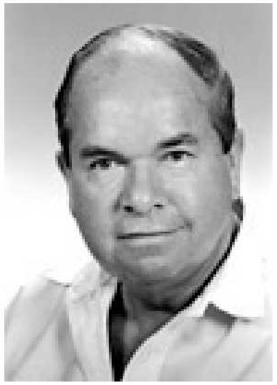


Schematické znázornění základního stavu teorie BCS



The Nobel Prize in Physics 2003

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



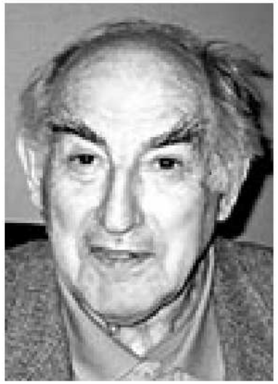
Alexei A. Abrikosov

1/3 of the prize

USA and Russia

Argonne National Laboratory
Argonne, IL, USA

b. 1928



Vitaly L. Ginzburg

1/3 of the prize

Russia

P.N. Lebedev Physical Institute
Moscow, Russia

b. 1916

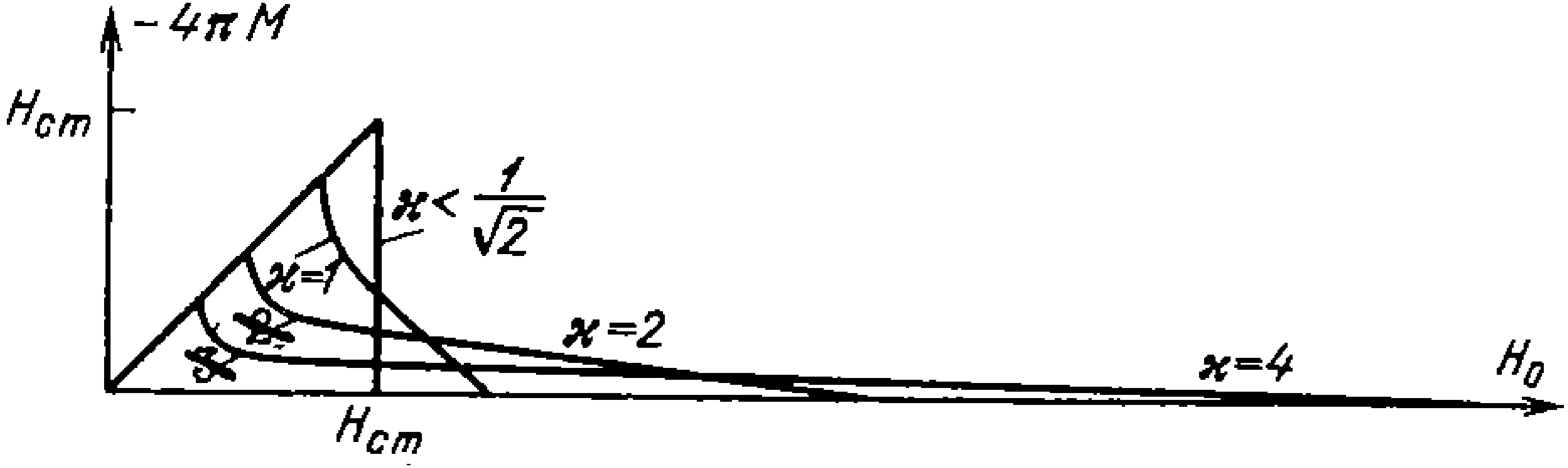
Anthony J. Leggett

1/3 of the prize

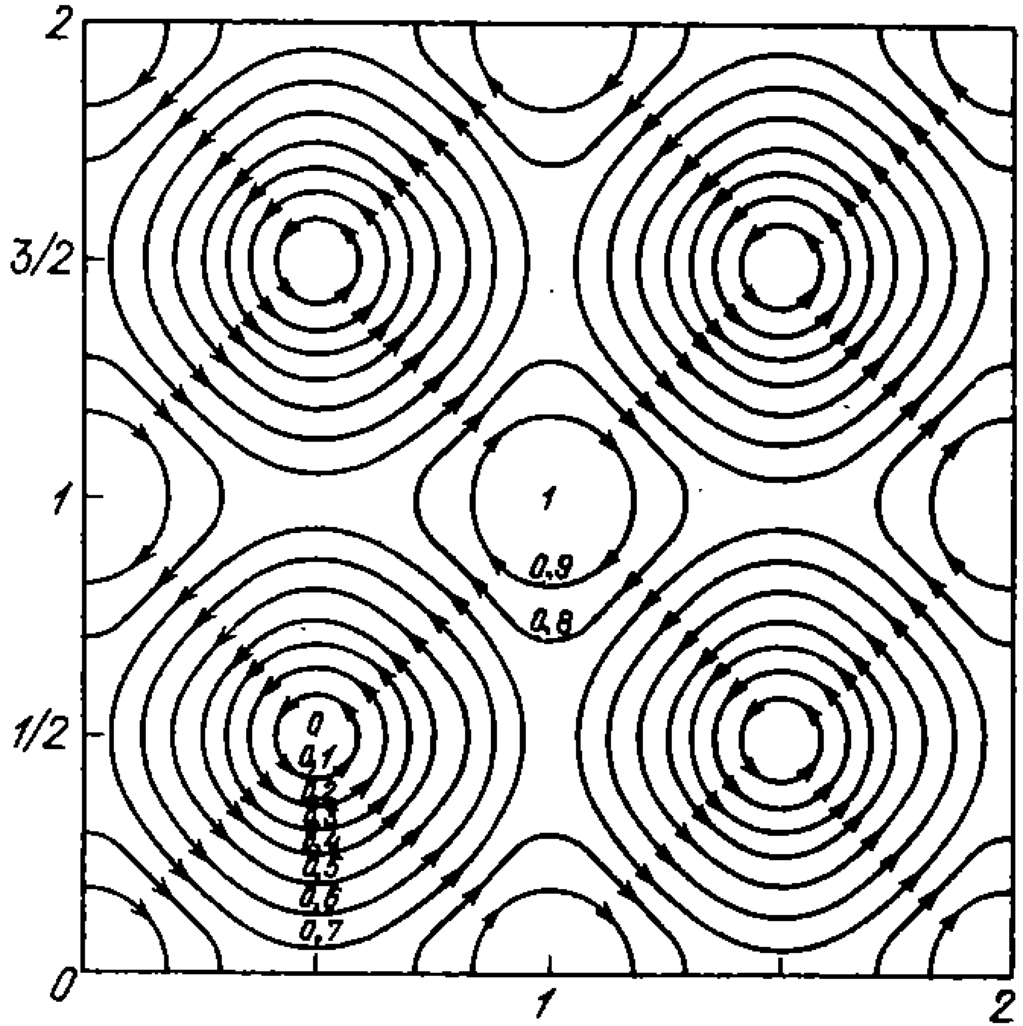
United Kingdom and USA

University of Illinois
Urbana, IL, USA

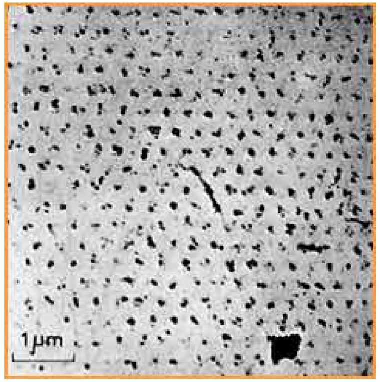
b. 1938



−4π M
Hcm
ϰ < 1/√2
ϰ=1
ϰ=2
ϰ=4
H0
Hcm


2
3/2
1
1/2
0
1
2
1
0,9
0,8
0
0,1
0,7

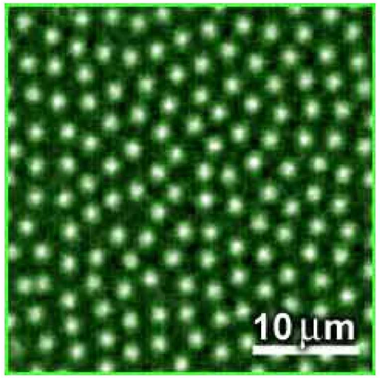
Vírové mřížky I



First image of Vortex lattice, 1967

Bitter Decoration
Pb-4at%In rod, 1.1K, 195G

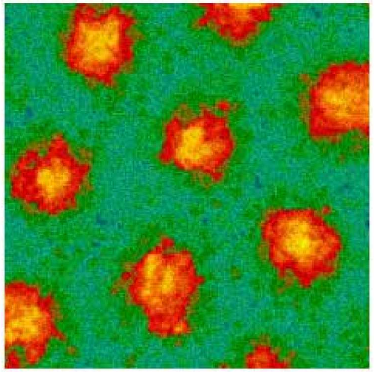
U. Essmann and H. Trauble
Max-Planck Institute, Stuttgart
Physics Letters 24A, 526 (1967)



Magneto-optical image of Vortex lattice, 2001

Magneto-Optical Imaging
NbSe2 crystal, 4.3K, 3G

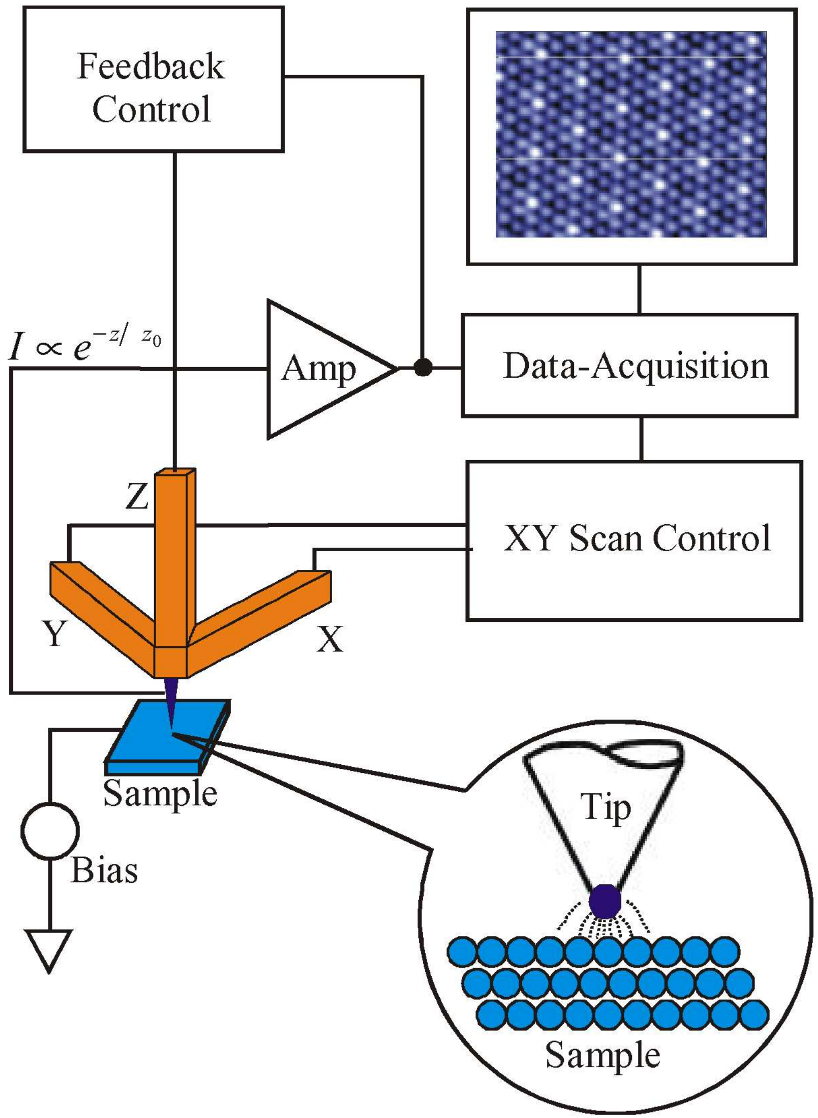
P.E. Goa et al.
University of Oslo
Supercond. Sci. Technol. 14, 729 (2001)

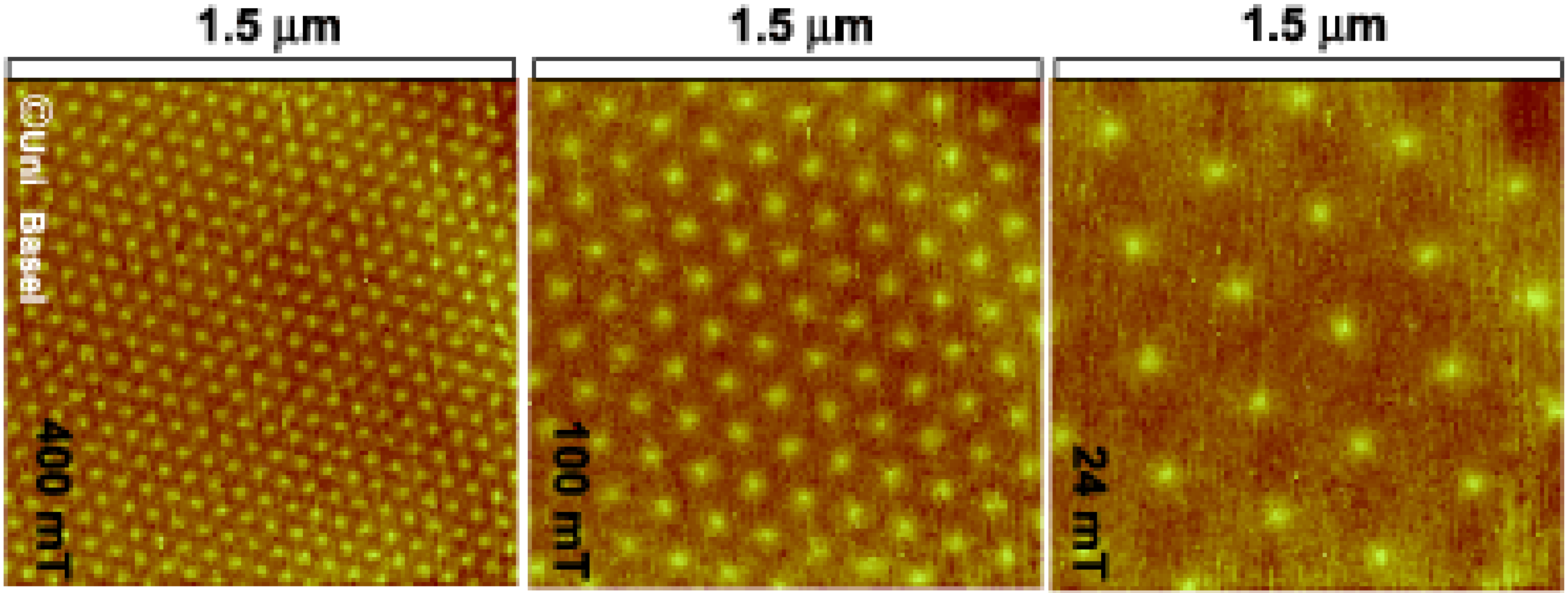


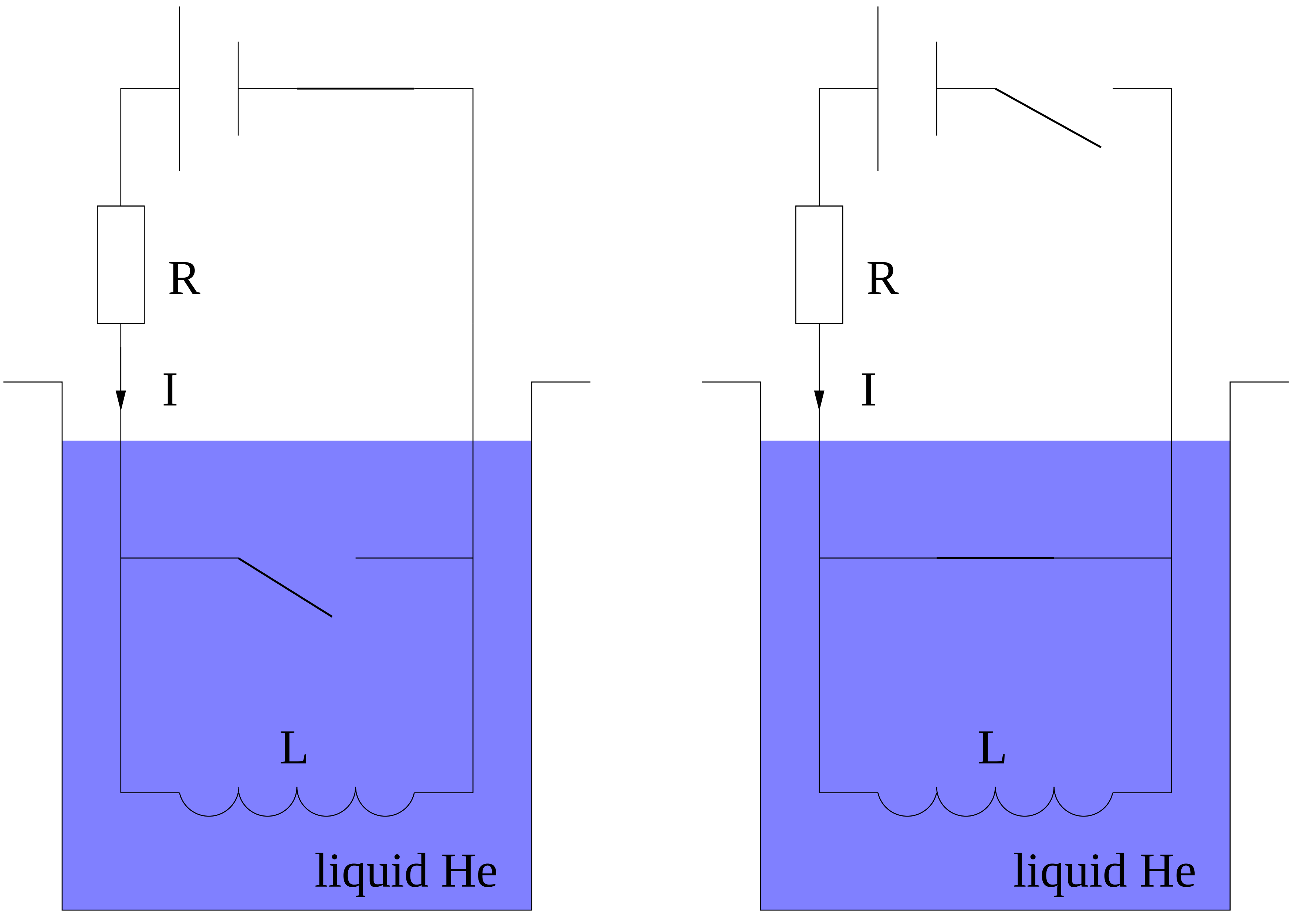
Vortices in MgB2, 2002

Scanning Tunnel Spectroscopy
MgB2 crystal, 2K, 2000G

M. R. Eskildsen et al.
University of Geneva
Phys. Rev. Lett. 89, 187003 (2002)


Feedback Control
Data-Acquisition
Amp
$I \propto e^{-z/z_0}$
XY Scan Control
Z
Y
X
Sample
Bias
Tip
Sample

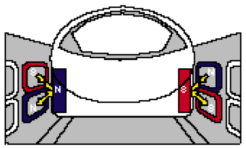

1.5 μm
1.5 μm
1.5 μm
©Uni Basel
400 mT
100 mT
24 mT


R
I
L
liquid He
R
I
L
liquid He

Principle of Maglev

Maglev is a system in which the vehicle runs levitated from the guideway (corresponding to the rail tracks of conventional railways) by using electromagnetic forces between superconducting magnets on board the vehicle and coils on the ground. The following is a general explanation of the principle of Maglev.

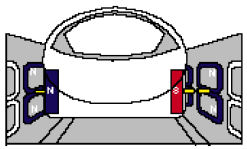
Principle of magnetic levitation



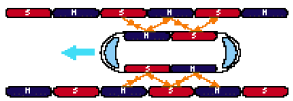
The "8" figured levitation coils are installed on the sidewalls of the guideway. When the on-board superconducting magnets pass at a high speed about several centimeters below the center of these coils, an electric current is induced within the coils, which then act as electromagnets temporarily. As a result, there are forces which push the superconducting magnet upwards and ones which pull them upwards simultaneously, thereby levitating the Maglev vehicle.

Principle of lateral guidance

The levitation coils facing each other are connected under the guideway, constituting a loop. When a running Maglev vehicle, that is a superconducting magnet, displaces laterally, an electric current is induced in the loop, resulting in a repulsive force acting on the levitation coils of the side near the car and an attractive force acting on the levitation coils of the side farther apart from the car. Thus, a running car is always located at the center of the guideway.



Principle of propulsion



A repulsive force and an attractive force induced between the magnets are used to propel the vehicle (superconducting magnet). The propulsion coils located on the sidewalls on both sides of the guideway are energized by a three-phase alternating current from a substation, creating a shifting magnetic field on the guideway. The on-board superconducting magnets are attracted and pushed by the shifting field, propelling the Maglev vehicle.

(a) (b)

Figure 3. Magnets for (a) NMR 900 MHz, superfluid helium cooled and (b) full-body MRI, liquid helium bath cooled with active shield refrigeration (Bruker)

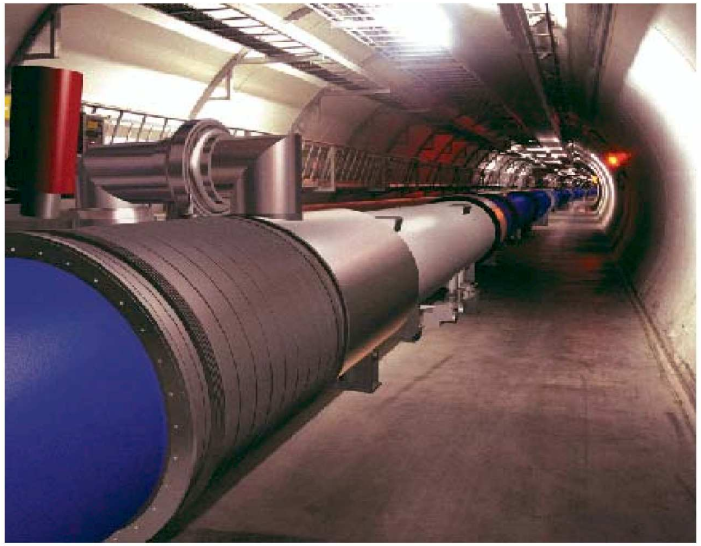


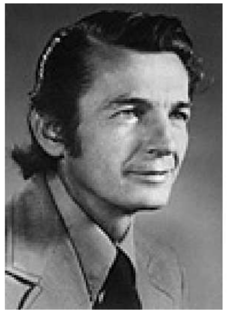
Figure 4. View of the Large Hadron Collider (LHC), a high-energy particle accelerator with superfluid-helium cooled superconducting magnets in construction at CERN

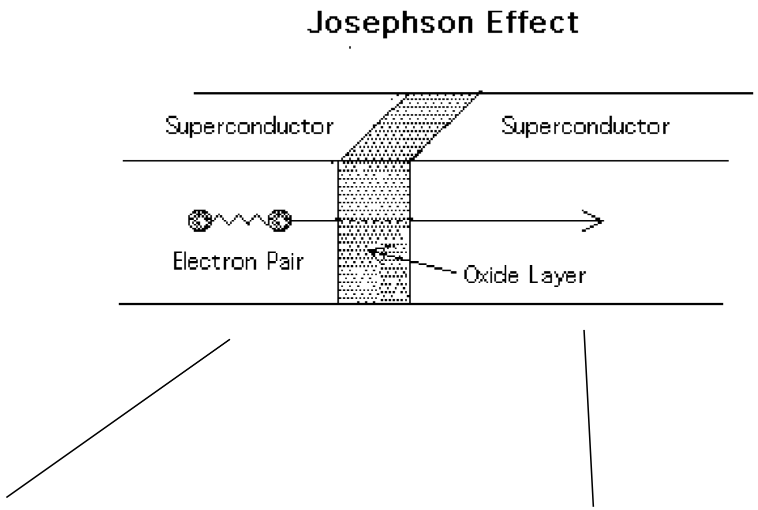
Nobelova cena za fyziku v roce 1973

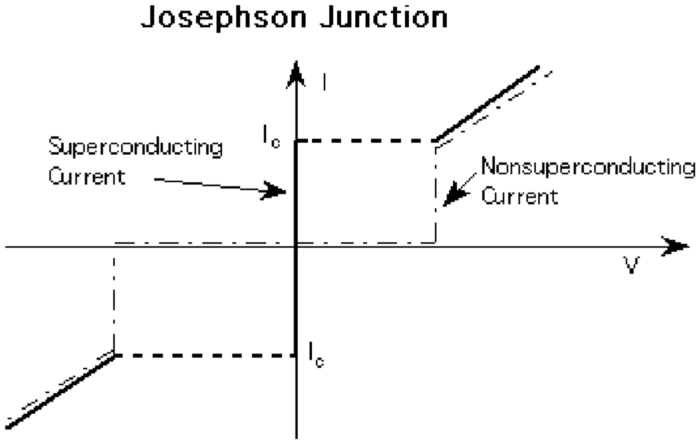
The Nobel Prize in Physics 1973

"for their experimental discoveries regarding tunneling phenomena in semiconductors and superconductors, respectively"

"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"

		
Leo Esaki	**Ivar Giaever**	**Brian David Josephson**
1/4 of the prize	1/4 of the prize	1/2 of the prize
Japan	USA	United Kingdom
IBM Thomas J. Watson Research Center Yorktown Heights, NY, USA	General Electric Company Schenectady, NY, USA	University of Cambridge Cambridge, United Kingdom
b. 1925	b. 1929 (in Bergen, Norway)	b. 1940





$\psi_1 = |\psi_1|\, e^{\,i\varphi_1}$ $\qquad$ $\psi_2 = |\psi_2|\, e^{\,i\varphi_2}$

$$j = j_c \sin(\Delta\varphi)$$

Na přechodu napětí V: ⟶ Střídavý proud o frekvenci

$\Delta\varphi = \text{konst} + 2eVt/\hbar$ $\qquad$ $f = 2eV/h$

1 V = napětí potřebné pro vznik proudu o frekvenci 483 597.9 GHz.

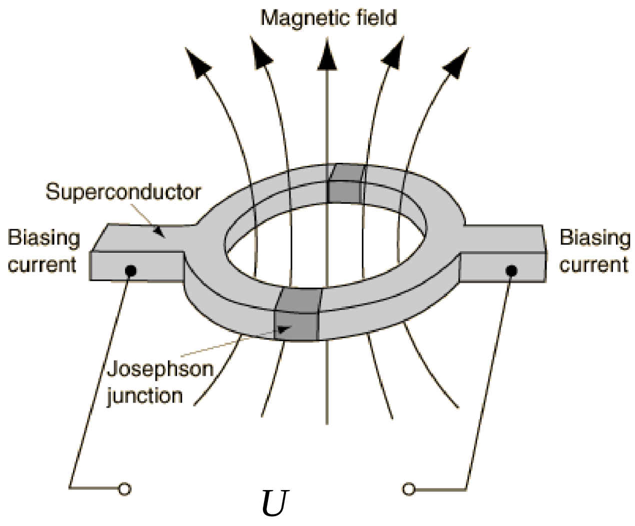



Figure 2: Neuromag Ltd. 122 MEG system

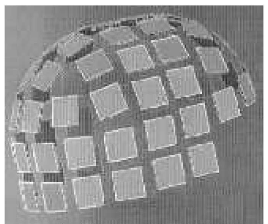


Figure 3: Neuromag Ltd. 122 sensor array

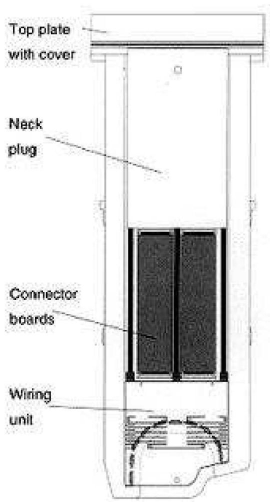
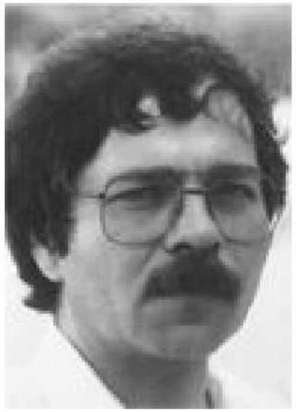


Figure 4: Neuromag Ltd. 122 probe

The Nobel Prize in Physics 1987

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



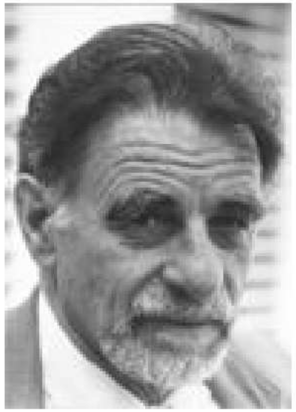
J. Georg Bednorz

1/2 of the prize

Federal Republic of Germany

IBM Zurich Research Laboratory
Rüschlikon, Switzerland

b. 1950



K. Alexander Müller

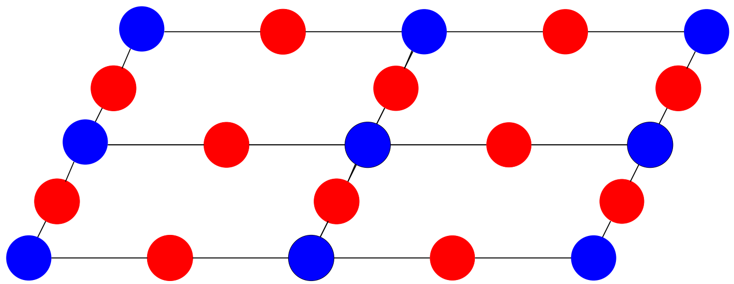
1/2 of the prize

Switzerland

IBM Zurich Research Laboratory
Rüschlikon, Switzerland

b. 1927

CuO_2 plane

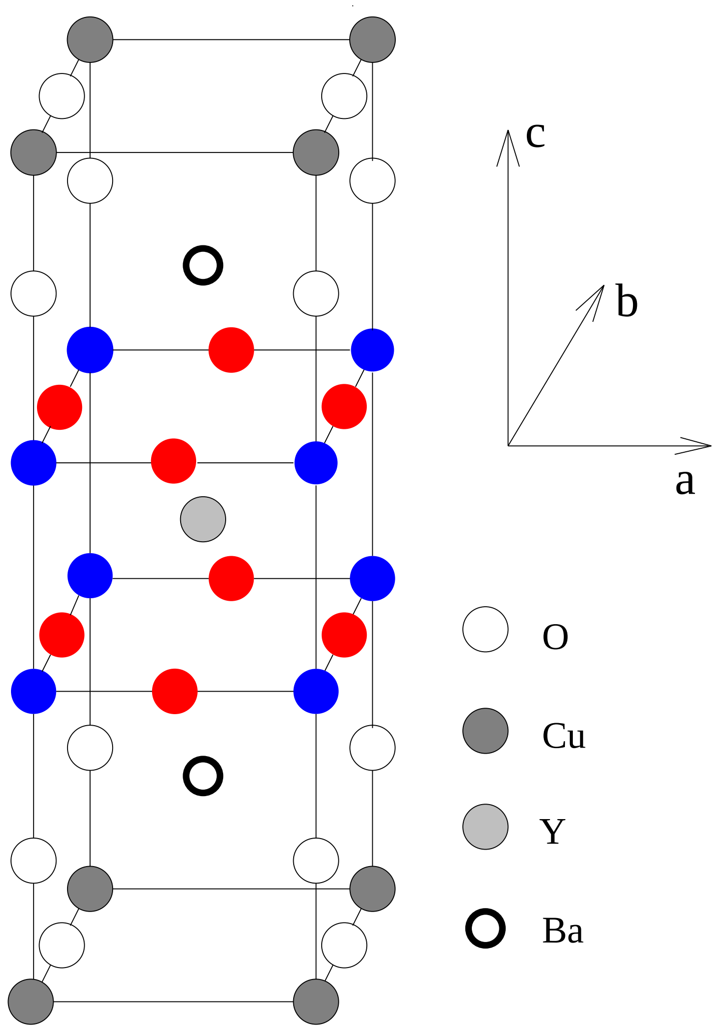


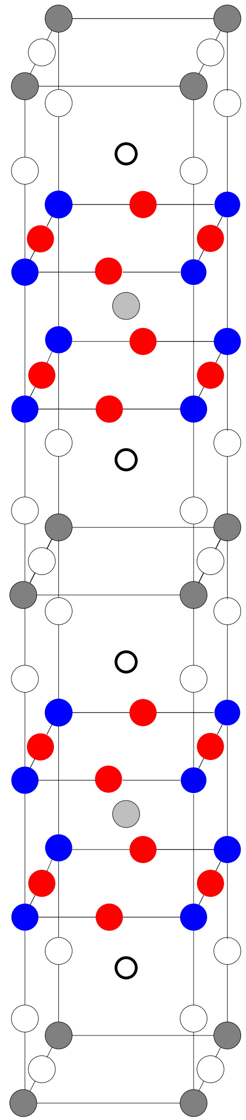
O, Cu in the Cu_2O planes

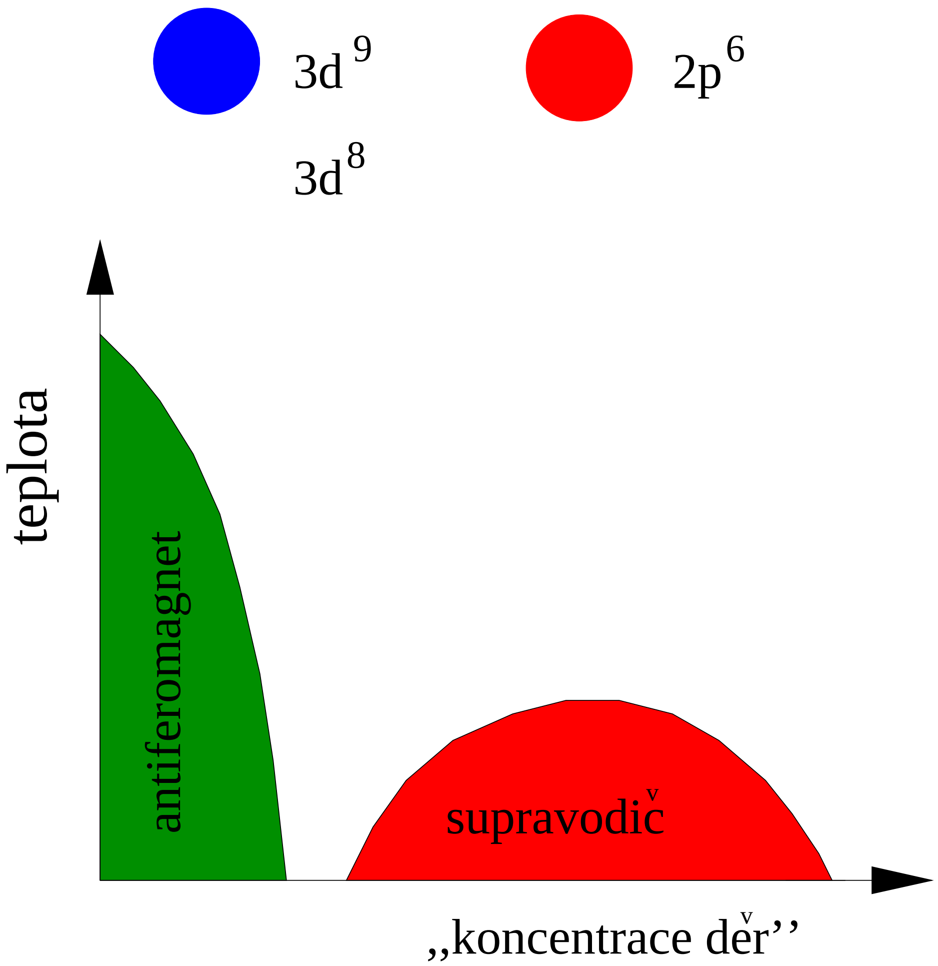
$3d^9 - 3d^8$

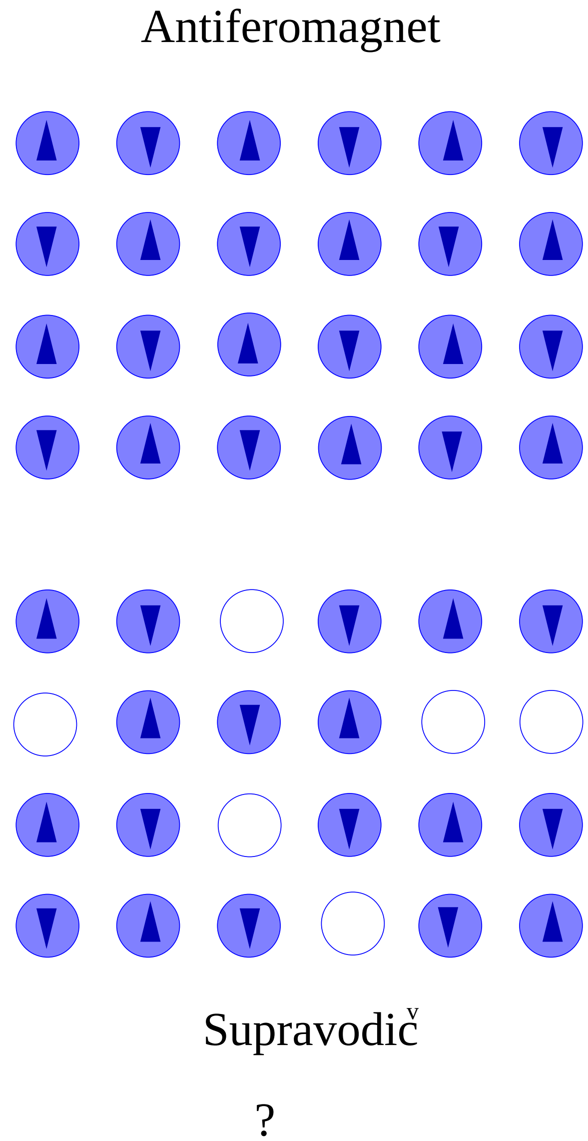
$2p^6$

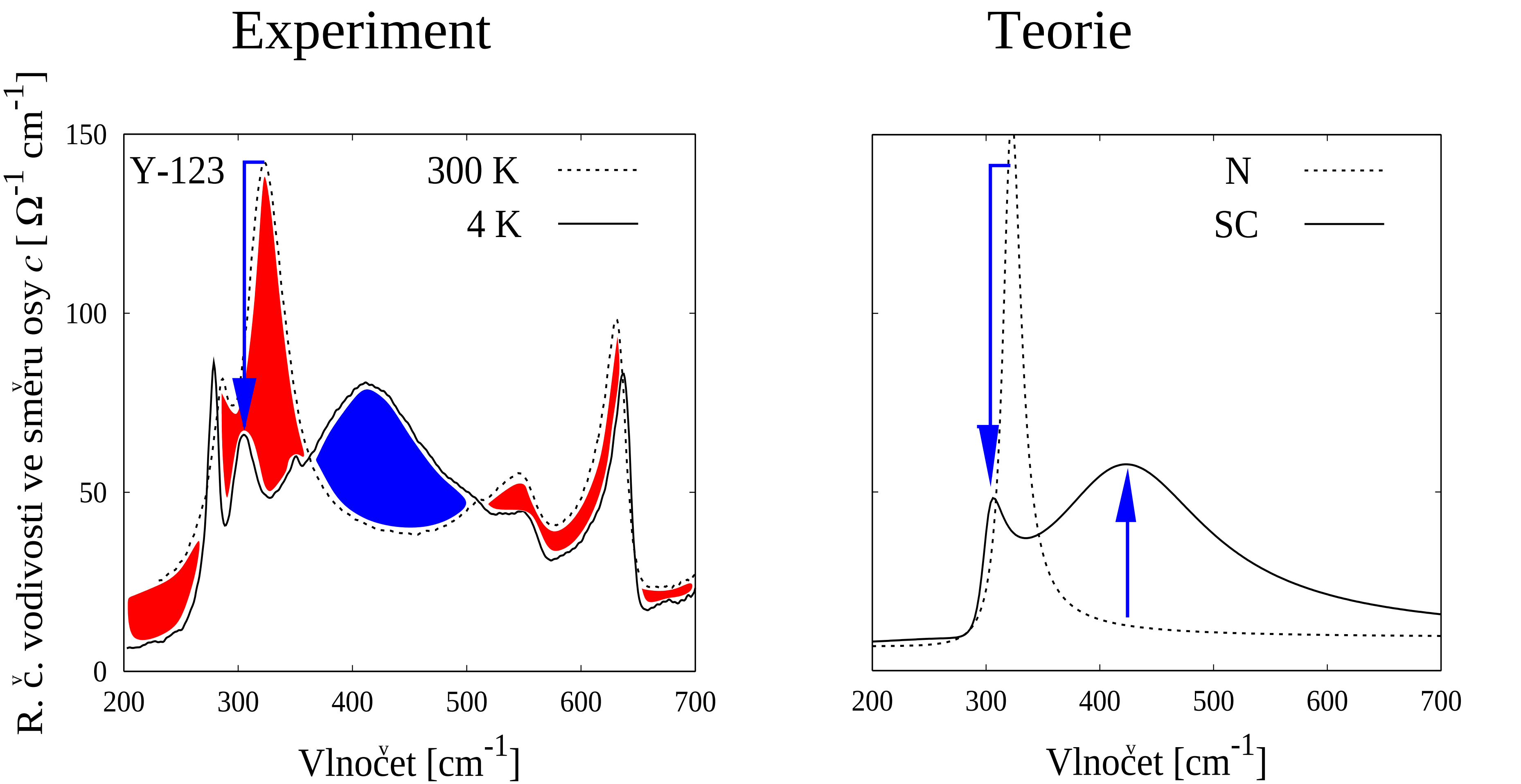
$YBa_2Cu_3O_7$



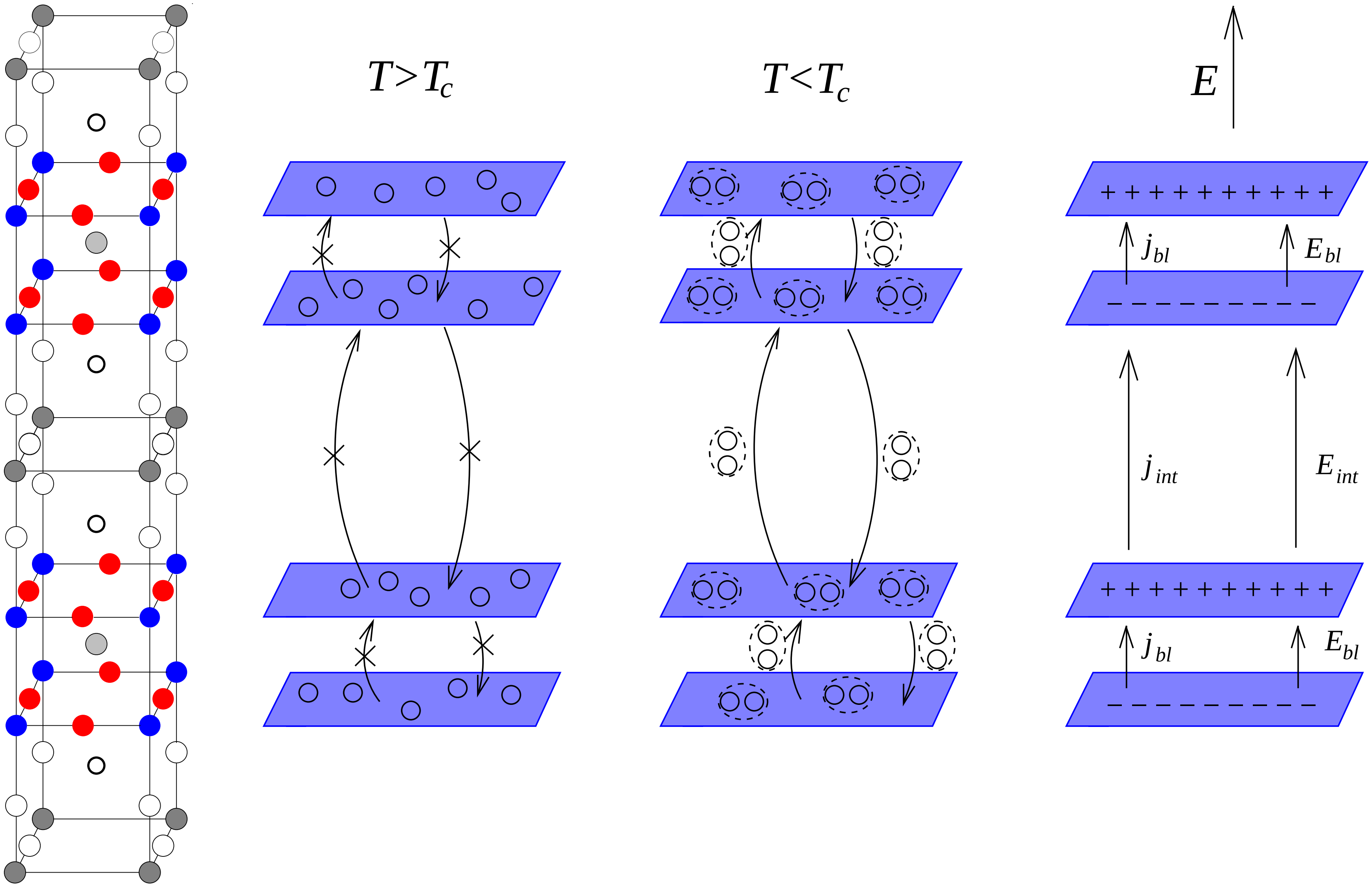


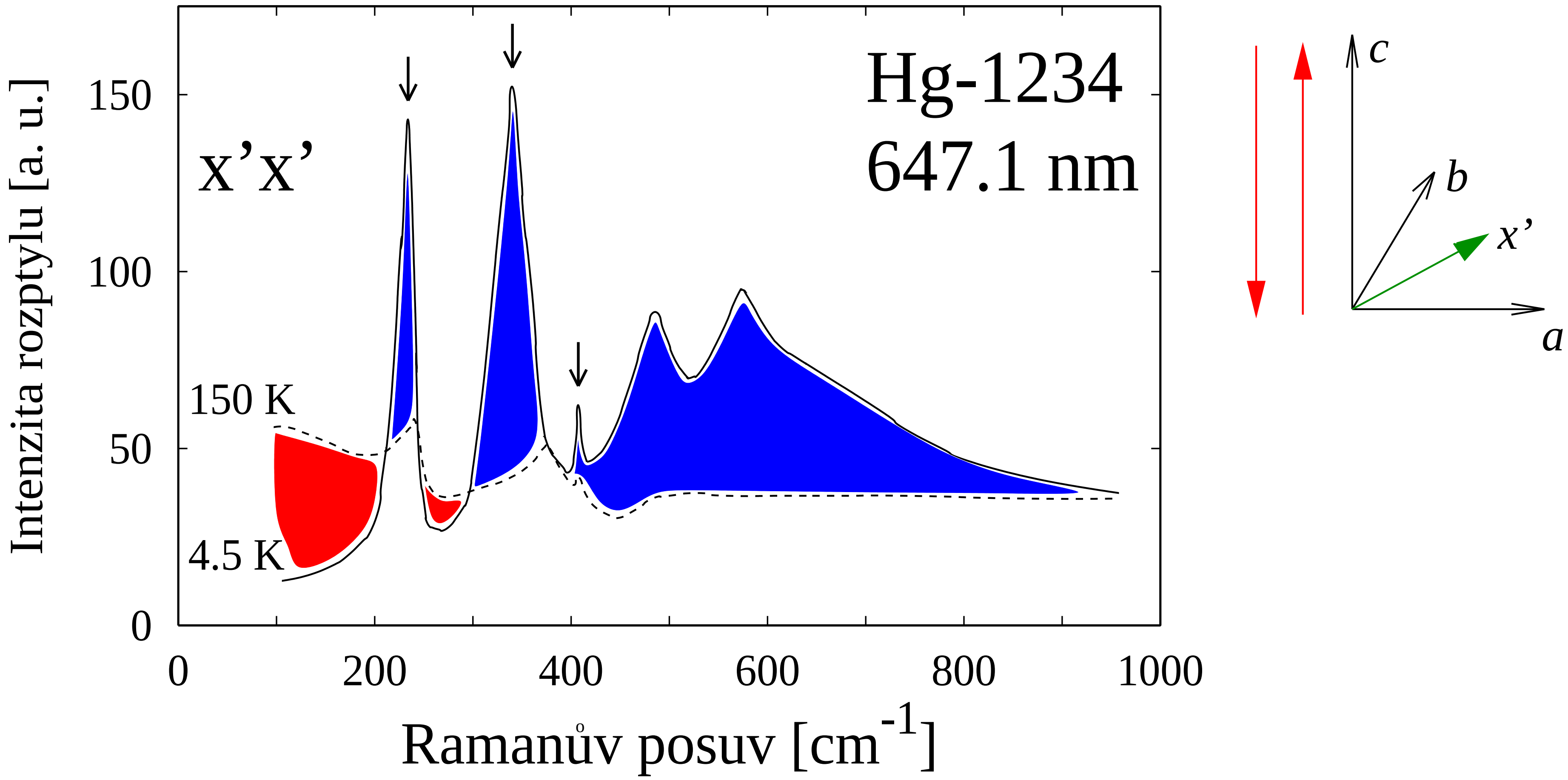

3d 9
2p 6
3d8
teplota
antiferomagnet
supravodič
„koncentrace děr"


Antiferomagnet
Supravodič
?

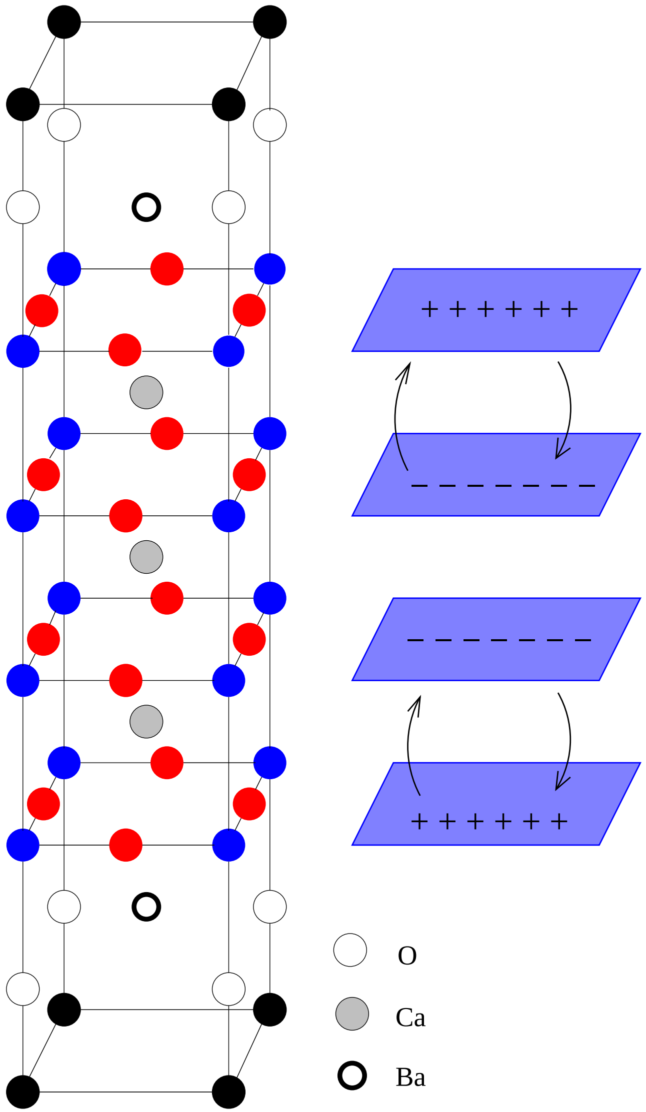

Experiment
Teorie
Y-123
300 K
4 K
N
SC
R. č. vodivosti ve směru osy c [Ω-1 cm-1]
Vlnočet [cm-1]
Vlnočet [cm-1]
0
50
100
150
200
300
400
500
600
700
200
300
400
500
600
700

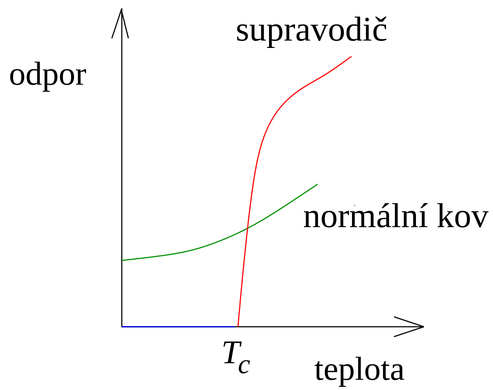
Anomálie v optické odezvě - schematické vysvětlení

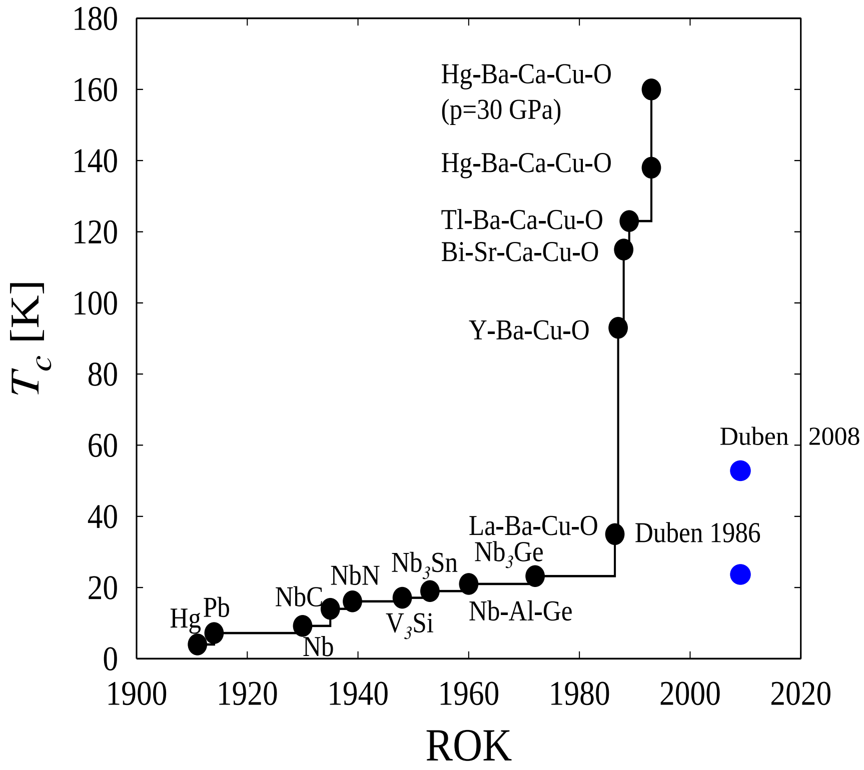



Hg-1234
647.1 nm
x'x'
150 K
4.5 K
Intenzita rozptylu [a. u.]
0
50
100
150
0
200
400
600
800
1000
Ramanův posuv [cm-1]
c
b
x'
a

Anomálie ve spektrech intenzity Ramanova rozptylu - schematické vysvětlení




odpor
supravodič
normální kov
T_c
teplota


T_c [K]
ROK
Hg-Ba-Ca-Cu-O
(p=30 GPa)
Hg-Ba-Ca-Cu-O
Tl-Ba-Ca-Cu-O
Bi-Sr-Ca-Cu-O
Y-Ba-Cu-O
Duben 2008
La-Ba-Cu-O
Duben 1986
Nb_3Ge
Nb_3Sn
NbN
NbC
Hg
Pb
Nb
V_3Si
Nb-Al-Ge

J|A|C|S COMMUNICATIONS

Published on Web 02/23/2008

Iron-Based Layered Superconductor $La[O_{1-x}F_x]FeAs$ ($x = 0.05-0.12$) with $T_c = 26$ K

Yoichi Kamihara,*,† Takumi Watanabe,‡ Masahiro Hirano,†,§ and Hideo Hosono†,‡,§

ERATO-SORST, JST, Frontier Research Center, Tokyo Institute of Technology, Mail Box S2-13, Materials and Structures Laboratory, Tokyo Institute of Technology, Mail Box R3-1, and Frontier Research Center, Tokyo Institute of Technology, Mail Box S2-13, 4259 Nagatsuta, Midori-ku, Yokohama 226-8503, Japan

Received January 9, 2008; E-mail: hosono@msl.titech.ac.jp

Discovery of the copper-based superconductor $La_{2-x}Ba_xCuO_4$[1] with a high transition temperature (T_c) triggered extensive research with the intention of developing new transition-metal-based superconductors.[2,3] Currently, high T_c superconductors are limited to layered perovskites that contain CuO_2 structural units as the conduction layers. However, the T_c of the non-Cu-based superconductors in this category has remained low, although spin triplet superconductivity has been found in UPt_3 ($T_c \sim 0.54$ K)[4] and Sr_2RuO_4 ($T_c \sim 1.4$ K).[5,6] Here, we report a layered iron-based compound, LaOFeAs, which undergoes superconducting transition under doping with F^- ions at the O^{2-} site. Its T_c exhibits a trapezoidal shape dependence on F^- content, with the highest T_c of ~26 K at 5−11 atom %. Further, its magnetic susceptibility indicates that F-doped LaOFeAs exhibits Curie−Weiss-like behavior in the normal conducting state.

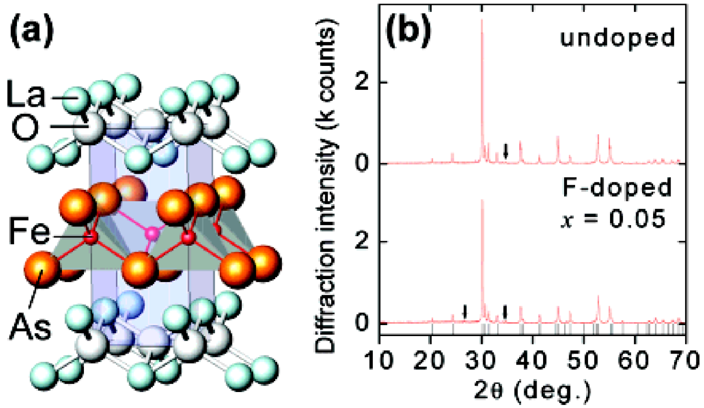
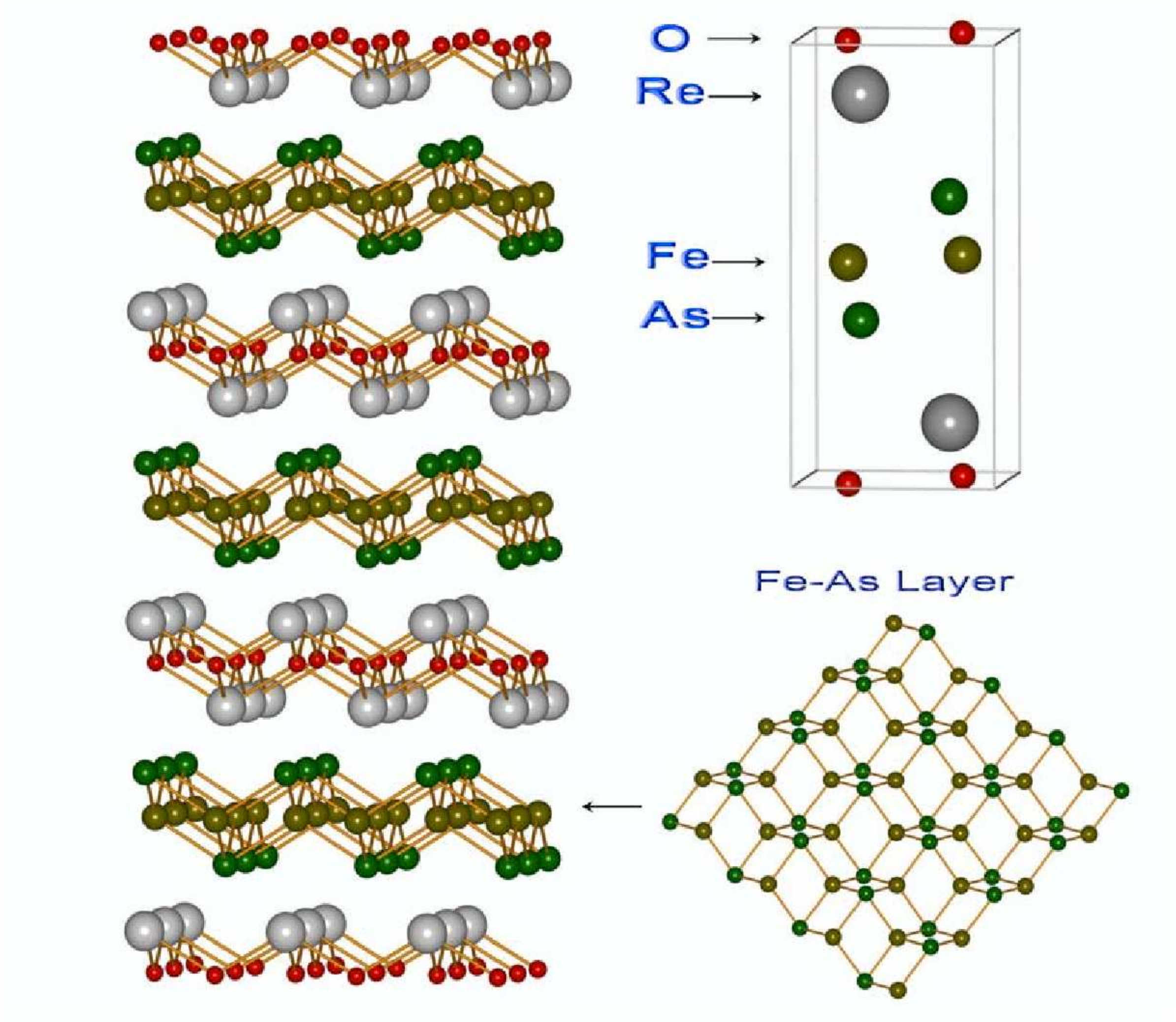
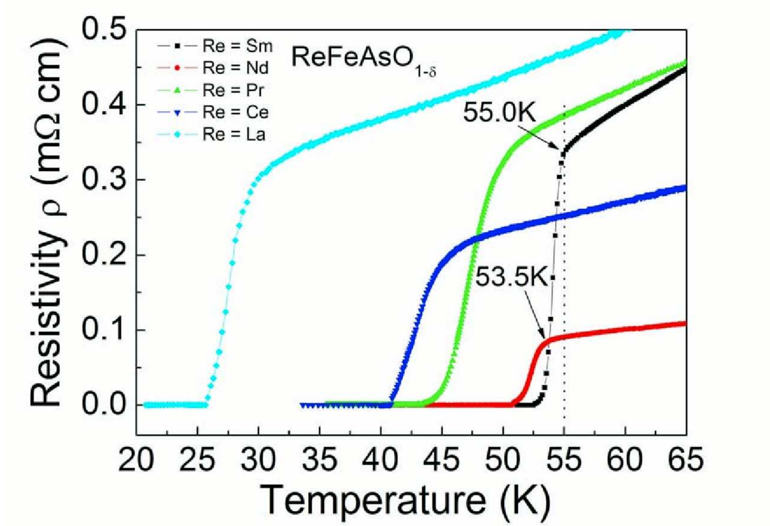
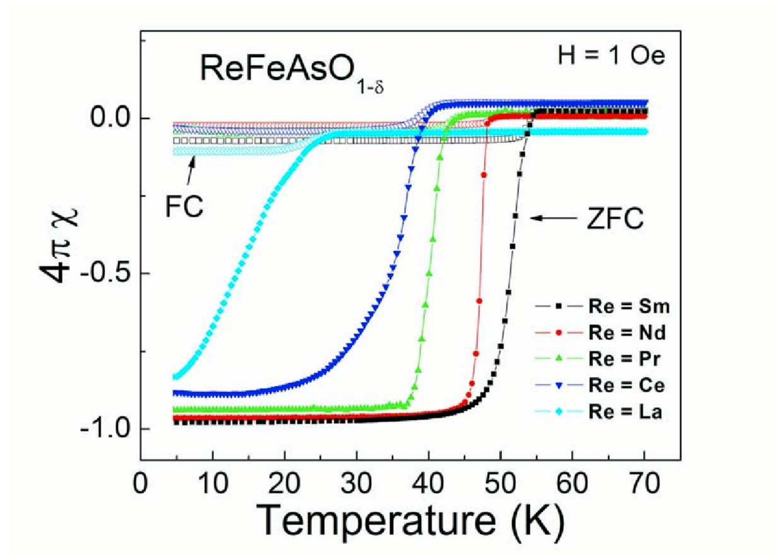


Figure 1. (a) Crystal structure of LaOFeAs. (b) Powder XRD patterns of undoped LaOFeAs and $La[O_{1-x}F_x]FeAs$: $x = 0.05$. Black bars at bottom show calculated Bragg diffraction positions of LaOFeAs. Arrows denote peaks due to impurity phases, FeAs (helimagnetic),[13] and LaOF.


O
Re
Fe
As
Fe-As Layer


ReFeAsO1-δ
Re = Sm
Re = Nd
Re = Pr
Re = Ce
Re = La
55.0K
53.5K
Resistivity ρ (mΩ cm)
0.0
0.1
0.2
0.3
0.4
0.5
20 25 30 35 40 45 50 55 60 65
Temperature (K)


ReFeAsO1-δ
H = 1 Oe
FC
ZFC
Re = Sm
Re = Nd
Re = Pr
Re = Ce
Re = La
4π χ
0.0
-0.5
-1.0
0 10 20 30 40 50 60 70
Temperature (K)