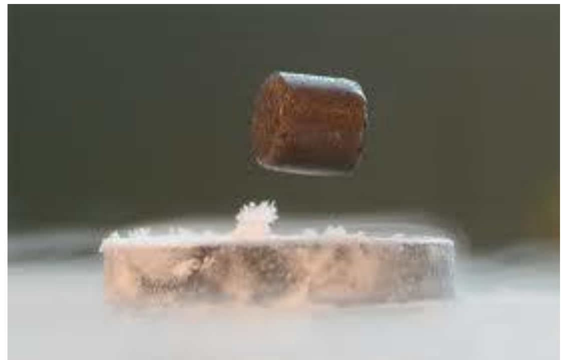
Prvih 100 let superprevodnosti



Peter Prelovšek

FMF - 21. januar 2012

Teme

1. **Superprevodnost in HTC: 2011 – memorialno leto**
   - pregled zgodovine SP

2. **Osnovne lastnosti (standardnih) superprevodnikov**
   - temperatura prehoda, energijska vrzel itd.
   - izvor in mikroskopski popis

3. **Novi materiali in njihovo razumevanje**

4. **Fenomenološka teorija in makroskopske lastnosti SP**

5. **Uporaba**

Superprevodnost : čudo fizike

Superprevodno stanje: **makroskopska realizacija kvantne mehanike**

- valovna funkcija, interferenca na makroskopski razdaljah

- gibanje brez upora

Osnovne lastnosti SP stanja:

- idealna prevodnost, permanentni tokovi

- Meissnerjev efekt, izrivanje magnetnega polja

- obstoj energijske vrzeli $\Delta(T < T_c) > 0$,

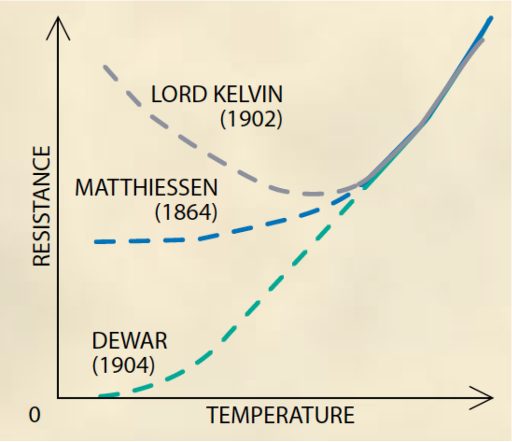
  SP kolektivno stanje vezanih parov elektronov (Cooperjevih) parov

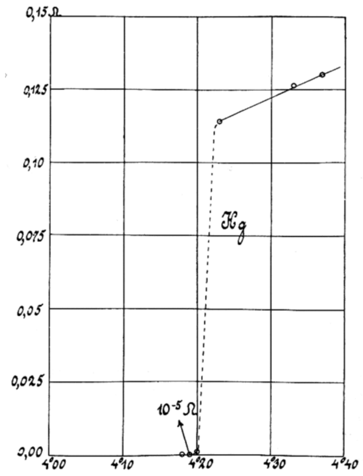
- makroskopska interferenca - efekti Josephsona

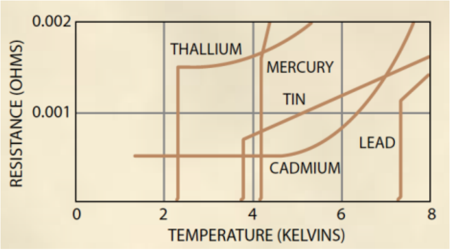
Nobelove nagrade za SP: (1913), 1972, 1973, 1988, 2003

Odkritje superprevodnosti

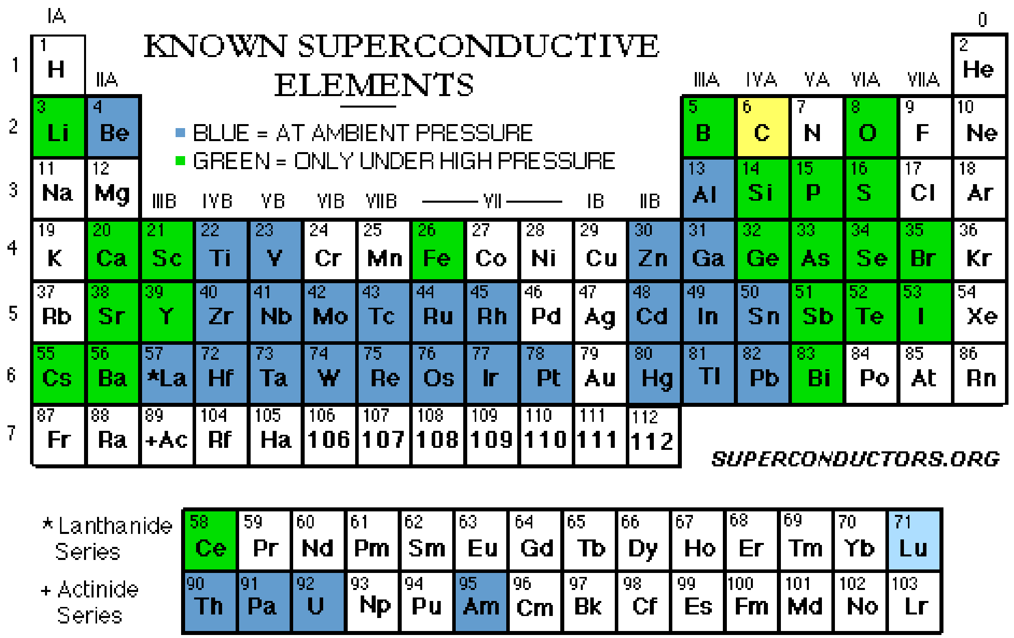
Kamerlingh Onnes, Leiden – April 8, 1911







Superprevodnost v periodičnem sistemu elementov



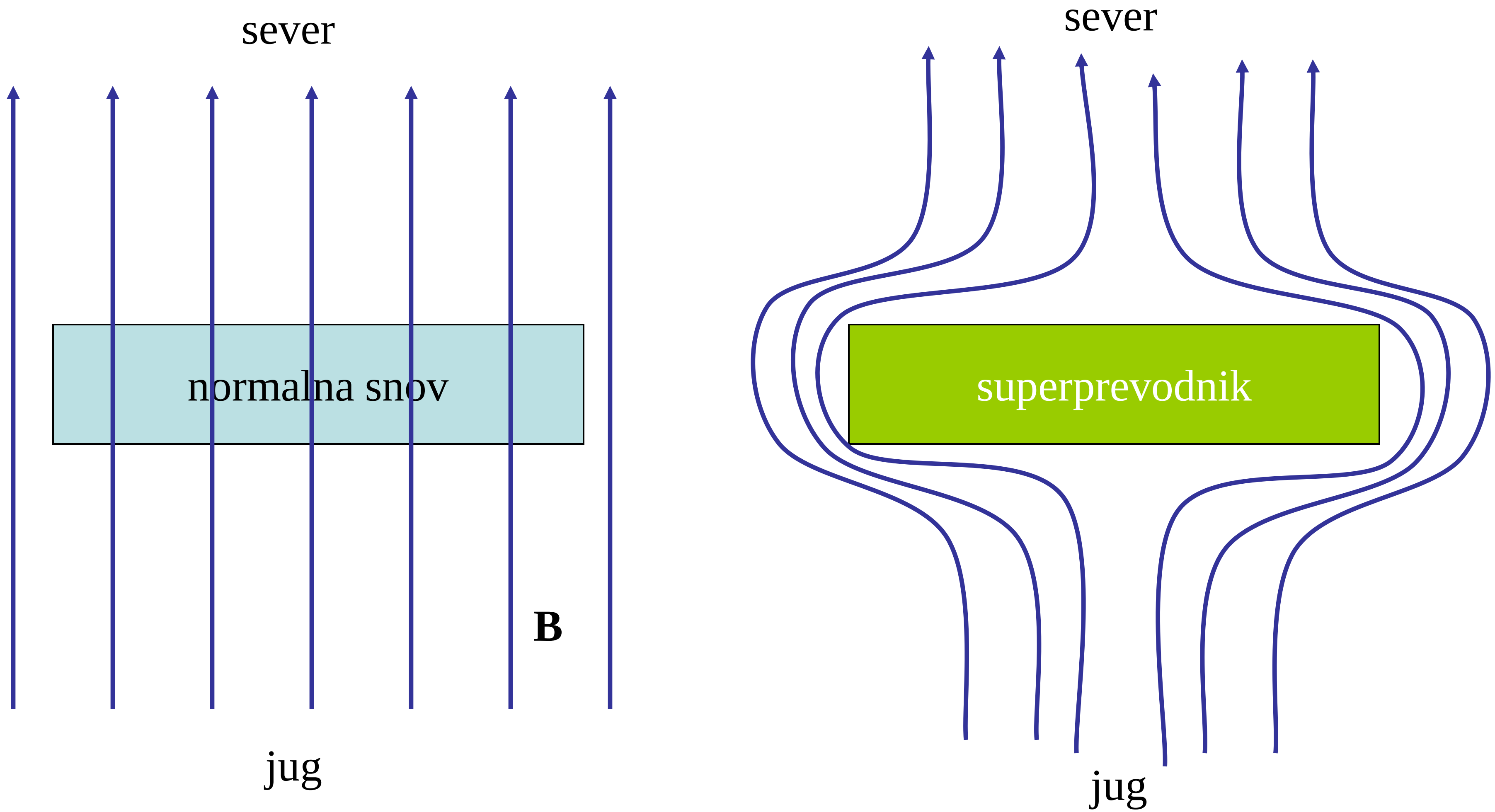
SP je nizkotemperaturno stanje – faza v mnogih enostavnih **kovinah**

temperatura prehoda T_c (< 10 K) je zelo nizka

nizkotemperaturna konkurenca: feromagnetizem, magnetna ureditev..

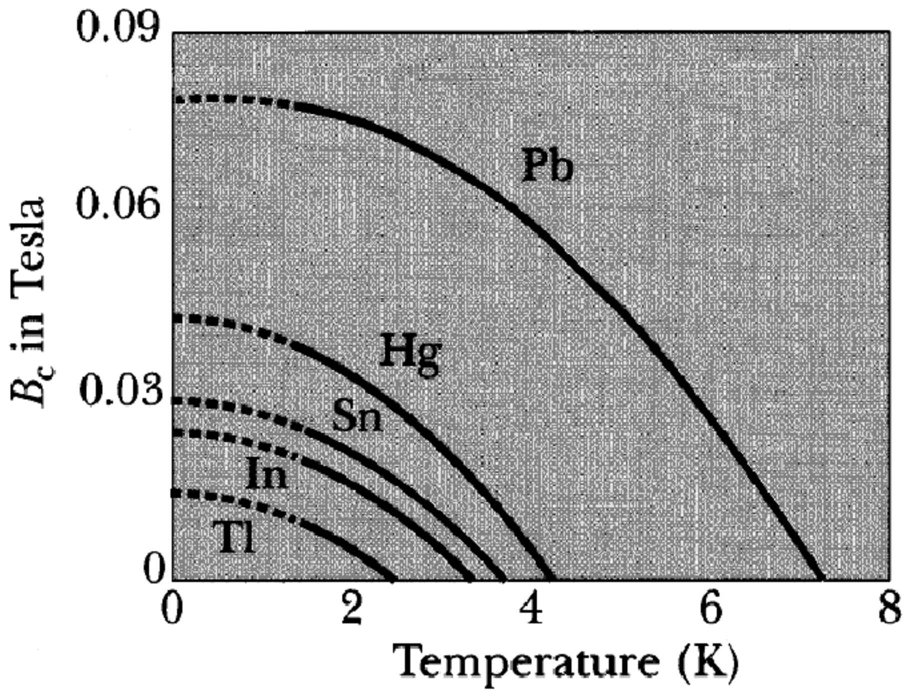
SP: idealni diamagnet

Meissner - Ochsenfeld 1933: (popolno) izrinjeno magnetno polje - SP I. vrste



Kritično magnetno polje: SP I. vrste

$$B_c(T) \cong B_c(0)[1-(T/T_c)^2]$$

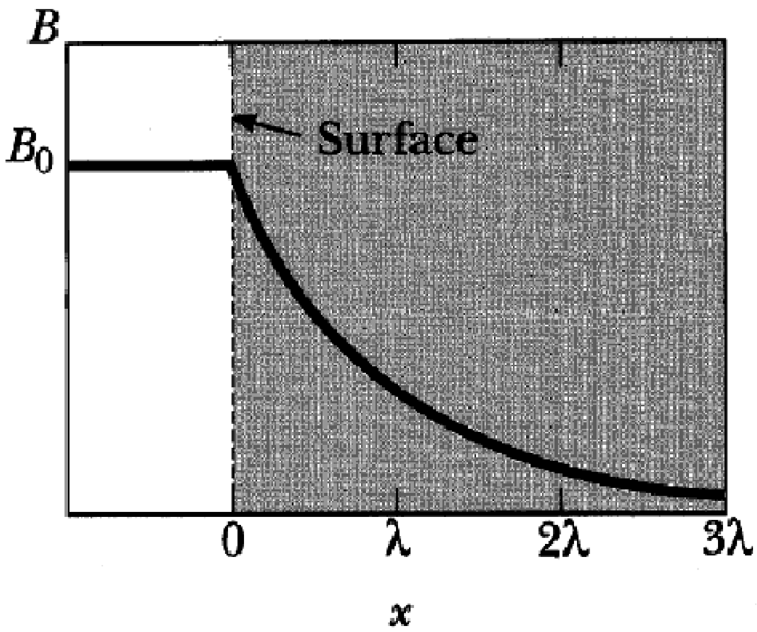


Enačbe Londonov

Fritz in Heinz London: 1935 - idealna prevodnost + Meissnerjev efekt

$$m\frac{d\vec{v}_s}{dt} = -e_0\vec{E} \Longrightarrow \frac{d\vec{j}_s}{dt} = \frac{n_s e_0^2}{m}\vec{E} \qquad \nabla\times\vec{E} = -\frac{\partial\vec{B}}{\partial t}$$

$$\Longrightarrow \frac{\partial}{\partial t}\left(\nabla\times\vec{j}_s + \frac{n_s e_0^2}{m}\vec{B}\right) = 0 \qquad \boxed{\nabla^2\vec{B} = \frac{1}{\lambda^2}\vec{B}}$$



$$\lambda = \sqrt{\frac{m}{n_s\mu_0 e_0^2}}$$ vdorna globina

$$B(x) = B_0\, e^{-x/\lambda}$$

Izotopski efekt

$$T_c \sim M^{-\alpha}$$

Substance	α
Zn	0.45
Hg	0.50
Pb	0.49
Nb_3Sn	0.08
BCS theory	1/2

BCS teorija

John Bardeen   Leon Cooper Robert Schrieffer - Nobel 1972

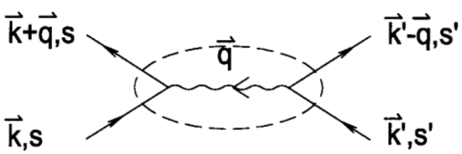


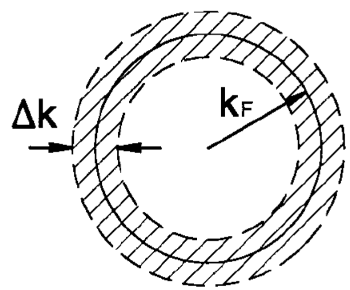
Theory of Superconductivity*

J. BARDEEN, L. N. COOPER,† AND J. R. SCHRIEFFER‡
Department of Physics, University of Illinois, Urbana, Illinois
(Received July 8, 1957)

Cooperjevi pari: privlačna interakcija med elektroni (blizu v energiji)

Standardni SP: posrednik mrežna nihanja





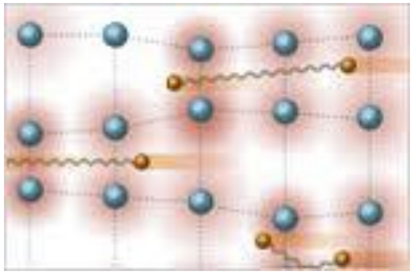
Fermijeva krogla

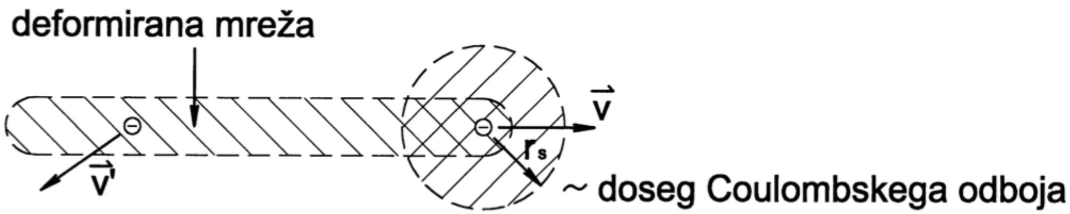
kako se izogniti Coulombskemu odboju ? retardacija bistvena !

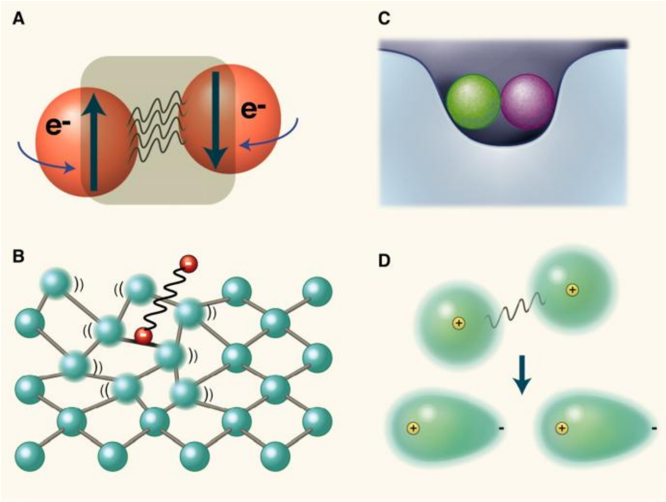
Cooperjevi pari

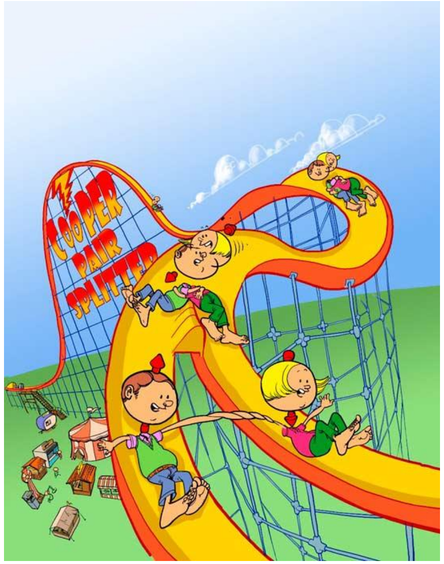
Standardni SP: par k, spin ↑ in -k, spin ↓

privlačna interakcija: posrednik fononi









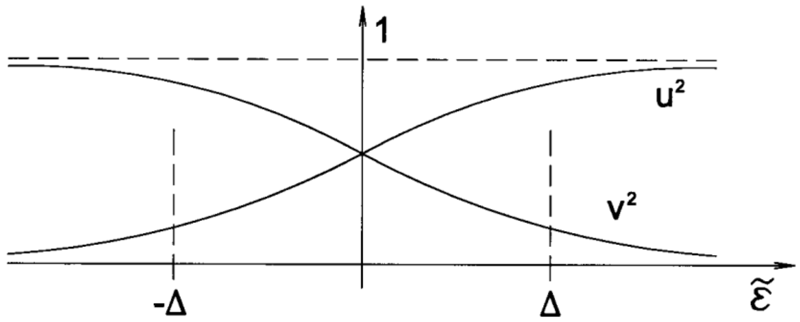
b) SP osnovno stanje - kolektivno stanje (vezanih) Cooperjevih parov

$$\Psi^0_{BCS} = \prod_{\vec{k}} (u_{\vec{k}} + v_{\vec{k}} b^+_{\vec{k}}) |\emptyset\rangle$$

BCS valovna funkcija

$$b^+_{\vec{k}} = c^+_{-\vec{k}\downarrow} c^+_{\vec{k}\uparrow}$$

$$\langle b_{\vec{k}} \rangle = u_{\vec{k}} v_{\vec{k}} = \frac{1}{2} \sin\vartheta_{\vec{k}} = \frac{\Delta}{2E_{\vec{k}}}$$



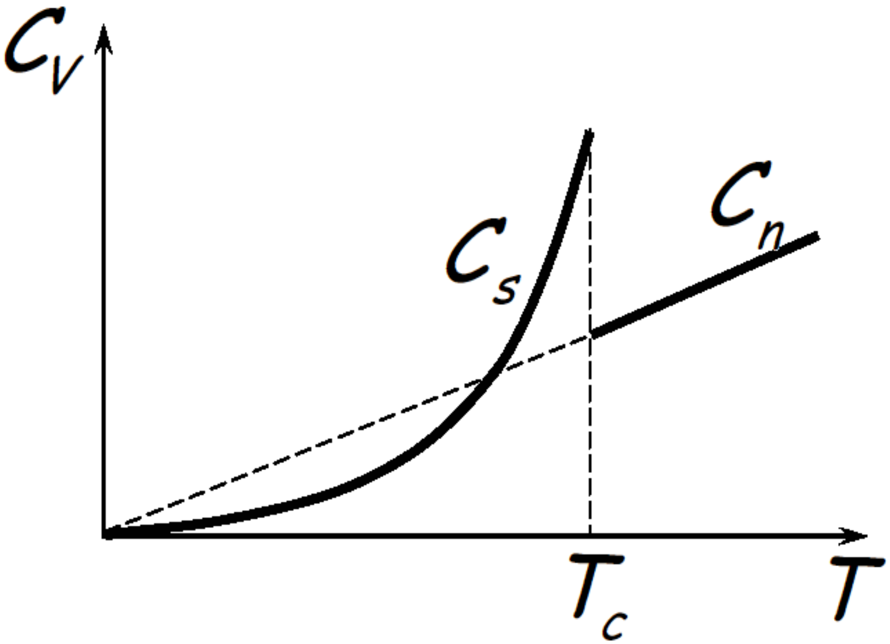
$$E_{\vec{k}} = \sqrt{\tilde{\epsilon}^2_{\vec{k}} + \Delta^2}$$

energijska vrzel Δ – gap

s wave pairing

$$\boxed{2\Delta(0) \simeq 3.5 k_B T_c}$$

Specifična toplota ima skok (prehod II. reda)



$$C_n(T) = \gamma T$$

$$C_s(T) = A\,T^{-3/2} e^{-\Delta_0 / k_B T}$$

vrzel

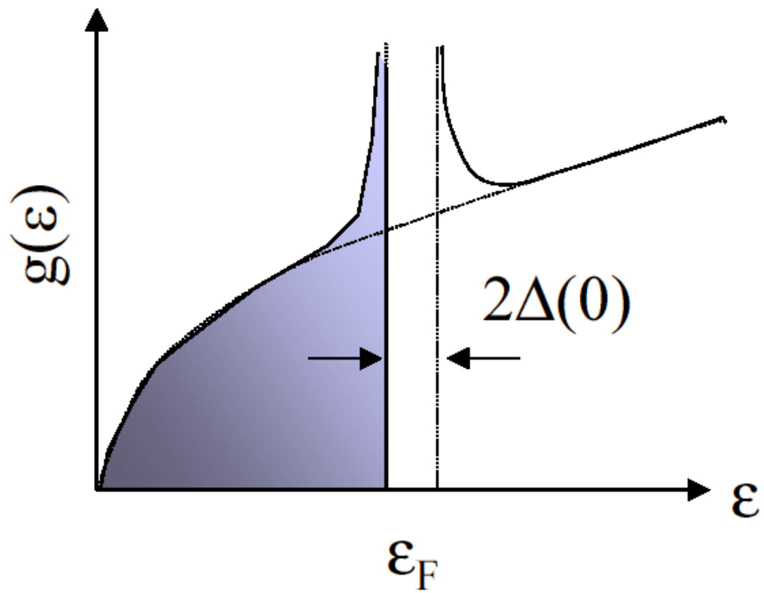
$$\boxed{\left.\frac{C_{es} - \gamma T_c}{\gamma T_c}\right|_{T_c} = 1.52}$$

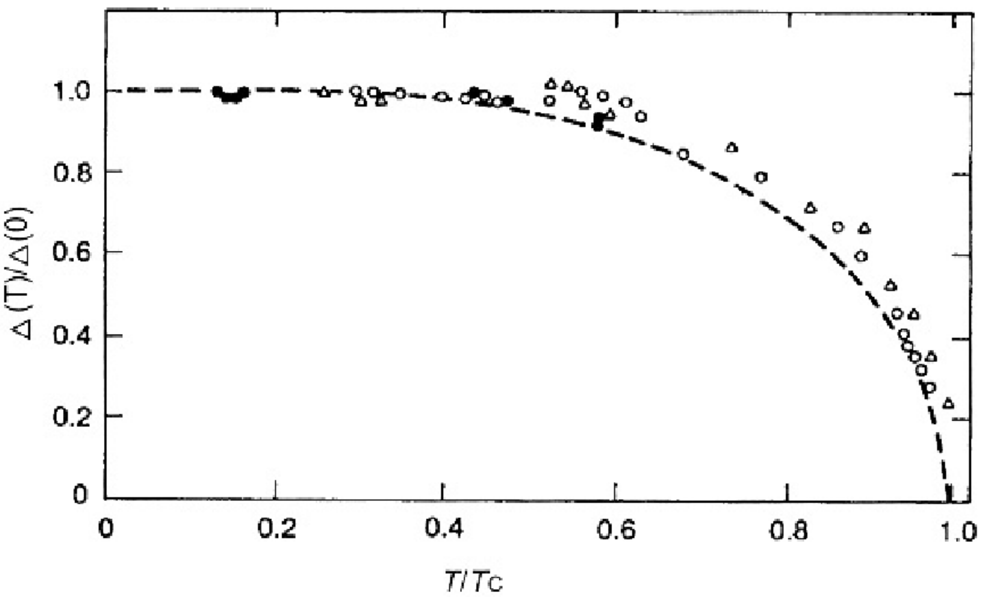
BCS relacija–

ekperimentalno velja za standardne SP

Energijska vrzel - gap

gostota energijskih stanj elektronov





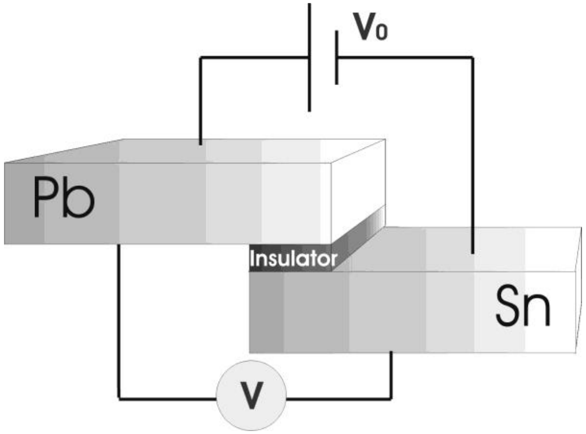
gap merljiv z absopcijskimi eksperimenti – EM valovanje, ultrazvok

$h\nu < \Delta$ - ni absorpcije

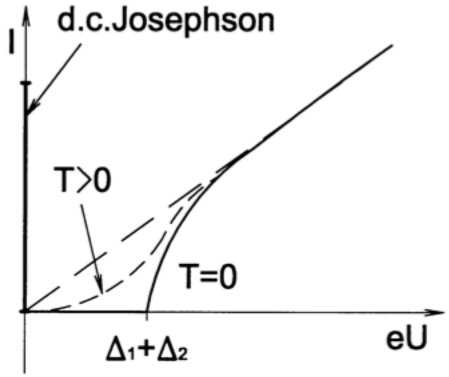
Makroskopska interferenca - Josephsonovi efekti 1962

Nobel 1973: Ivar Giaever, Leo Esaki, Brian Josephson

B. Josephson: "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"

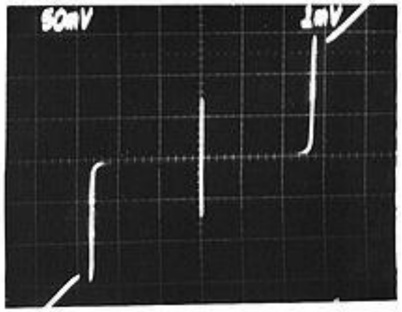


SIS junction



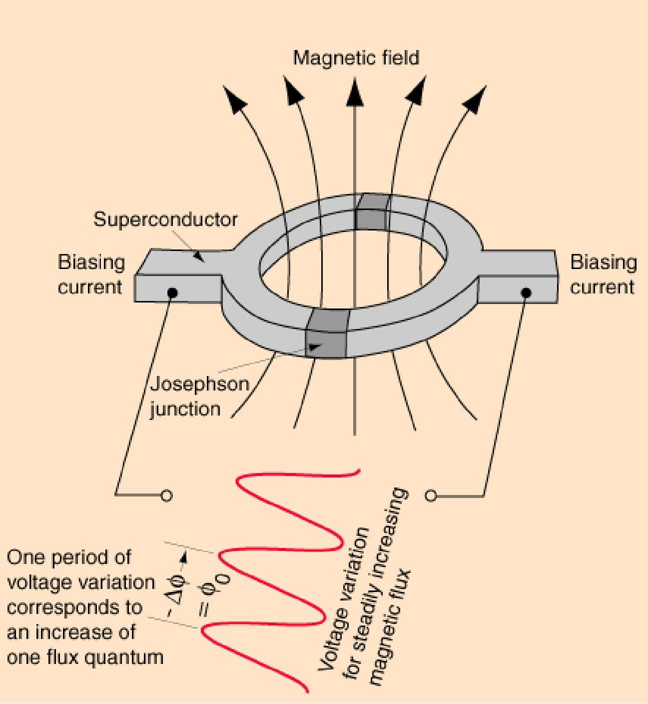
a.c. Josephson efekt

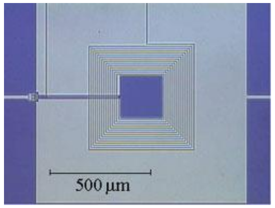
$$I = I_0 \sin \omega_0 t \ , \qquad \omega_0 = \frac{2e_0}{\hbar} U$$



SQUID: superconducting quantum interference device

$$\Phi_0 = \frac{h}{2e_0} = 2,0678.10^{-15} Tm^2$$





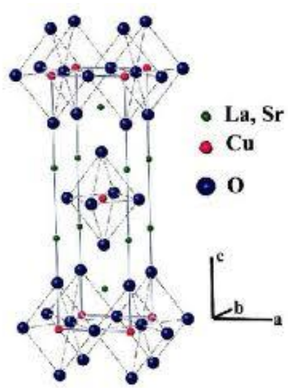
SQUID

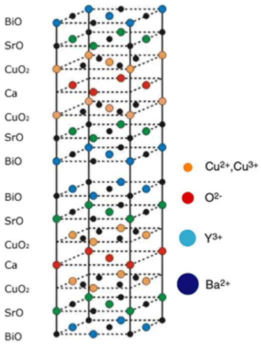
magnetometer

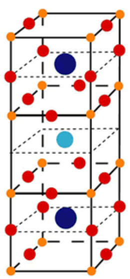
HTC – visokotemperaturna superprevodnost

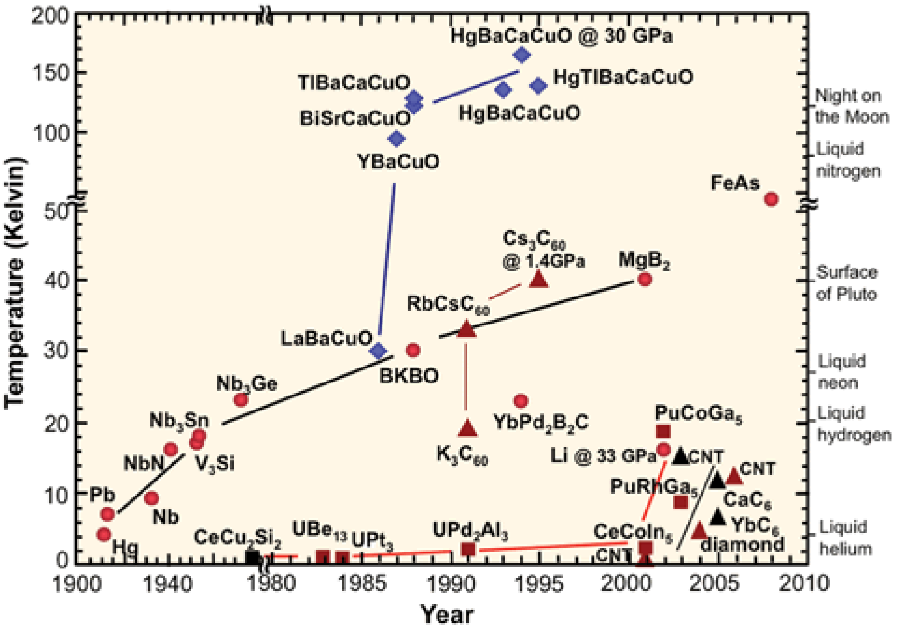
G. Bednorz and K.A. Mueller 1986

25 let

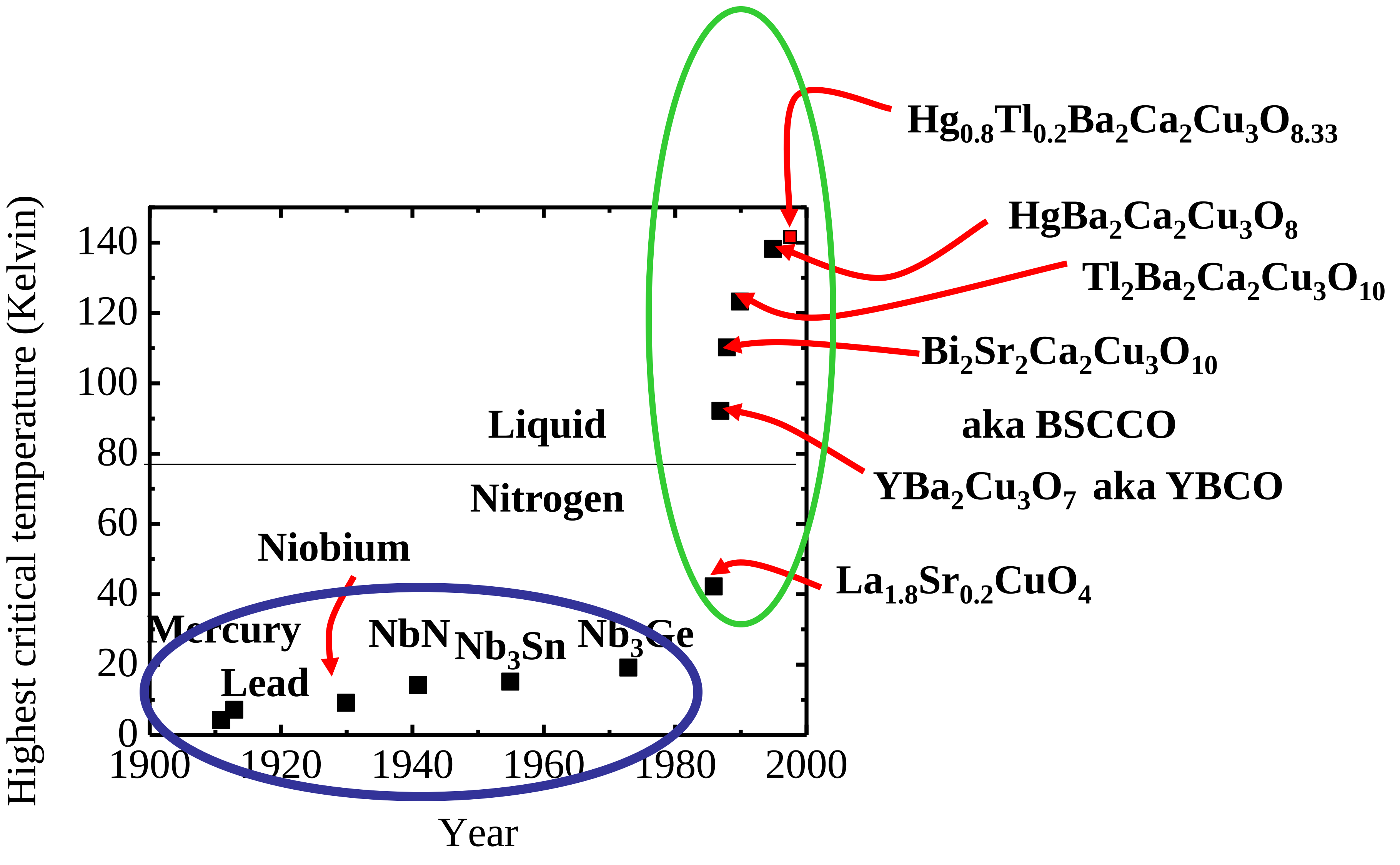






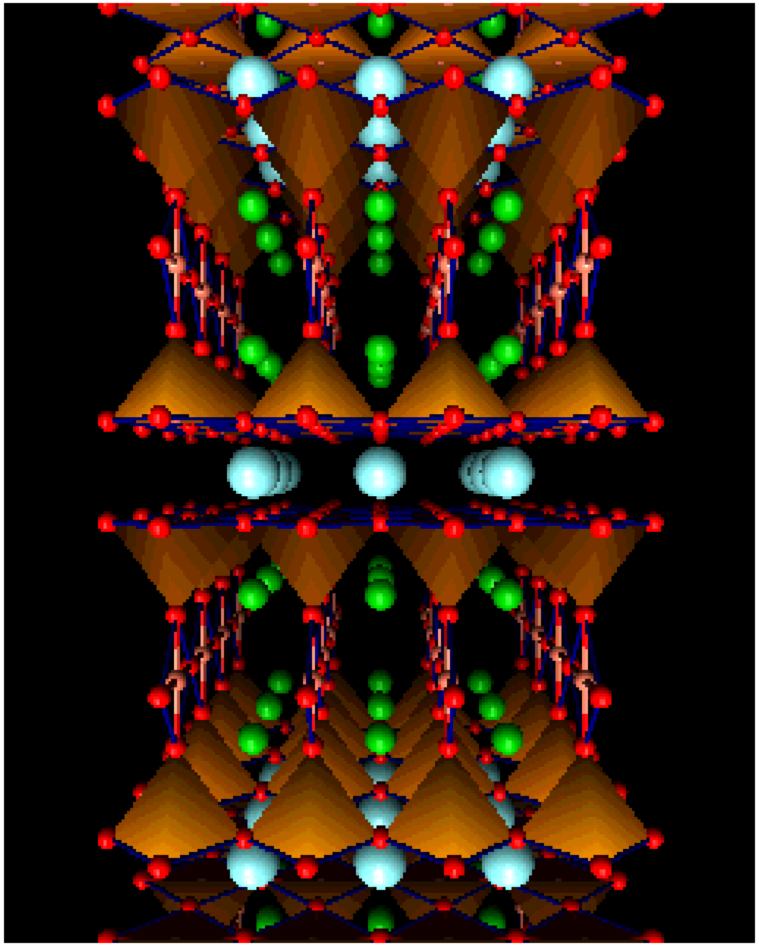


LaSrCuO BiSrCaCuO YBaCuO

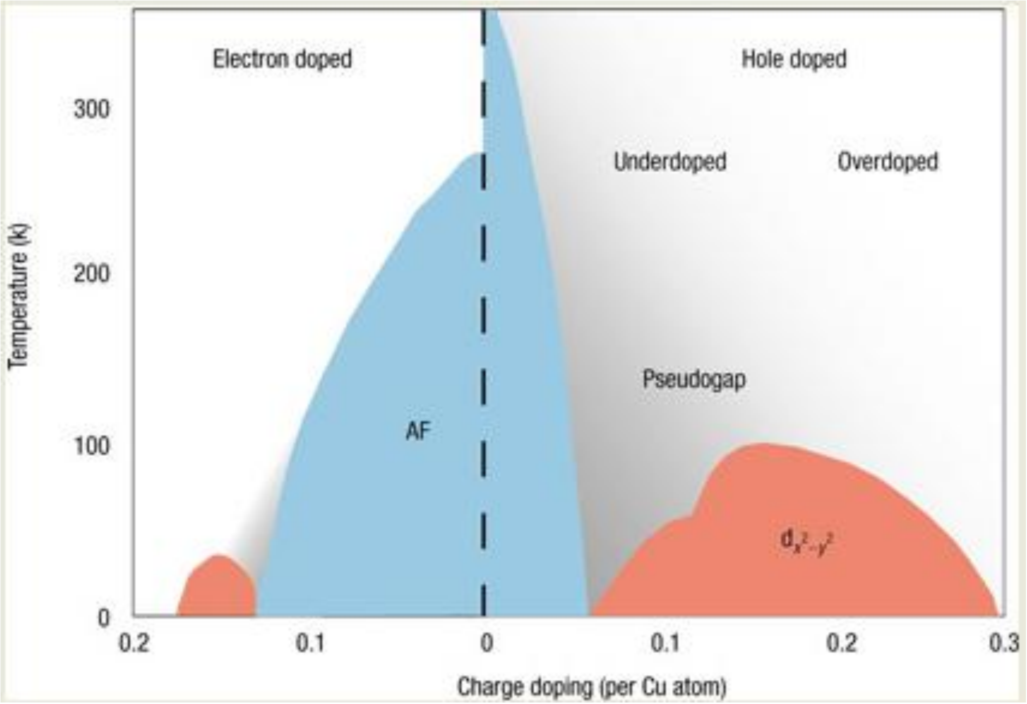


$Hg_{0.8}Tl_{0.2}Ba_2Ca_2Cu_3O_{8.33}$
$HgBa_2Ca_2Cu_3O_8$
$Tl_2Ba_2Ca_2Cu_3O_{10}$
$Bi_2Sr_2Ca_2Cu_3O_{10}$
aka BSCCO
$YBa_2Cu_3O_7$ aka YBCO
$La_{1.8}Sr_{0.2}CuO_4$
Liquid
Nitrogen
Niobium
Mercury
Lead
NbN
Nb_3Sn
Nb_3Ge
Highest critical temperature (Kelvin)
Year
0
20
40
60
80
100
120
140
1900
1920
1940
1960
1980
2000

Ravnine CuO



Kuprati – fazni diagram



nedopirani kuprati:

Mottovi izolatorji, antiferomagneti

dopirani kuprati: dopirani Mottovi izolatorji

nekonvencionalna (d-wave) SP, mehanizem – spinske fluktuacije, AFM magnoni

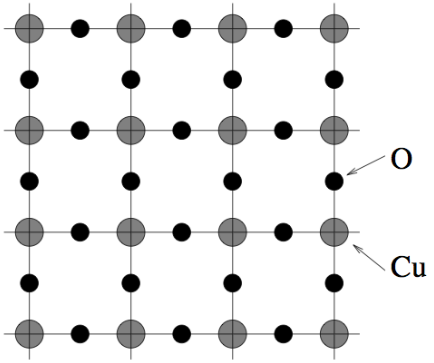
anomalne lastnosti v N stanju, non-Fermi liquid, **energijska pseudovrzel**

Mikroskopski kvantni model: kuprati

preskakovanje elektronov med mesti (kovina) +

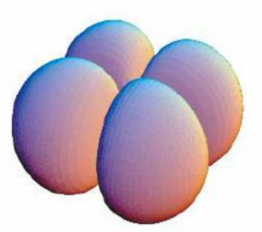
močan Coulombski odboj med elektroni **močne korelacije: U >> t**

nedopiran sistem = 1 elektron (vrzel) = Mottov izolator

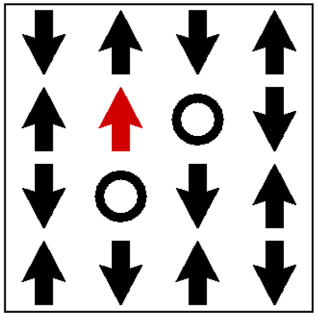


Cu: d orbitala $x^2 – y^2$

1 orbitala / osnovno celico



2D kvadratna mreža

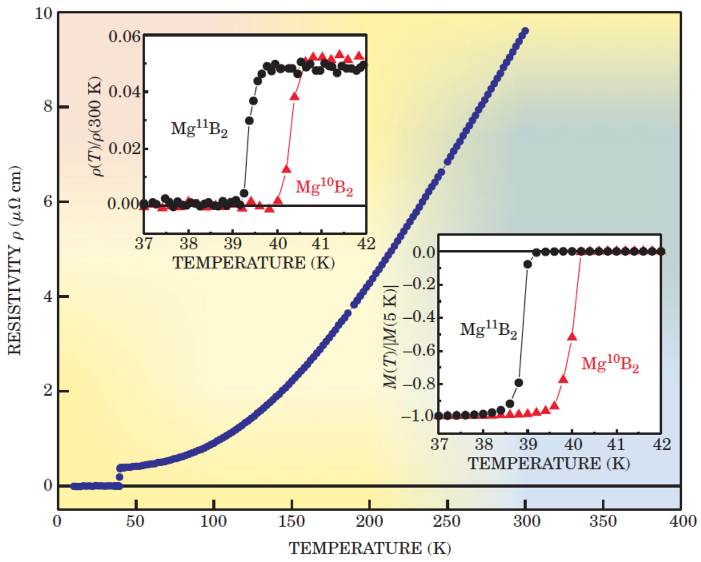


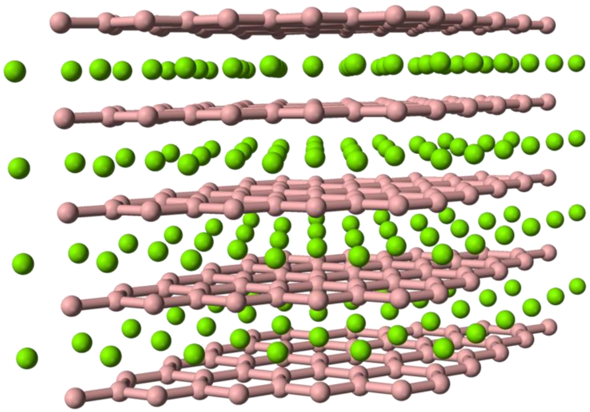
Intermezzo – Mg B_2

Jun Akimitsu: 2001

better late than never

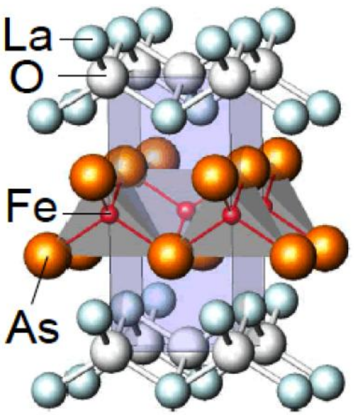
standardni s – tip SP: fononski mehanizem





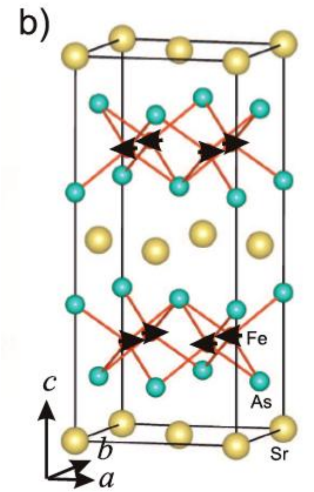
Pniktidi – spojine železa

1111 družina

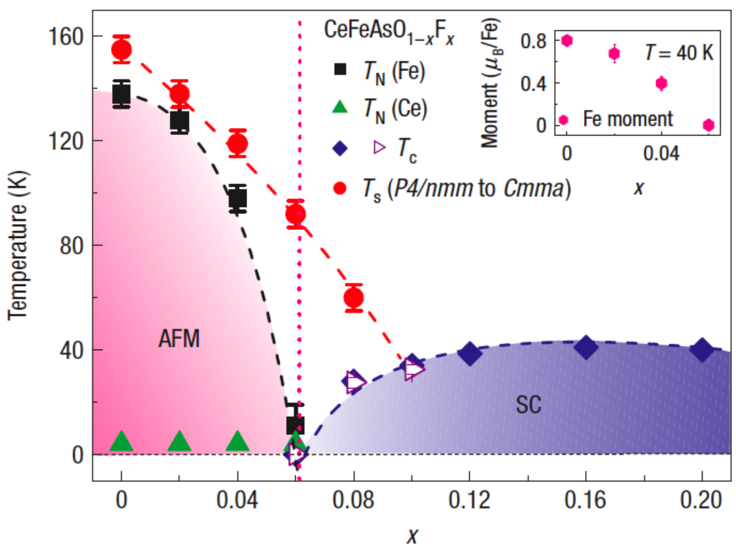


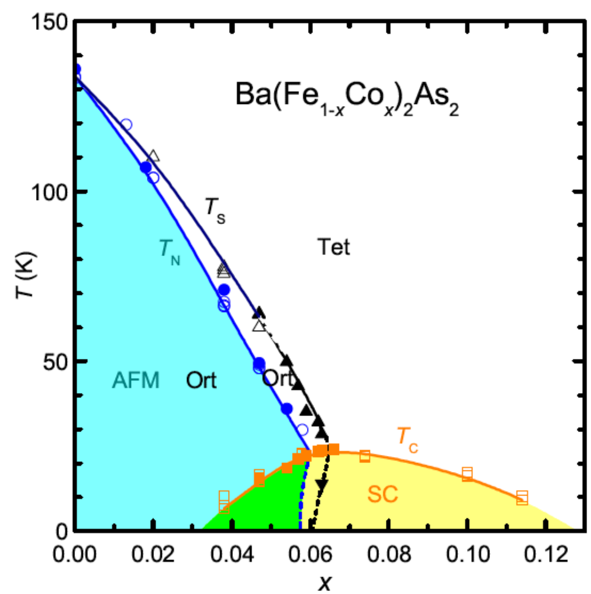
Kamihara, Hosono et al. (08)

122 družina



pnictogen: skupina 5 – N, P, As, Sb





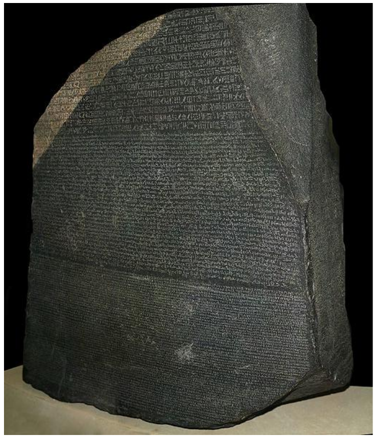
Visoko (nizko) – temperaturni SP

Transition temperatures of well-known superconductors (Boiling point of liquid nitrogen for comparison)

Transition temperature (in kelvins)	Material	Class
133	$HgBa_2Ca_2Cu_3O_x$	Copper-oxide superconductors
110	$Bi_2Sr_2Ca_2Cu_3O_{10}$(BSCCO)	
90	$YBa_2Cu_3O_7$ (YBCO)	
77	Boiling point of liquid nitrogen	
55	SmFeAs(O,F)	Iron-based superconductors
41	CeFeAs(O,F)	
26	LaFeAs(O,F)	
20	Boiling point of liquid hydrogen	
18	Nb_3Sn	Metallic low-temperature superconductors
10	NbTi	
9.2	Nb	
4.2	Hg (mercury)	

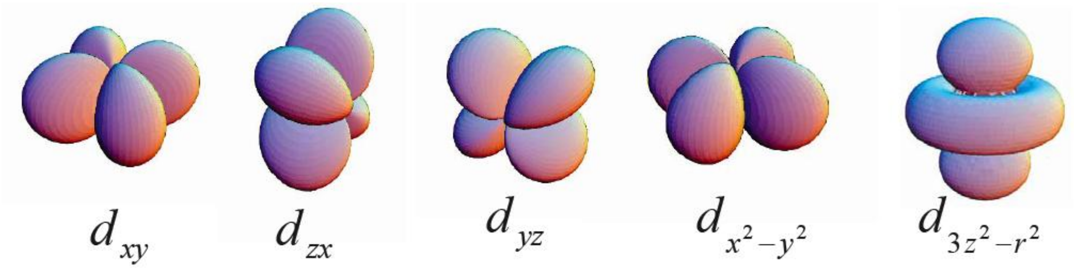
Železovi pniktidi: kuprati

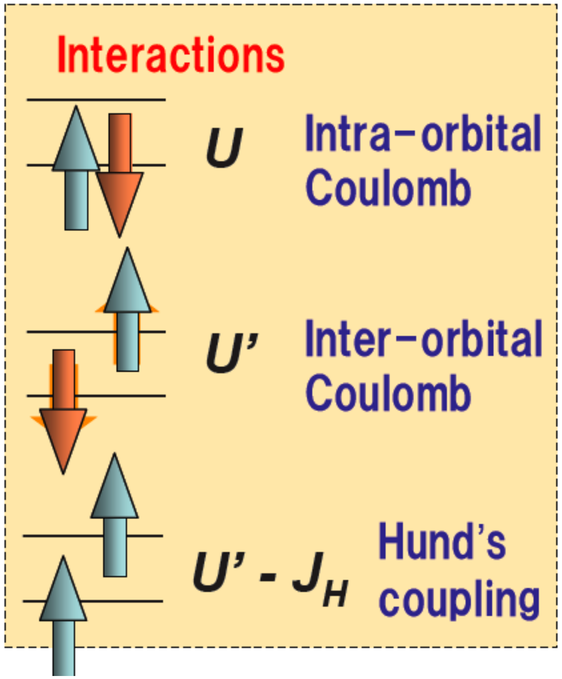
- podobnosti: fazni diagram, magnetne lastnosti nekonvencionalna SP, transportne lasnosti – NFL
- razlike: mikroskopski model – več pasov, več orbital
- **Rosetta plošča za razumevanje HTC ?**



Železovi pniktidi: mikroskopsko modeliranje

Fe d orbitale





večorbitalni Hubbardov model

Pniktidi: globalna fizika – novi igralci

Electronic Structure of the $BaFe_2As_2$ Family of Iron Pnictides

M. Yi,[1,2] D. H. Lu,[1,2] J. G. Analytis,[3] J.-H. Chu,[3] S.-K. Mo,[2,4] R.-H. He,[1,2] X. J. Zhou,[5] G. F. Chen,[5] J. L. Luo,[5] N. L. Wang,[5] Z. Hussain,[4] D. J. Singh,[6] I. R. Fisher,[3] and Z.-X. Shen[1,2,*]

Low Energy Spin Waves and Magnetic Interactions in $SrFe_2As_2$

Jun Zhao,[1] Dao-Xin Yao,[2] Shiliang Li,[1] Tao Hong,[3] Y. Chen,[4] S. Chang,[4] W. Ratcliff II,[4] J. W. Lynn,[4] H. A. Mook,[3] G. F. Chen,[5] J. L. Luo,[5] N. L. Wang,[5] E. W. Carlson,[2] Jiangping Hu,[2] and Pengcheng Dai[1,3,*]

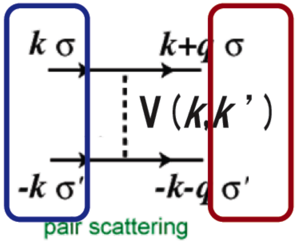
Spin waves and magnetic exchange interactions in $CaFe_2As_2$

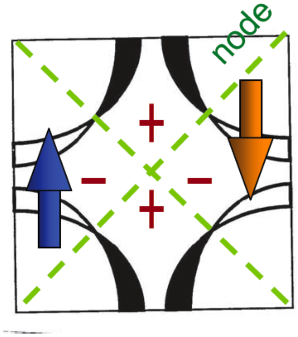
Jun Zhao[1], D. T. Adroja[2], Dao-Xin Yao[3], R. Bewley[2], Shiliang Li[1,4], X. F. Wang[5], G. Wu[5], X. H. Chen[5], Jiangping Hu[3] and Pengcheng Dai[1,4,6★]

Superprevodnost samo iz odbojnih interakcij ?

odboj – anizotropna SP: BCS gap enačba

$$\Delta(\boldsymbol{k}) = -\sum_{\boldsymbol{k}'} V(\boldsymbol{k},\boldsymbol{k}') \frac{\Delta(\boldsymbol{k}')}{2E(\boldsymbol{k}')} \tanh\left(\frac{1}{2}\beta E(\boldsymbol{k}')\right)$$

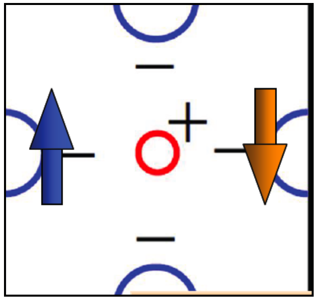




privlak, če Δ menja znak – **d wave**

kuprati:

zakaj T_c tako visok (nizek) ? $T_c \sim \omega_D \sim J \sim 0.1$ t



Fe pniktidi - s+- tip

What do we expect from theory ?

Trivial: If an elegant theory agrees with experiment, there is nothing to worry about.

Heisenberg: If an elegant theory does not agree with experiment, the experiment is wrong.

Bohr (compromise): If an elegant theory disagrees with experiment, the case is not lost, since by improving theory one can make it agree with experiment.

Dirac: If an inelegant theory agrees with experiment, the case is hopeless.

Fenomenološka teorija superprevodnikov

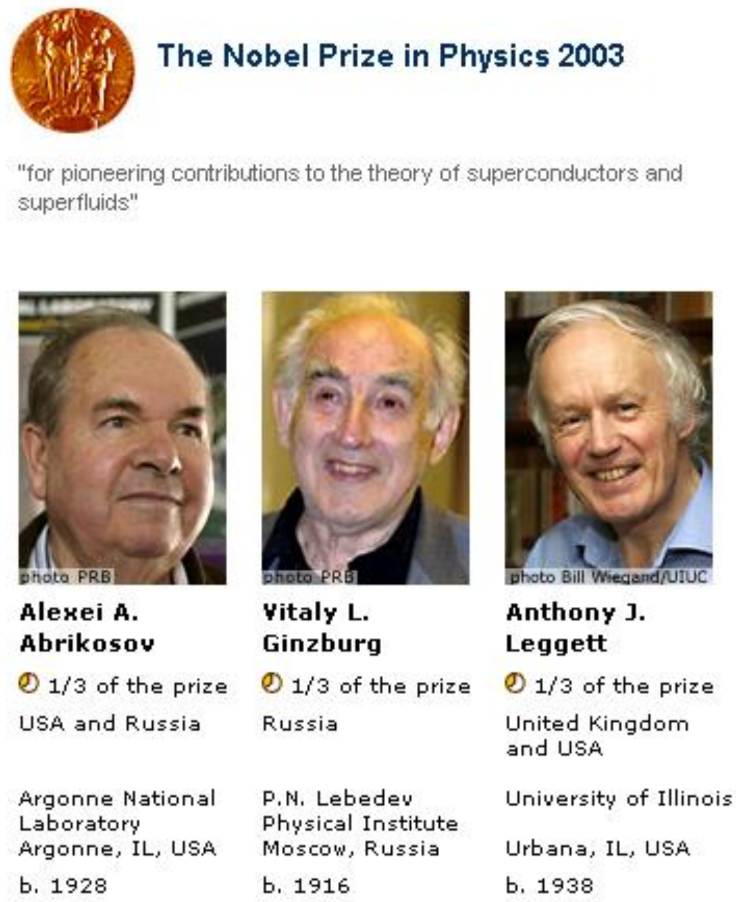
in supertekočin

Aleksej Abrikosov,

Vitalij Ginzburg

in Anthony Leggett

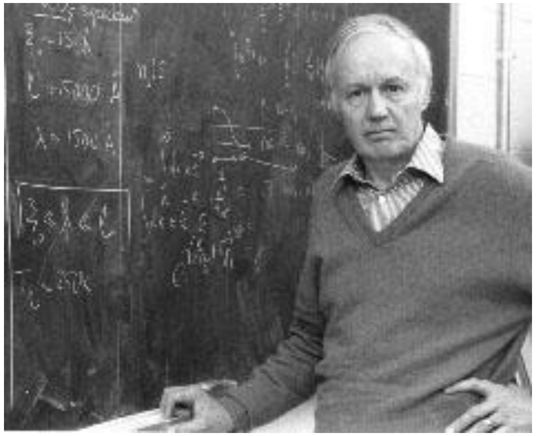
for pioneering contribution to the theory of superconductors and superfluids



L. Landau (v zaporu)

L.Gorkov, A. Abrikosov, I.Dzialoshinski

V. Ginzburg



A. Leggett

Predhodnica

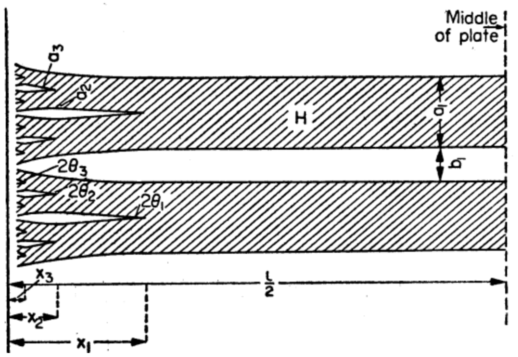
F. in H. London (1935): Idealna prevodnost + Meissnerjev efekt

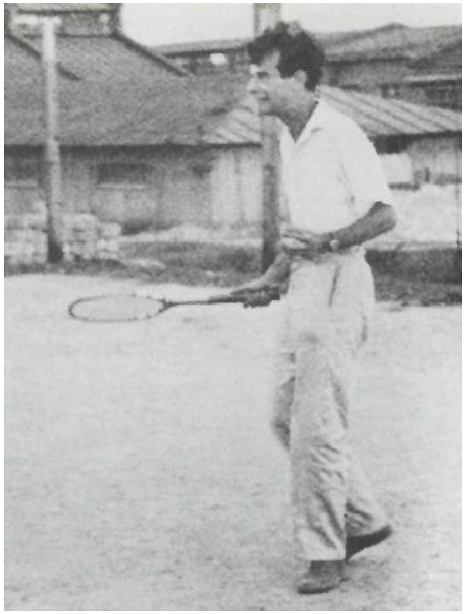
$$\nabla^2 \mathbf{B} = \frac{1}{\lambda_L^2}\mathbf{B}$$

vdorna globina $\lambda_L^2 = \frac{m}{\mu_0 e^2 n_s}$ gostota SP elektronov

L. Landau (1937, 1943) : teorija mešanega SP stanja

v prisotnosti magn. polja





L. Landau (1937): fenomenoška teorija zveznih faznih prehodov

ureditveni parameter

razvoj proste energije po UP

Fenomenološka teorija SP Ginzburga in Landaua (1950)

ureditveni parameter kompleksen $\Psi(\vec{r})$ efektivna v.f. SP elektronov

$|\Psi|^2 = n_s$ gostota SP elektronov

$$\boxed{f = f_0 + \alpha|\Psi|^2 + \frac{\beta}{2}|\Psi|^4 + \frac{1}{2m^*}|(-i\hbar\nabla - e^*\vec{A})\Psi|^2 + \frac{1}{2\mu_0}B^2}$$

$$\alpha = \alpha_0(T - T_c)$$

prispevek magn.polja

GL $e^* = e_0$: ‘charge, which there is no reason to consider as different from the electronic charge’

Bardeen, Cooper, Schrieffer (57) $e^* = 2e_0$: Cooperjevi pari

GL enačbe

$$F = \int dV\, f(\Psi, \vec{A}) = min$$

celotna prosta energija je minimalna

pogoj za magn. polje B (A) in v.f. Ψ

$$\boxed{\alpha\Psi + \beta|\Psi|^2\Psi + \frac{1}{2m^*}(i\hbar\nabla + e^*\vec{A})^2\Psi = 0}$$

$$\frac{1}{\mu_0}\nabla \times \vec{B} \equiv \vec{j} \quad = \quad \boxed{\frac{e^*\hbar}{2m^*i}[\Psi^*\nabla\Psi - \Psi\nabla\Psi^*] - \frac{e^{*2}}{m^*}|\Psi|^2\vec{A}}$$

vključuje enačbe Londonov

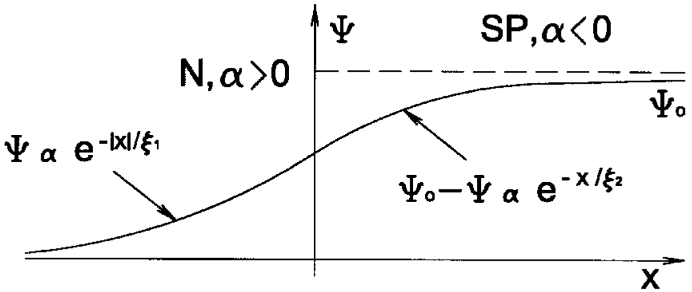
Značaj ureditvenega parametra

$\Psi = |\Psi| \mathrm{e}^{i\varphi}$ v SP stanju zlomljena zvezna umeritvena (gauge) simetrija

φ določen

Karakteristične dolžine in parametri

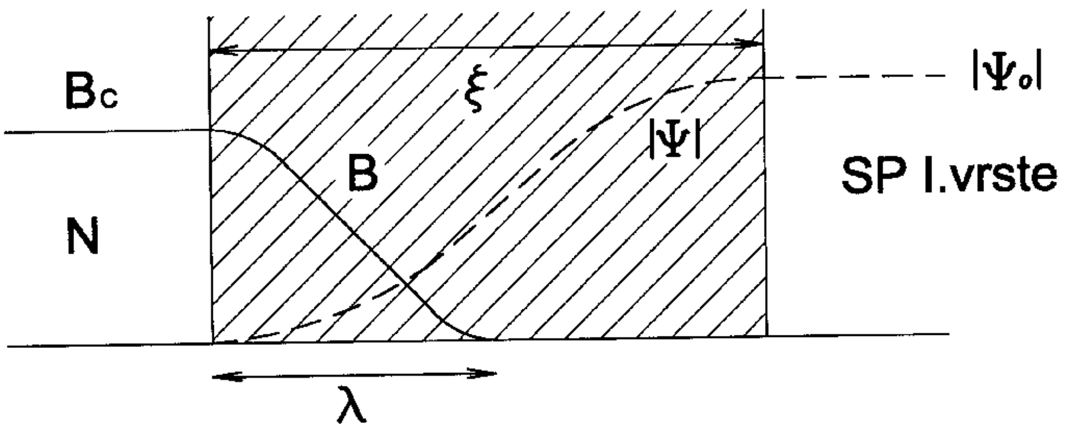
koherenčna dolžina $\xi(T) = \sqrt{\dfrac{\hbar^2}{2m^*|\alpha|}}$



vdorna globina polja $\lambda = \sqrt{\dfrac{m^*}{\mu_0 e^{*2}|\Psi_0|^2}} = \sqrt{\dfrac{m^*\beta}{\mu_0 e^{*2}|\alpha|}}$

GL parameter $\kappa = \lambda/\xi$

Energija domenske stene

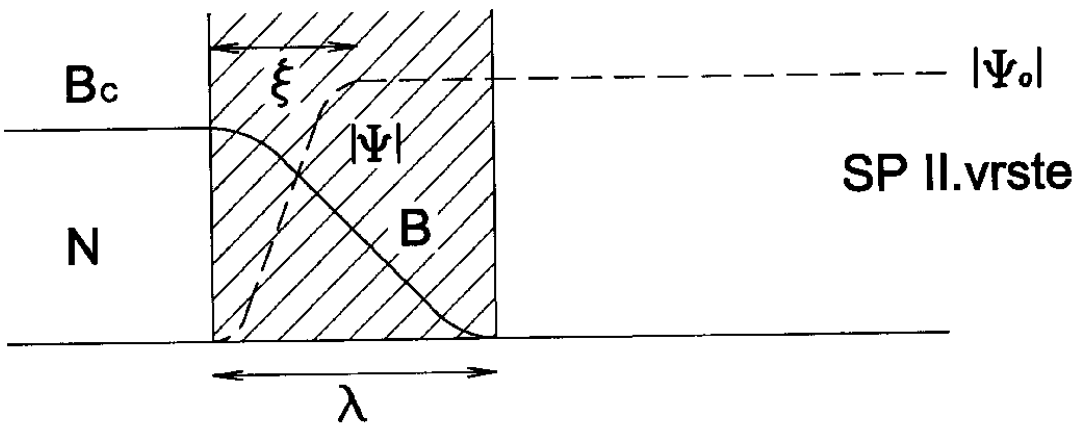


$\kappa < 1/\sqrt{2}, \delta > 0$

SP I. vrste:

B=0 v notranjosti

popoln Meissnerjev efekt



$\kappa > 1/\sqrt{2}, \delta < 0$

SP II. vrste:

B > 0 v notranjosti

nepopoln Meissnerjev efekt

GL: $\kappa < 1$: Hg $\kappa \sim 0.16$

$\kappa \gg 1$? ‘does not offer any intrinsic interest, we shall not discuss it’

О МАГНИТНЫХ СВОЙСТВАХ СВЕРХПРОВОДНИКОВ ВТОРОЙ ГРУППЫ

А. А. Абрикосов

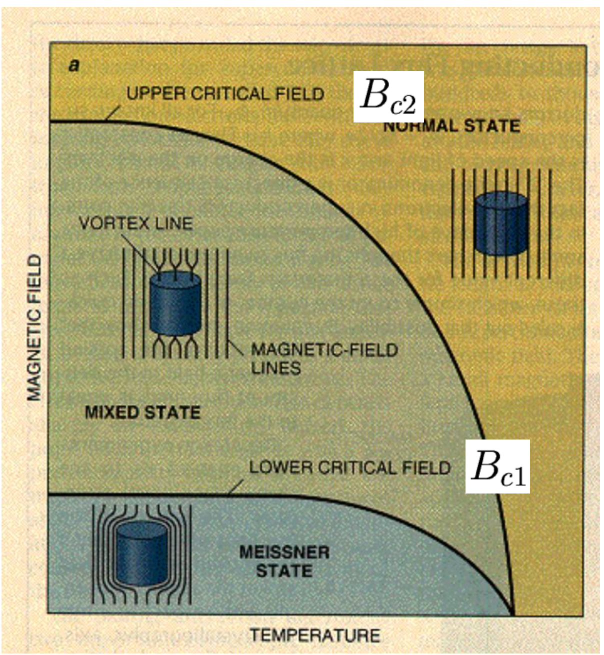
Рассматриваются магнитные свойства массивных сверхпроводников, для которых параметр ϰ, введенный в теории Гинзбурга и Ландау, больше $1/\sqrt{2}$ (сверхпроводники второй группы). Полученные данные объясняют ряд опытных закономерностей поведения сверхпроводящих сплавов в магнитном поле.

В работе автора [1] уже было отмечено, что из квазимикроскопической теории сверхпроводимости Гинзбурга и Ландау [2] можно сделать вывод о наличии двух групп сверхпроводников. Для сверхпроводников первой группы параметр ϰ, входящий в теорию Гинзбурга и Ландау, меньше $1/\sqrt{2}$, для сверхпроводников второй группы он больше $1/\sqrt{2}$.

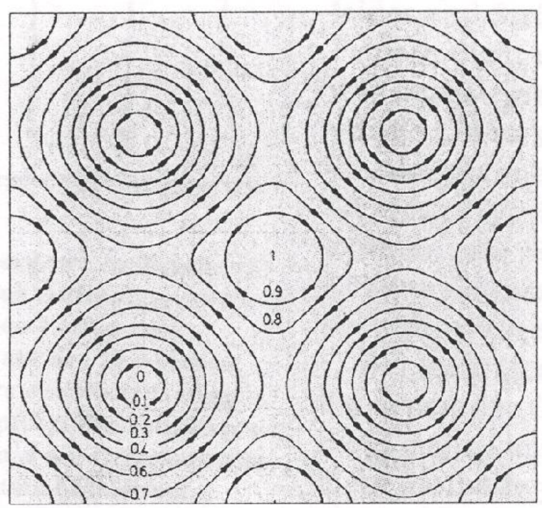
Teorija SP II. vrste:

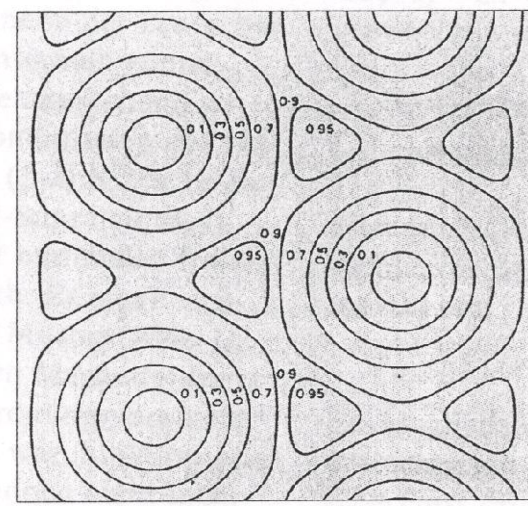
Abrikosov (1957)

$$\boxed{\kappa > 1/\sqrt{2}, \delta < 0}$$



$$B_{c1} < B < B_{c2}$$





Abrikosov 57: quadratic lattice

unstable !

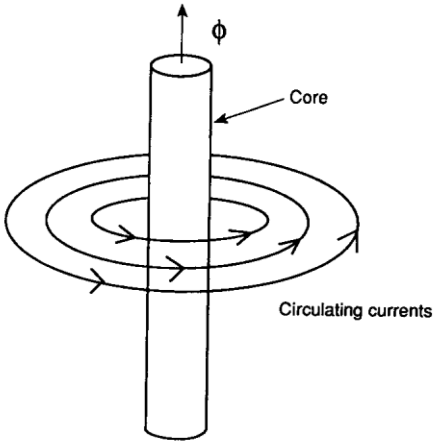
triangular lattice

Vrtinčne niti – vortex lines

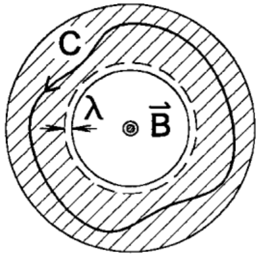
$$B_{c1} < B < B_{c2}$$

$B \sim B_{c1}$
posamezne

vrtinčne niti



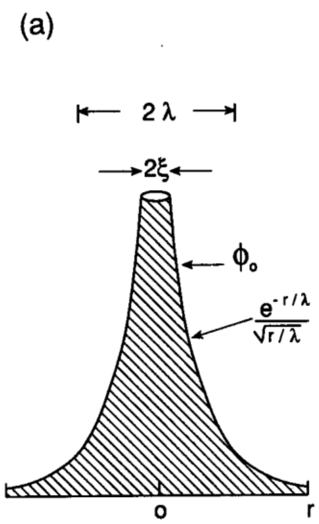
$$\oint_C d\vec{r} \cdot [\hbar \nabla \varphi - e^* \vec{A}] \;=\; 0$$

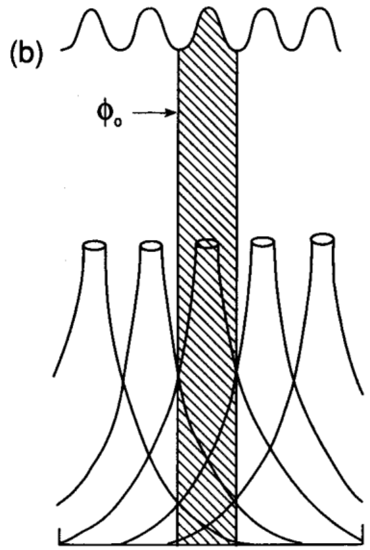


$$\Phi_n = 2\pi n \frac{\hbar}{e^*} = n\Phi_0$$

kvantizacija

magn. pretoka

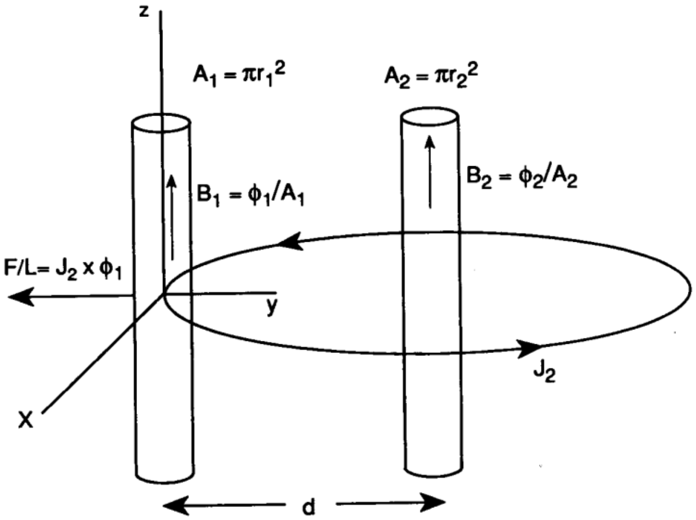




$B \sim B_{c2}$

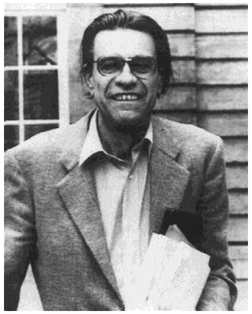
gosta mreža vrtincev

Gibanje vrtincev



energija dveh vrtincev

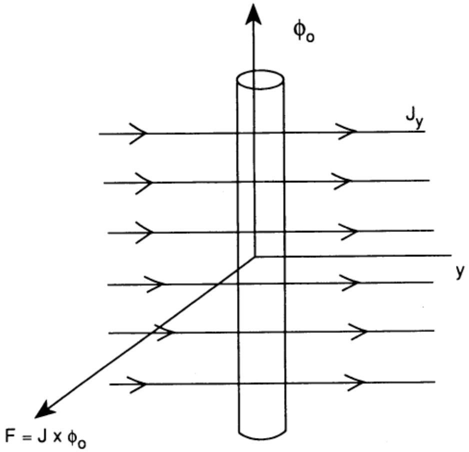
de Gennes



$$\boxed{\mathbf{F}/L = \mathbf{J} \times \mathbf{\Phi}_0}$$

sila na vrtinec pri homogenem toku

Lorentz



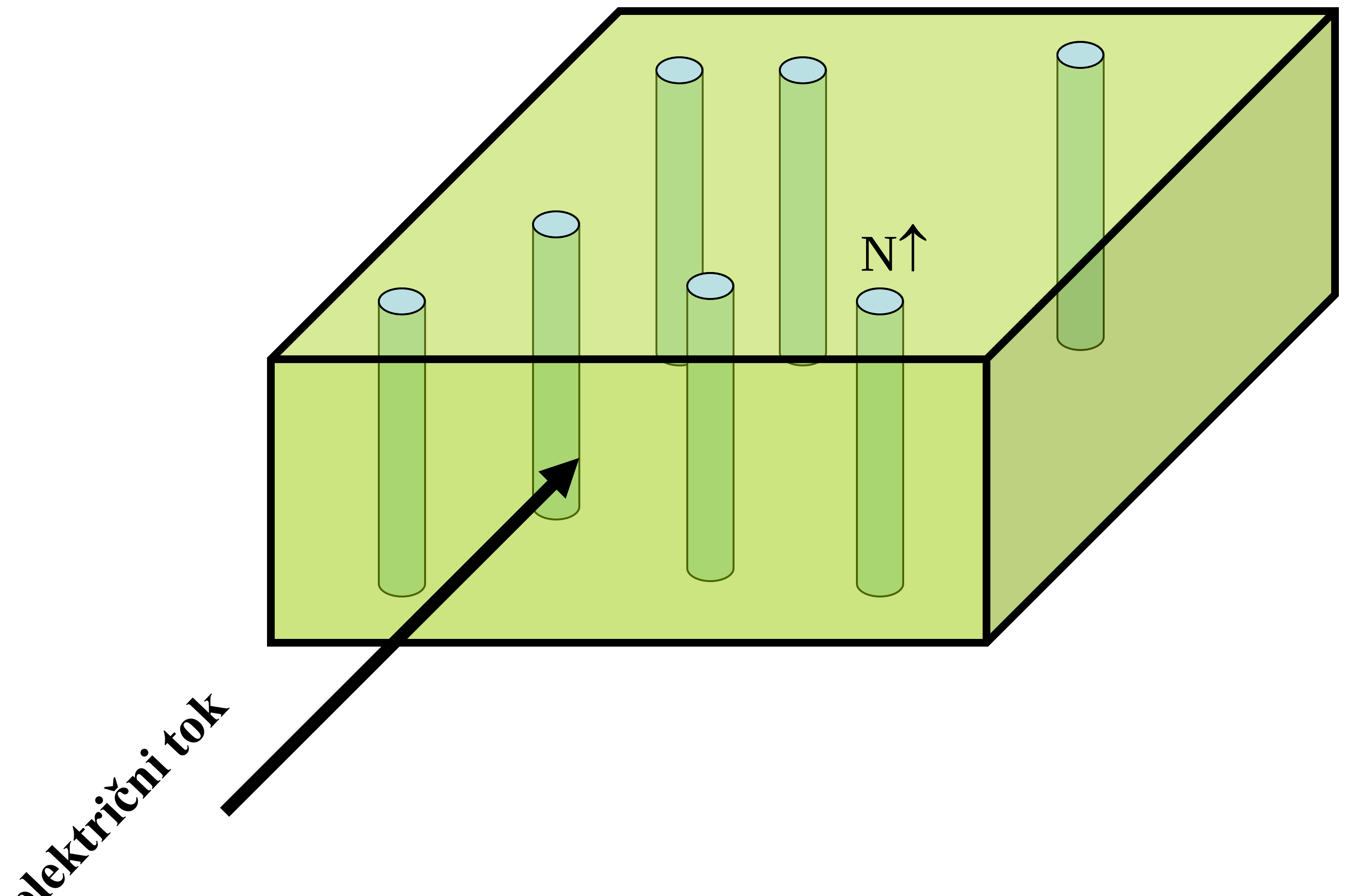
$$\boxed{\mathbf{E} = \mathbf{v}_\phi \times \mathbf{B} \parallel \mathbf{J} \rightarrow \rho > 0}$$

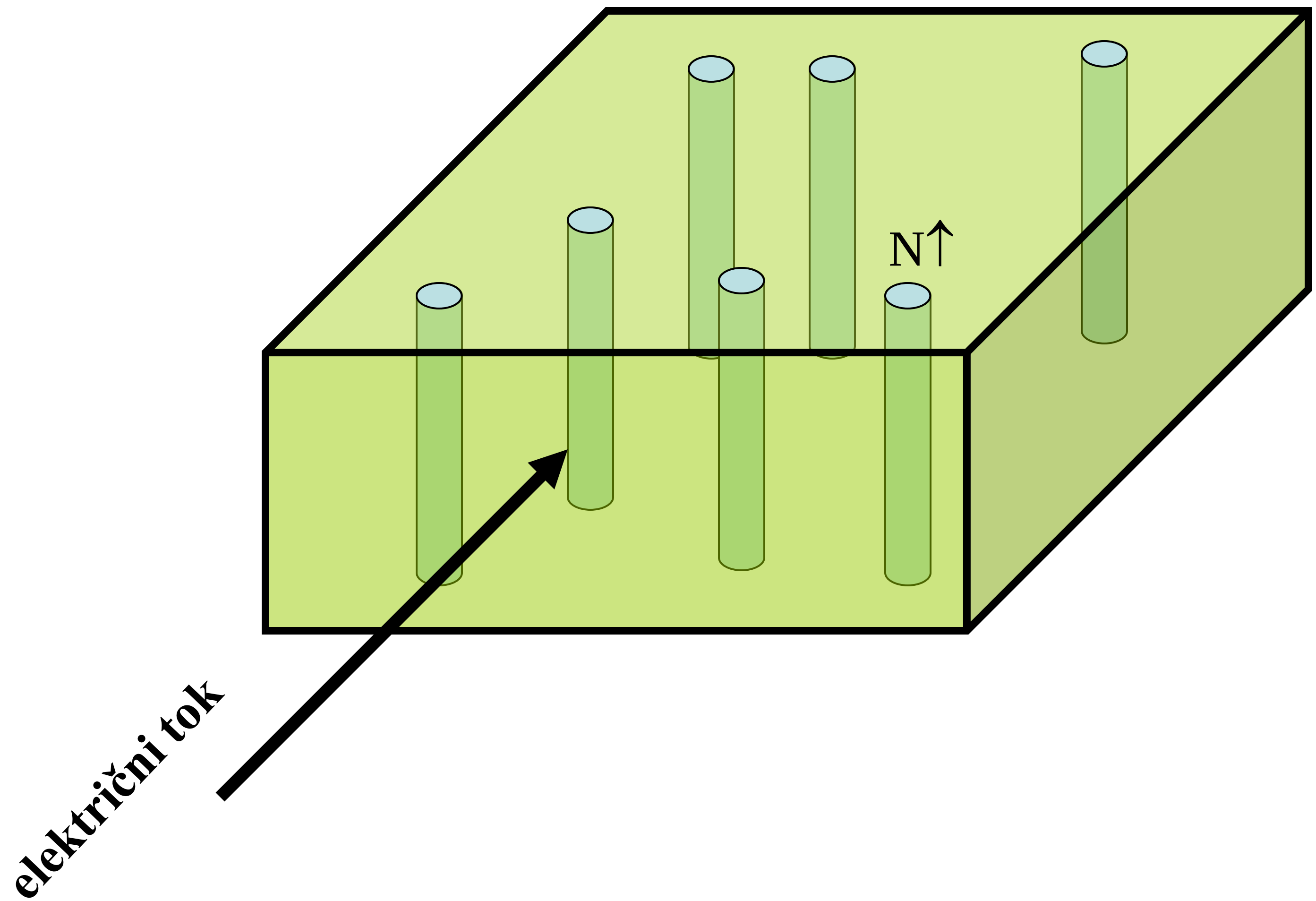
gibanje vrtincev povzroča

električni upor ρ>0

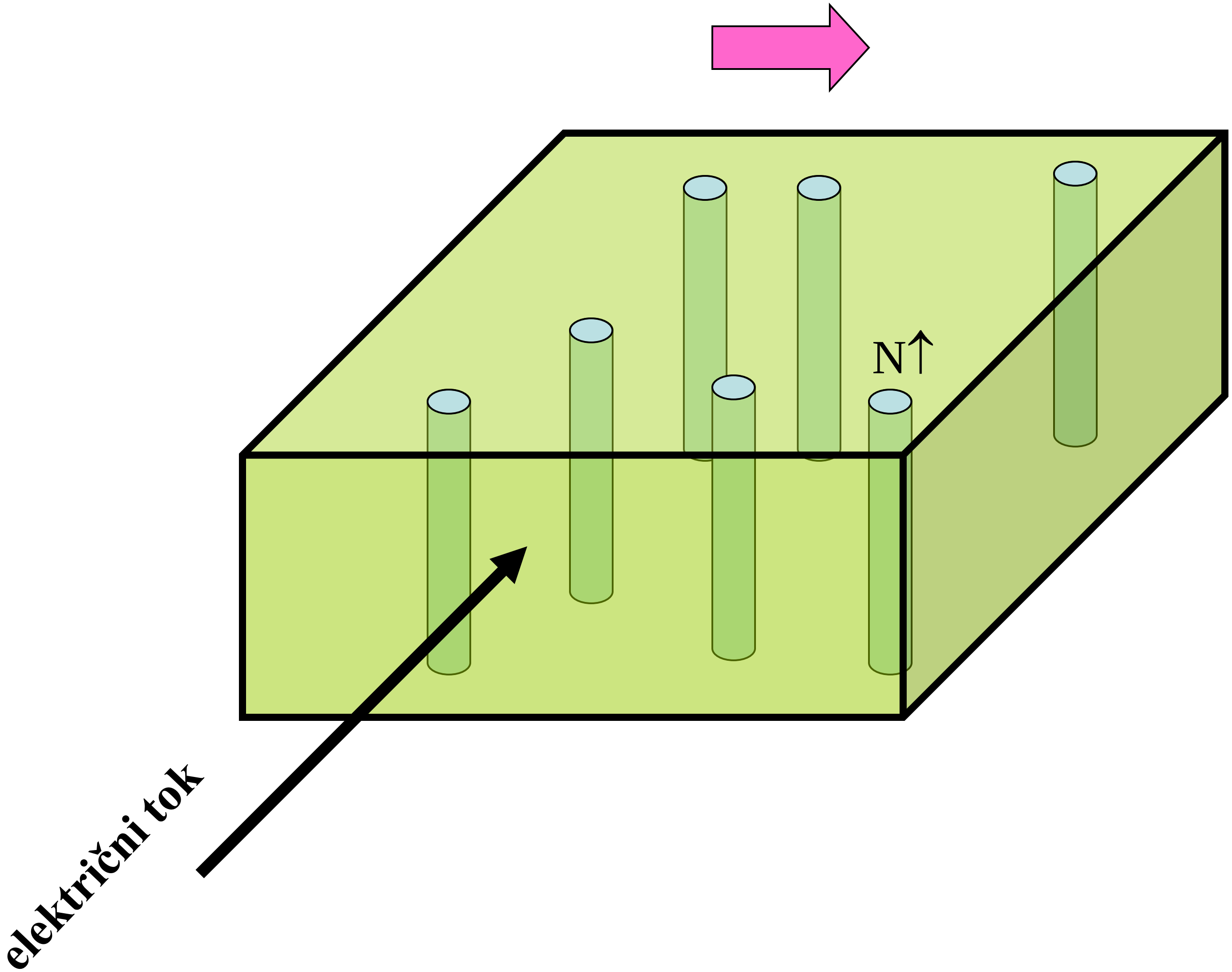
za idealno prevodnost ρ=0 potrebno

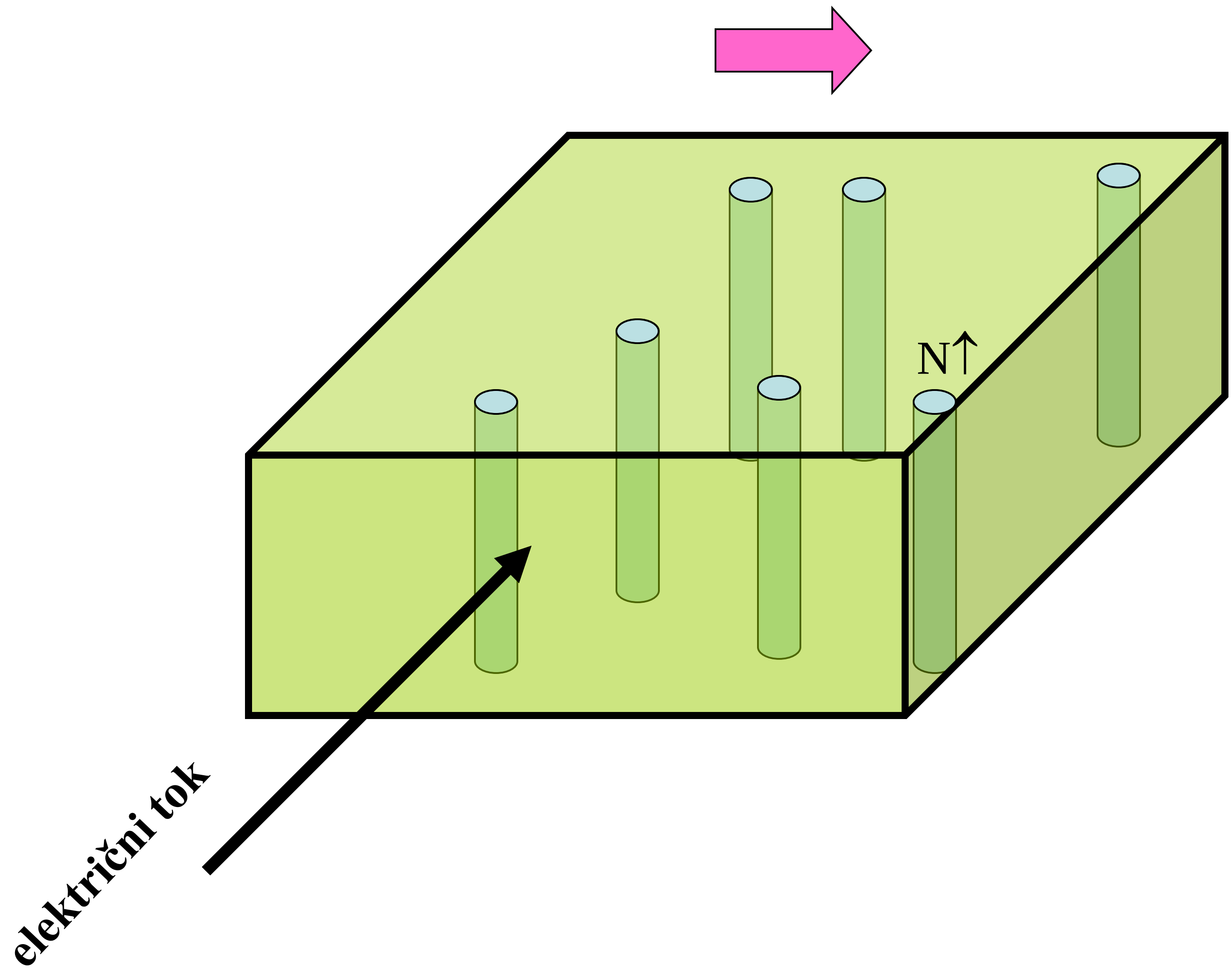
pripetje (pinning) vrtincev !


N↑
električni tok



N↑
električni tok


N↑
električni tok


N↑
električni tok

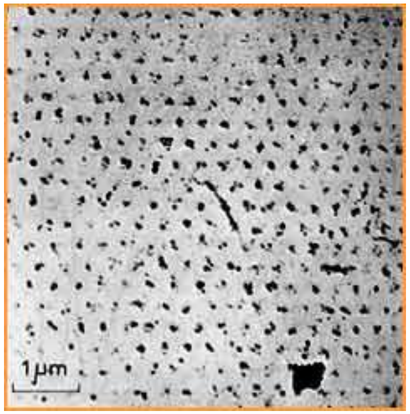
Superprevodne snovi

Table 9.1 Coherence Length ξ, Penetration Depth λ, and Ginzburg–Landau Parameter κ of Various Superconductors[a]

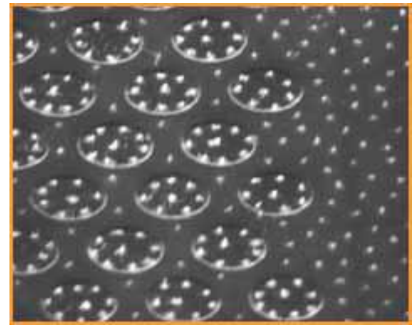
Material	T_c (K)	ξ (nm)	λ (nm)	κ (λ/ξ)	Source
Cd	0.56	760	110	0.14	Meservey and Schwartz (1969)
Al[a]	1.18	550	40	0.03	Table 9.2
In[a]	3.41	360	40	0.11	Table 9.2
Sn[a]	3.72	180	42	0.23	Table 9.2
Ta	4.4	93	35	0.38	Buckel (1991)
Pb[a]	7.20	82	39	0.48	Table 9.2
Nb[a]	9.25	39	50	1.28	Table 9.2
Pb–In	7.0	30	150	5.0	Orlando and Delin (1991)
Pb–Bi	8.3	20	200	10	Orlando and Delin (1991)
Nb–Ti	9.5	4	300	75	Orlando and Delin (1991)
Nb–N	16	5	200	40	Orlando and Delin (1991)
$PbMo_6S_8$ (Chevrel)	15	2	200	100	Orlando and Delin (1991)
V_3Ga (*A*15)	15	≈ 2.5	90	≈ 35	Orlando and Delin (1991)
V_3Si (*A*15)	16	3	60	20	Orlando and Delin (1991)
Nb_3Sn (*A*15)	18	3	65	22	Orlando and Delin (1991)
Nb_3Ge (*A*15)	23.2	3	90	30	Orlando and Delin (1991)
K_3C_{60}	19	2.6	240	92	Holczer *et al.* (1991)
Rb_3C_{60}	29.6	2.0	247	124	Sparn *et al.* (1992)
$(La_{0.925}Sr_{0.075})_2CuO_4$[b]	37	2.0	200	100	Poole *et al.* (1988)
$YBa_2Cu_3O_7$[b]	89	1.8	170	95	Poole *et al.* (1988)
HgBaCaCuO	126	2.3			Gao *et al.* (1993)
$HgBa_2Ca_2Cu_3O_{8+\delta}$	131			100	Schilling *et al.* (1994b)

High Tc

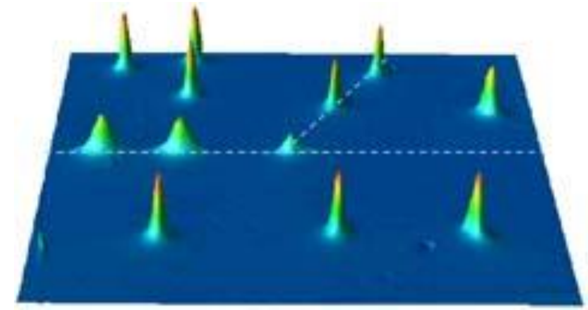
kuprati



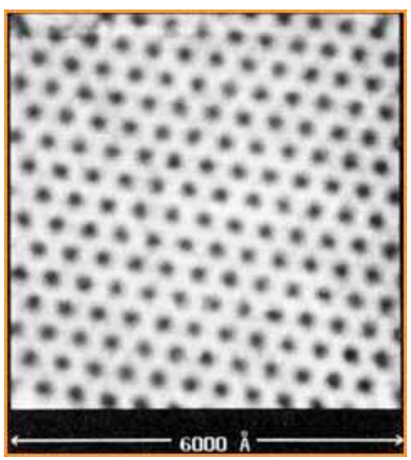
dekoracija - Pb



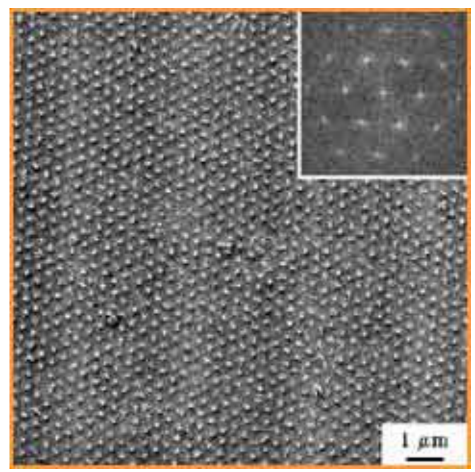
vzorec z luknjami



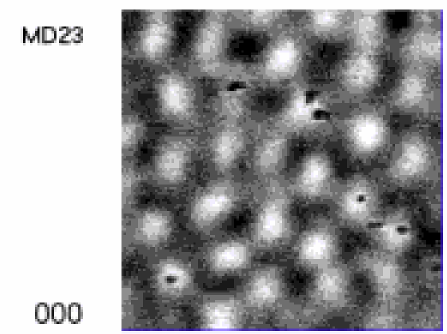
STM – HTC trikristal

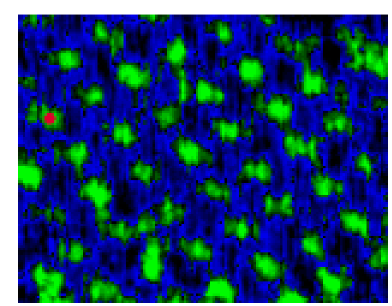


STM - $NbSe_2$



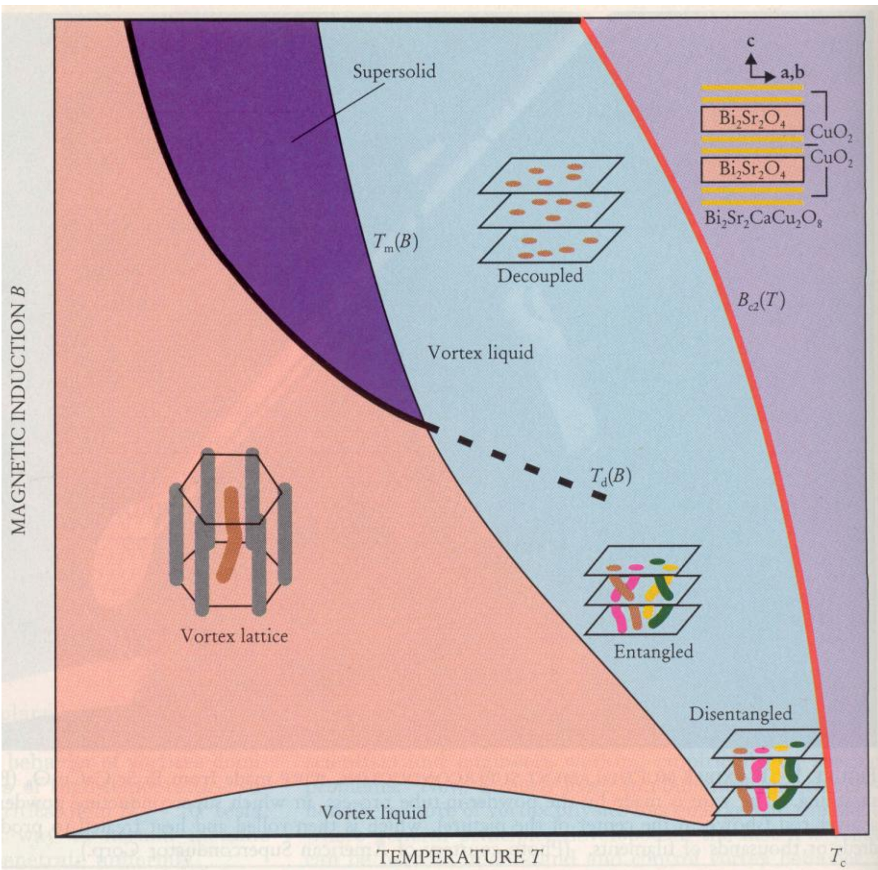
MgB_2

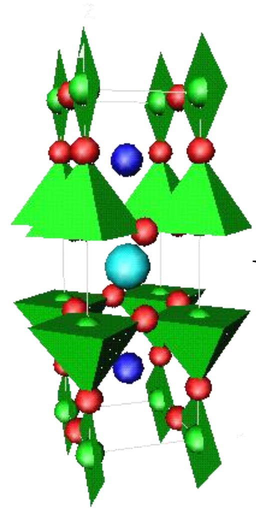




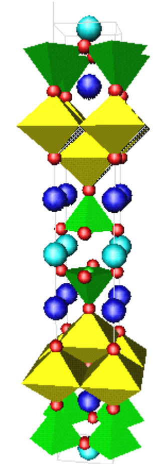
HTC kuprati

čisti superprevodnik

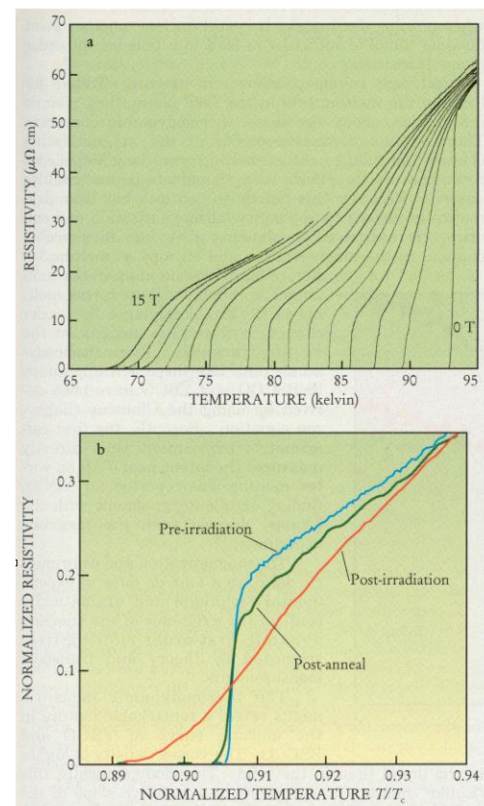




YBCO

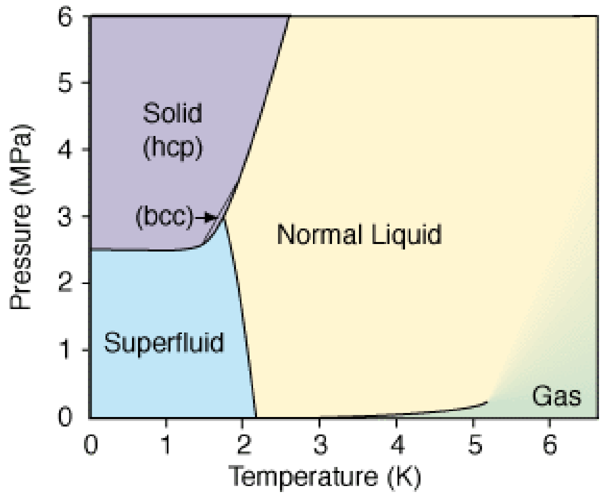


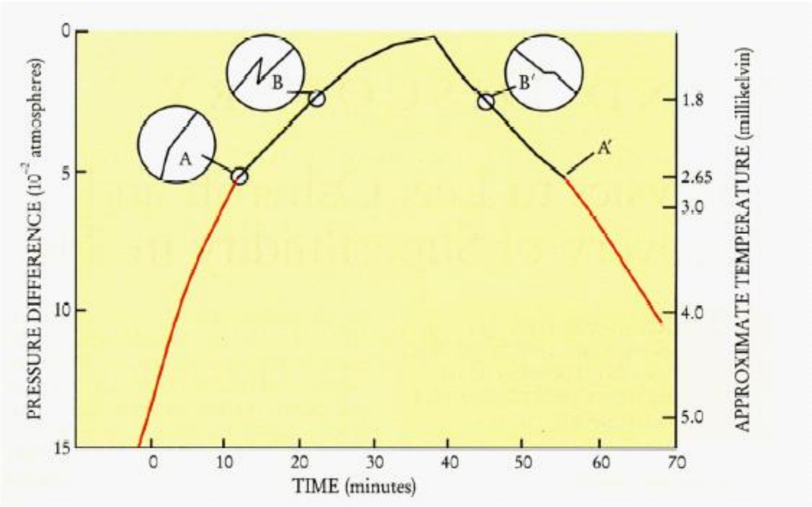
HgCuO..



^{3}He – anizotropna supertekočina

^{4}He

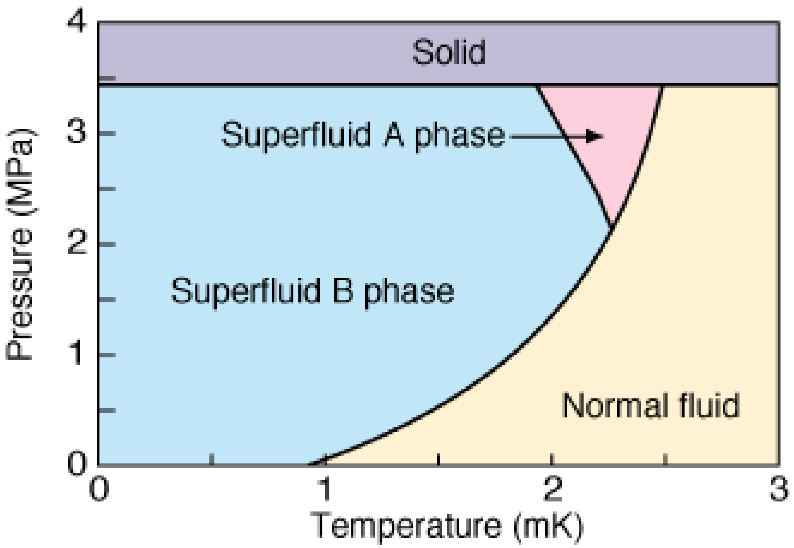




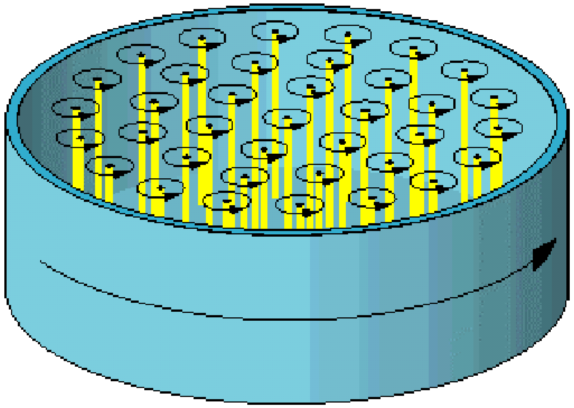
D. Osheroff, D. Lee in R. Richardson 1971

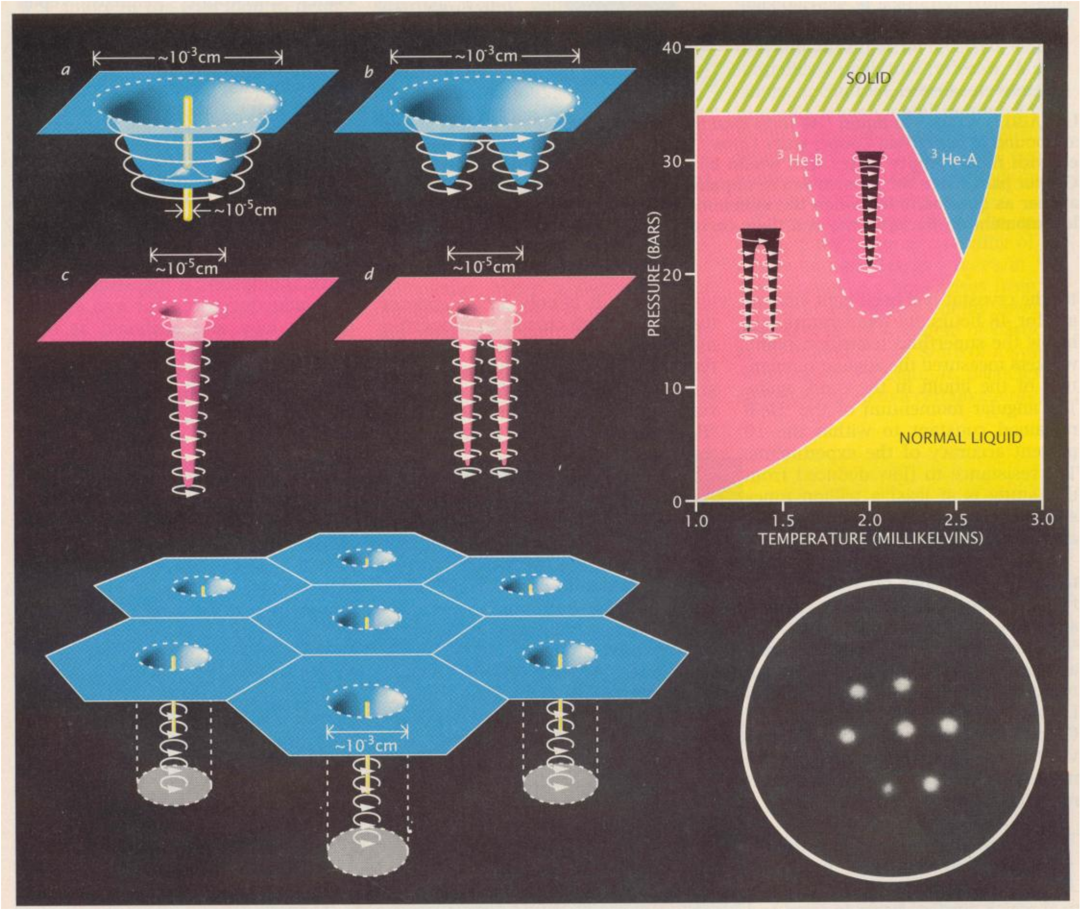
Nobelova nagrada 1996

^{3}He

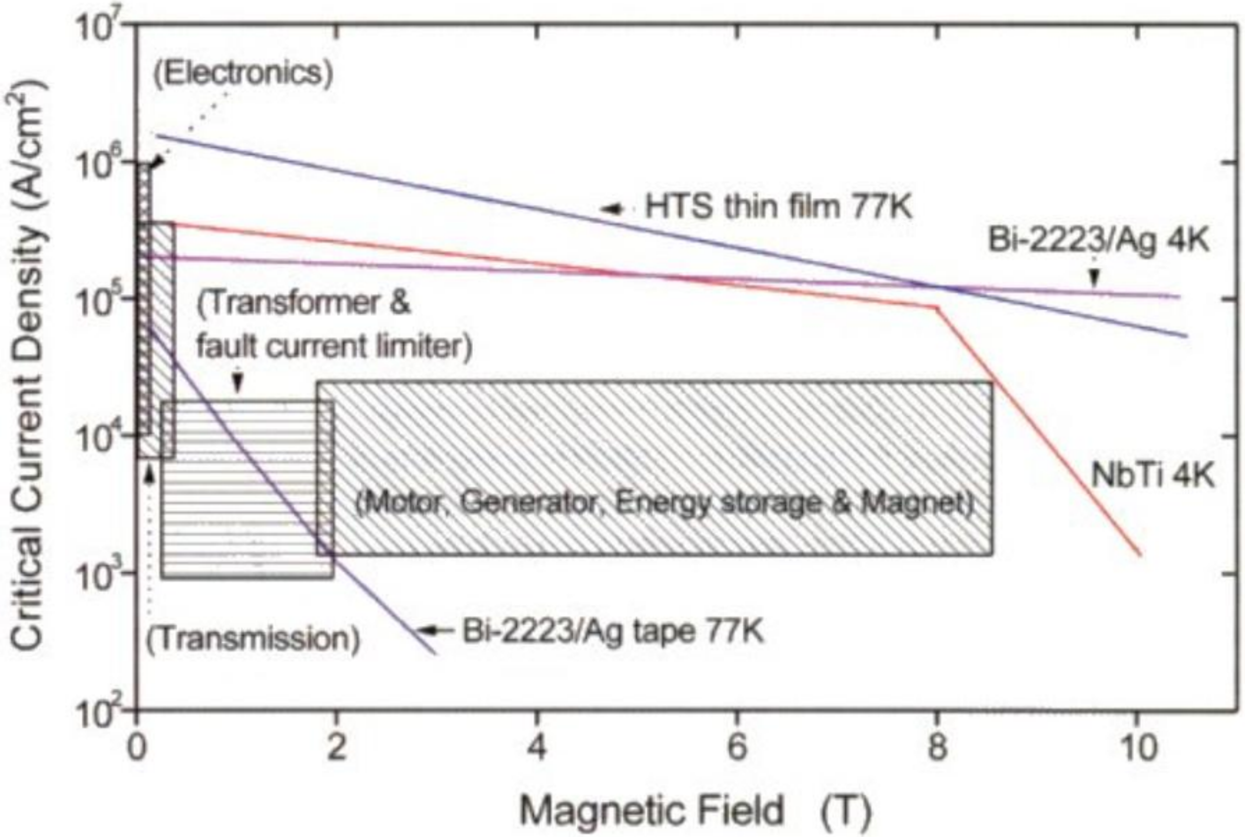


Vrtinci v superfluidu

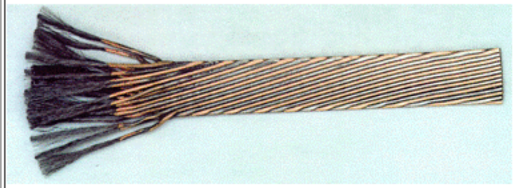
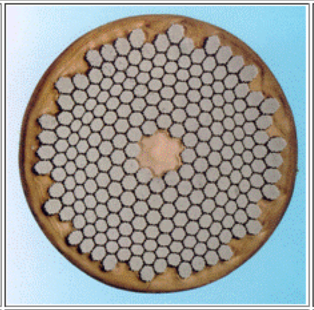




Uporaba superprevodnikov

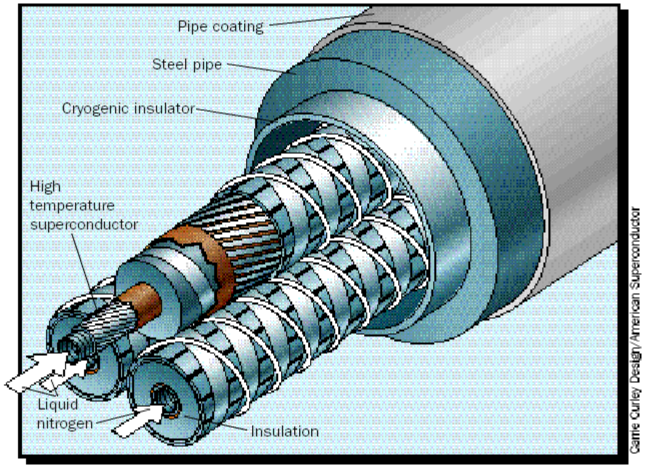


SP kabli

		
Cable	Strand	Filaments

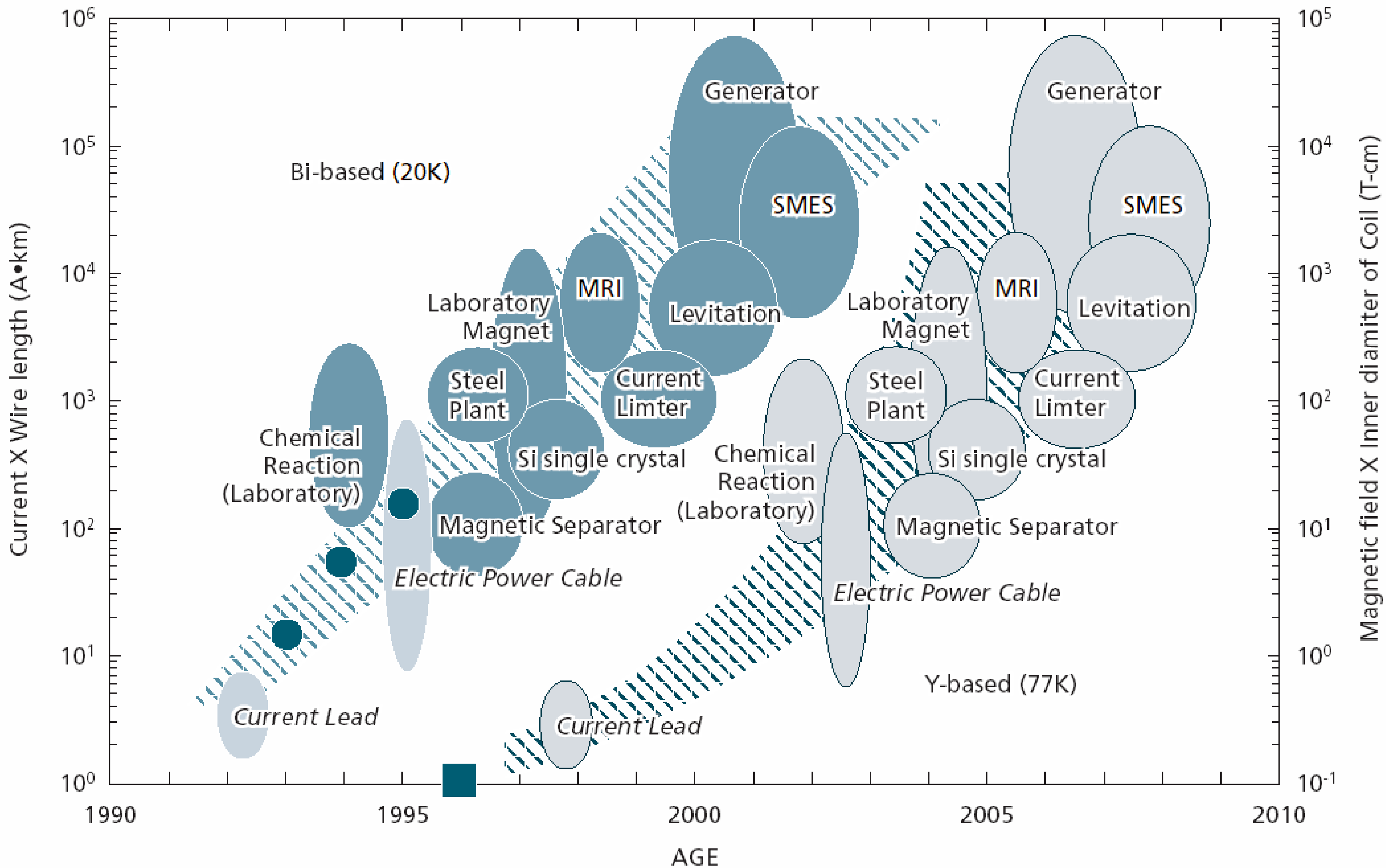
standardni SP: Nb Ti

LHC magneti



Superconducting power cable, with its low resistance, may transform the electric-power industry in much the same way that optical fibers transformed telecommunications.

HTC

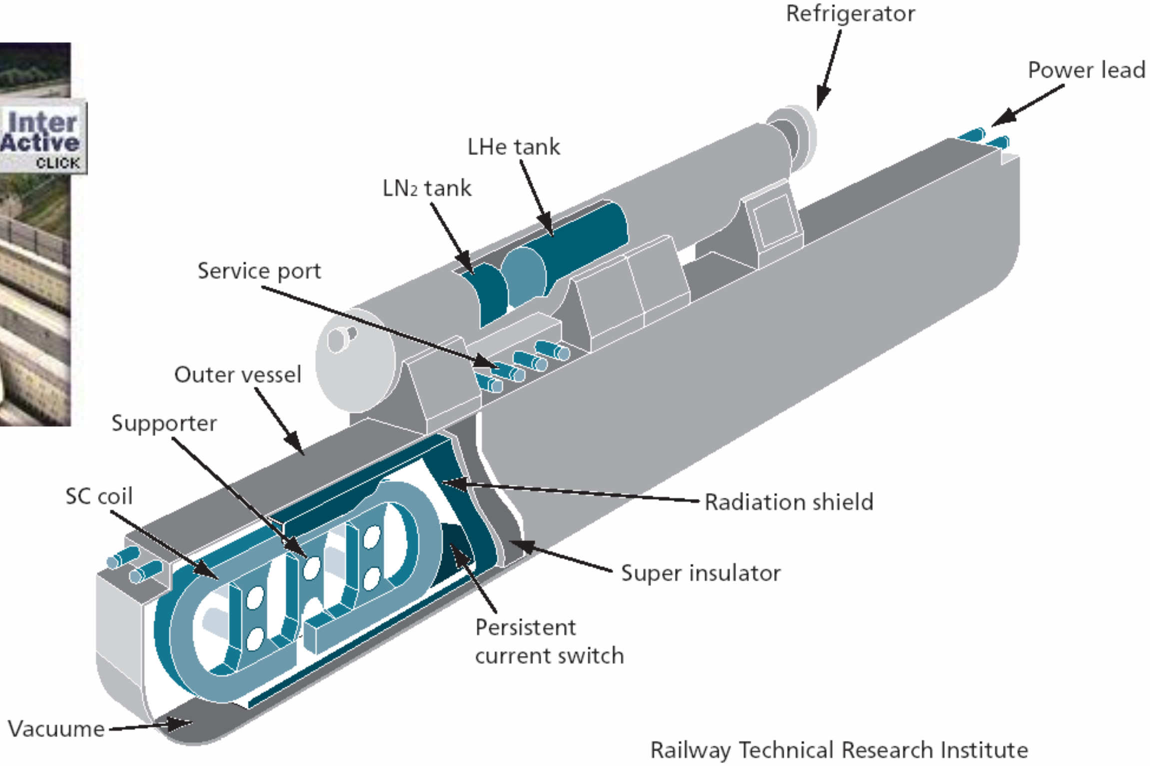


Expectations of the Development of Superconducting Tape

Levitacija

浮いた
土佐ノ海
TOSANOUMI
(Sumo Wrestler)
Height of Tosanoumi 186cm
Weight of Tosanoumi 142kg
Weight of disk 60kg
Total weight 202kg
協力：財団法人　日本相撲協会

MAGLEV



Superconducting Magnet for MAGLEV Train

SP naslednjih 100 let

Nove SP snovi: višji T_c ? boljše snovne lastnosti

Razumevanje nekonvencionalne SP

Uporaba in tehnološki razvoj