Vortices, and where is the critical field?

type-II superconductors, vortices,
lower and upper critical fields

Alexey Abrikosov

Nb-based intermetallic superconductors

by Alexander Tsirlin, Leipzig University

Lecture 6: May 16, 2024

Formula	T_C (K)	H_C (T)	Type	BCS	References
Elements					
Al	1.20	0.01	I	yes	[1][2][3]
Cd	0.52	0.0028	I	yes	[2][3]
Diamond:B	11.4	4	II	yes	[4][5][6]
Ga	1.083	0.0058	I	yes	[7][3][2]
Hf	0.165		I	yes	[2]
α-Hg	4.15	0.04	I	yes	[2][3]
β-Hg	3.95	0.04	I	yes	[2][3]
In	3.4	0.03	I	yes	[2][3]
Ir	0.14	0.0016[7]	I	yes	[2]
α-La	4.9		I	yes	[2]
β-La	6.3		I	yes	[2]
Mo	0.92	0.0096	I	yes	[2][7]
Nb	9.26	0.82	II	yes	[2][3]
Os	0.65	0.007	I	yes	[2]
Pa	1.4		I	yes	[8]
Pb	7.19	0.08	I	yes	[2][3]
Re	2.4	0.03	I	yes	[2][3][9]

type-II (Diamond:B)

type-II (Nb)

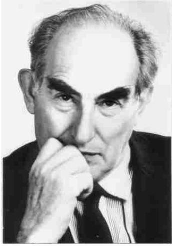
type-I according to recent data:
Phys. Rev. B
106, L180505 (2022)

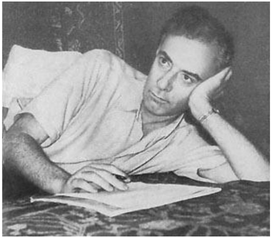
Source: Wikipedia

Substance	Class	T_C (K)	H_C (T)	Type	BCS	References
$C_{60}K_3$	Compound	19.8	0.013	II	yes	[15][19]
$C_{60}Rb_x$	Compound	28		II	yes	[20]
FeB_4	Compound	2.9		II		[21]
InN	Compound	3		II	yes	[22]
In_2O_3	Compound	3.3	~3	II	yes	[23]
LaB_6	Compound	0.45			yes	[24]
MgB_2	Compound	39	74	II	yes	[25]
Nb_3Al	Compound	18		II	yes	[2]
$NbC_{1-x}N_x$	Compound	17.8	12	II	yes	[26][27]
Nb_3Ge	Compound	23.2	37	II	yes	[28]
NbO	Compound	1.38		II	yes	[29]
NbN	Compound	16		II	yes	[2]
Nb_3Sn	Compound	18.3	30	II	yes	[30]
NbTi	Compound	10	15	II	yes	[2]
SiC:B	Compound	1.4	0.008	I	yes	[31]
SiC:Al	Compound	1.5	0.04	II	yes	[31]
TiN	Compound	5.6	5	I	yes	[32][33][34]
V_3Si	Compound	17				[35]
YB_6	Compound	8.4		II	yes	[36][37][38]

type-I

Source: Wikipedia



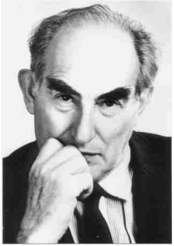


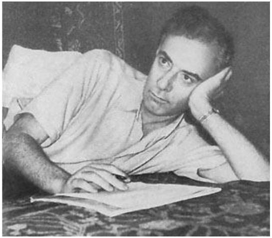
К ТЕОРИИ СВЕРХПРОВОДИМОСТИ

Совместно с В. Л. ГИНЗБУРГОМ

ЖЭТФ, 20, 1064, 1950

Since from the experimental data it follows that $\varkappa \ll 1$, and also for a reason indicated below the solution of equations (18) possible for another limiting case when $\varkappa \to \infty$ does not offer any intrinsic interest, we shall not discuss it.





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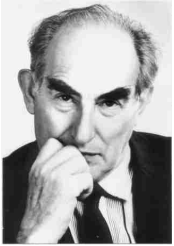

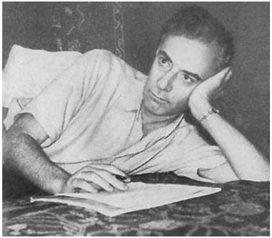

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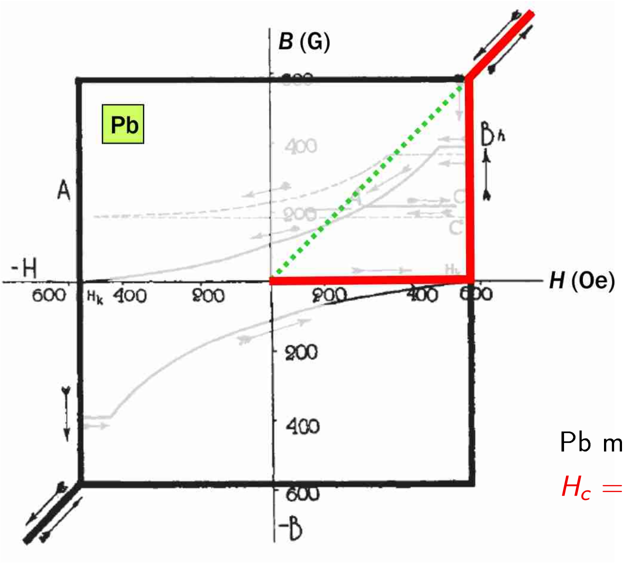
It has not been necessary to investigate the nature of the state which occurs when $\varkappa > \varkappa_0$ since from the experimental data, it is true somewhat preliminary and worked out on the basis of equation (22), it follows that $\varkappa \ll 1$.

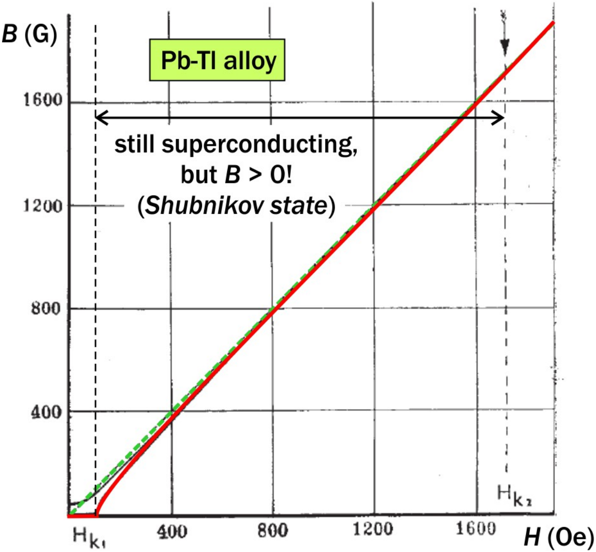
Type-I superconductor



Pb metal:

$H_c = 600\,\mathrm{Oe}$

Nature 134, 286 (1934)



Pb-Tl alloy:

$H_c = 1750\,\mathrm{Oe}\,!$

Nature 135, 581 (1935)

Personality

Alexey Abrikosov

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1928–2017

- 1947: passed Landau's "theory minimum"
- 1951: PhD on thermal diffusion in plasma
- Landau: "Be independent. Read the journals, attend the seminars, and most importantly, discuss with experimentalists"

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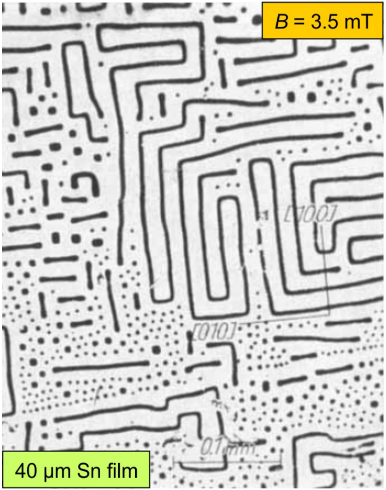
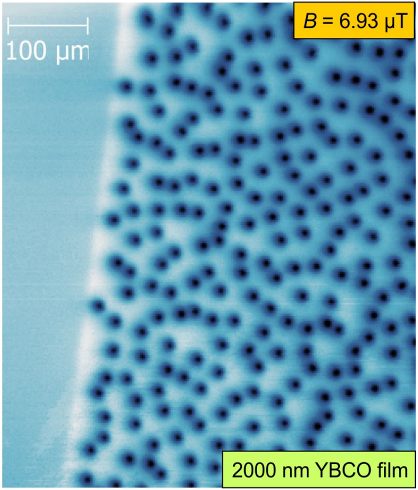
"I deem the applicant's theory wrong, but scientists have not reached a consensus on this problem yet, and the applicant's work contributes to developing this consensus"

recommendation letter by Abrikosov

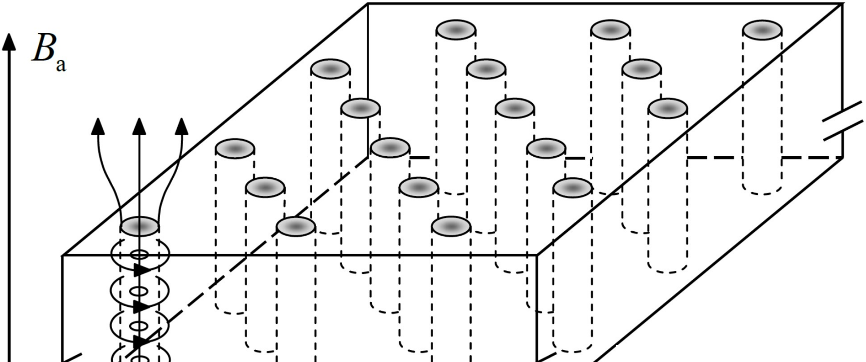
Intermediate state
(type-I superconductor)



Vortex state
(type-II superconductor)

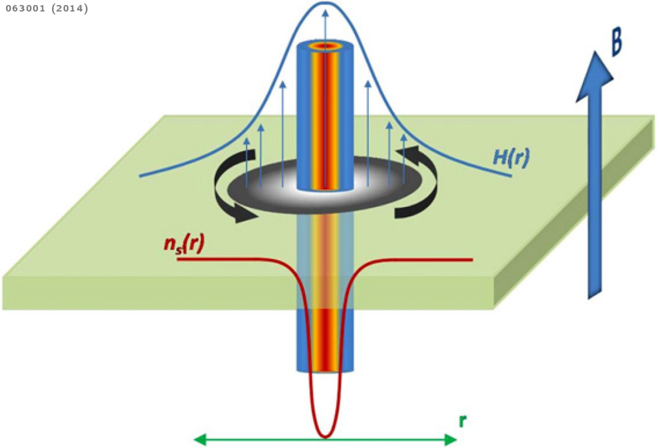


phys. stat. sol. 13, 471 (1972); Sci. Reports 5, 8677 (2015)

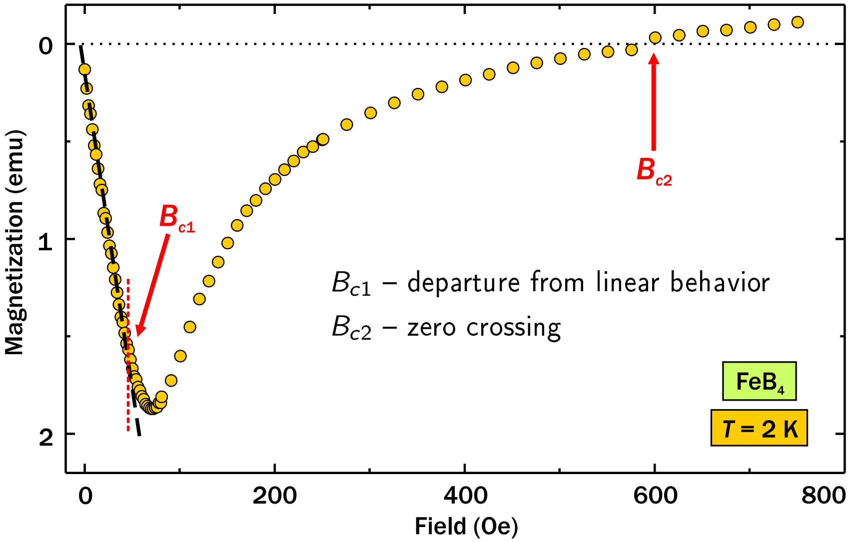


Each Abrikosov vortex carries the flux of Φ_0

Supercond. Sci. Tech. 27, 063001 (2014)

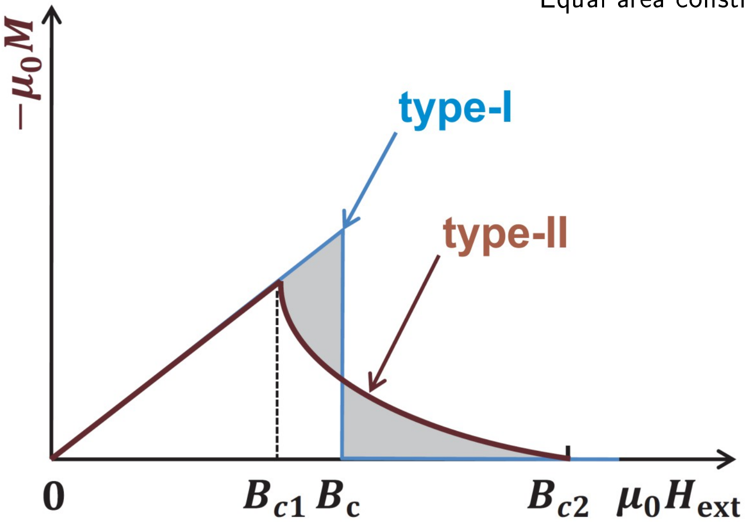


- Magnetic flux enclosed in a cylinder
- Supercurrent embraces the vortex
- $\xi \ll \lambda$, i.e., $\Psi \neq 0$ except in the very center of the vortex



Phys. Rev. Lett. 111, 157002 (2013)

Equal area construction



Gross and Marx, Festkörperphysik

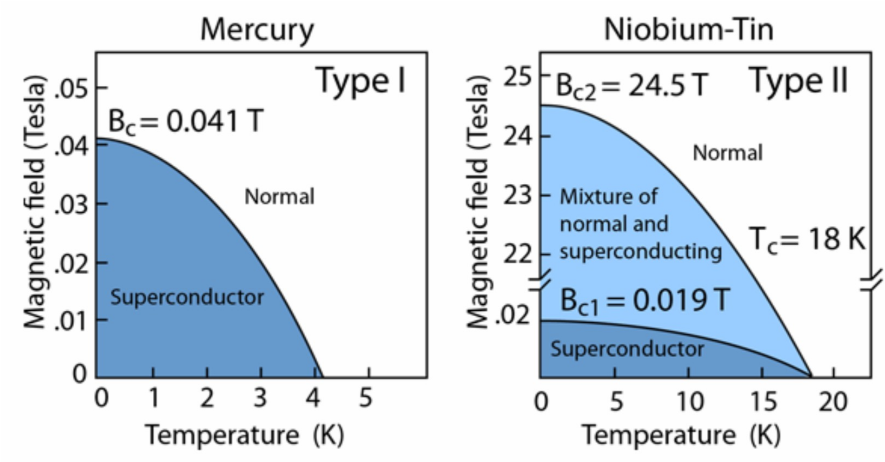


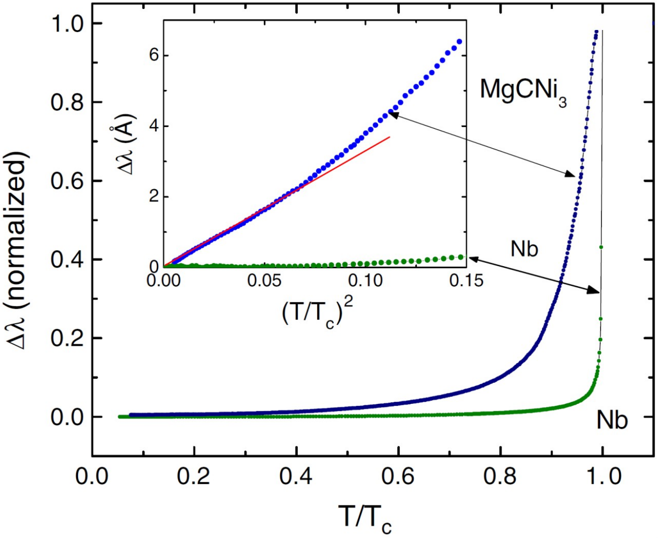
Image source: Hyperphysics

Material / Technology

Nb-based intermetallics

Supraleiter	$\xi_{GL}(0)$ (nm)	$\lambda_L(0)$ (nm)	κ
Al	1600	50	0.03
Cd	760	110	0.14
In	1100	65	0.06
Nb	106	85	0.8
NbTi	4	300	75
Nb_3Sn	2.6	65	25
NbN	5	200	40
Pb	100	40	0.4
Sn	500	50	0.1

Source: Gross and Marx, Festkörperphysik



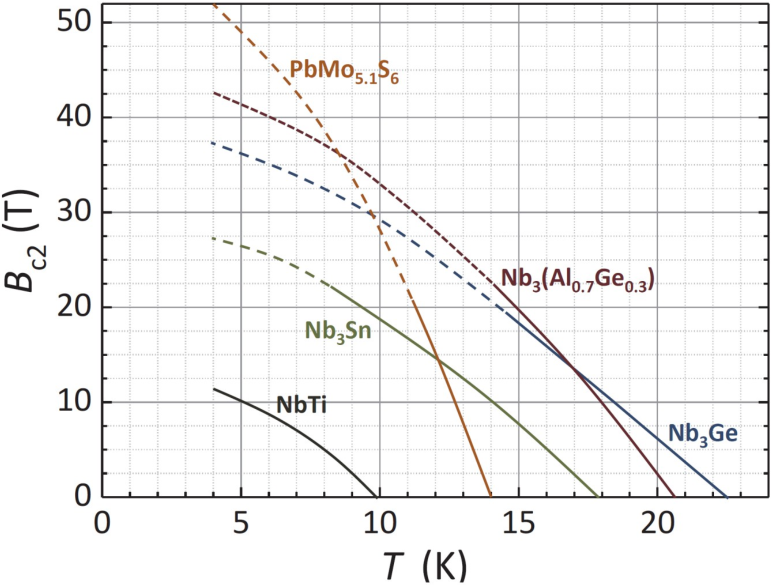
Nb

$T_c = 9.3\,\mathrm{K}$
$B_{c2} = 0.8\,\mathrm{T}$

$MgCNi_3$

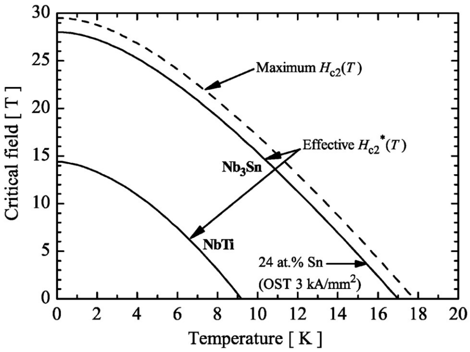
$T_c = 6.4\,\mathrm{K}$
$B_{c2} = 11.5\,\mathrm{T}$

Supercond. Sci. Technol. 19, R41 (2006)



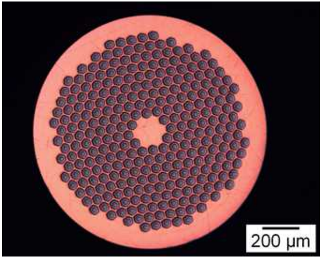
Source: Gross and Marx, Festkörperphysik

Nb_3Sn	**NbTi**
$T_c = 18\,\mathrm{K}$	$T_c = 9.2\,\mathrm{K}$
$B_{c2}(0) = 29\,\mathrm{T}$	$B_{c2}(0) = 14\,\mathrm{T}$
very brittle	ductile



- Discovered in 1954 (Nb_3Sn) and 1962 (NbTi)
- **(Very) difficult to fabricate**

Image source: IEEE Trans. Appl. Supercond. 17, 1149 (2007)



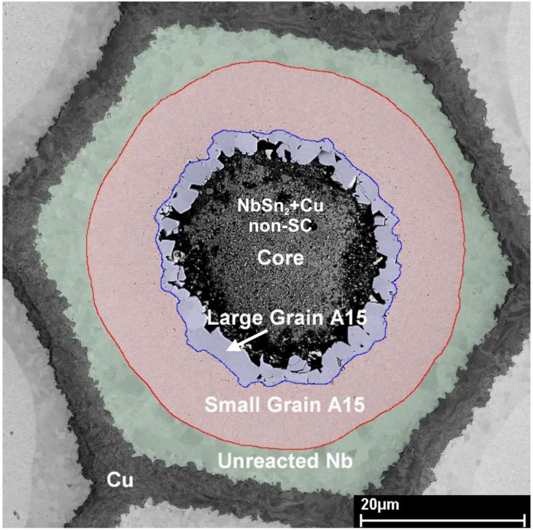


Image source: C.M. Fischer, Master Thesis (University of Wisconsin-Madison)

Nb_3Sn	NbTi
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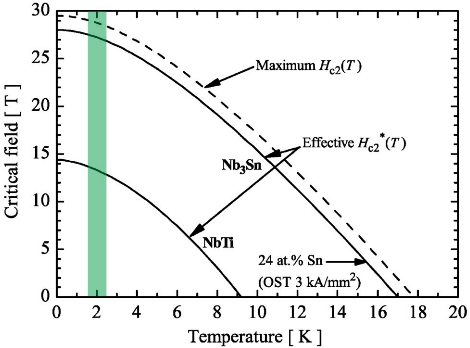

- Discovered in 1954 (Nb_3Sn) and 1962 (NbTi)
- **Very difficult to fabricate**
- Constitute almost all commercial superconducting magnets: NbTi below 10 T, Nb_3Sn up to 18 – 20 T

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Nb-based intermetallic superconductors

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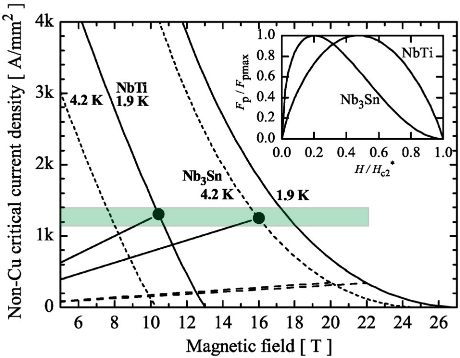

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CERN (2015)
NbTi: $150 per kg of wire
Nb_3Sn: $1500 per kg of wire

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Hyper Tech Research (2020)
NbTi: \$200 per kg of wire
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PPMS system
9 T magnet: at Uni Leipzig
14 T magnet: +\$100,000
16 T magnet: +\$200,000