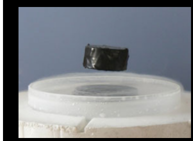
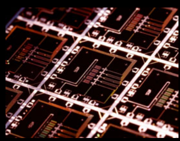
Superconductivity





Tien-Ming Chuang
Institute of Physics, Academia Sinica

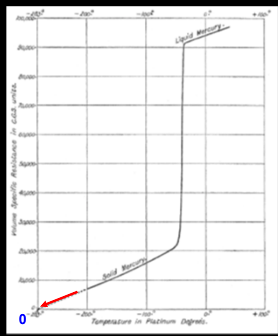
April 1, 2026

1

Resistance at T = 0K?

Sir John Ambrose Fleming

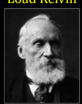
Sir James Dewar

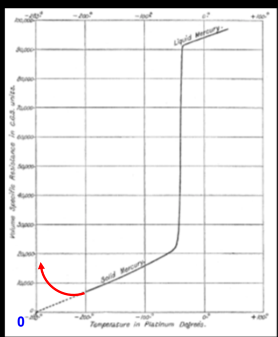


J. Dewar and J.A. Fleming, Proc. R. Soc. London 60, 76–81 (1896)

Resistance at T = 0K?

Load Kelvin

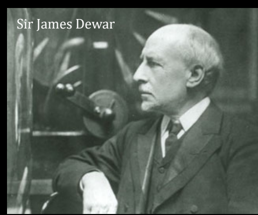




J. Dewar and J.A. Fleming, Proc. R. Soc. London 60, 76–81 (1896)

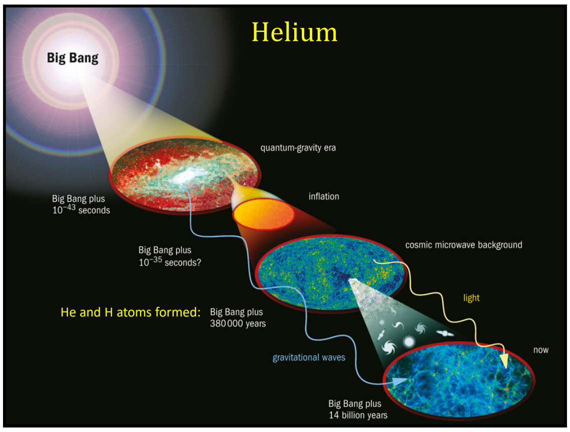
Race to liquefy hydrogen

- Invent the dewar flask in 1892
- Dewar succeed making 20cc of LH_2 on June 2, 1898
- Liquid H_2 T = 20.3 K at 1 bar.



© Royal Institution

Helium



Helium

Sir William Ramsay
Nobel in Chemistry, 1904

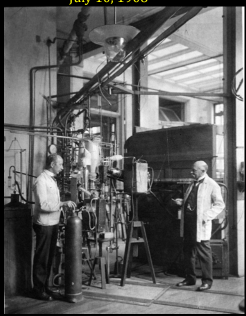
Cleveite

©University College London
Mathematical & Physical Sciences

- Ramsay received Nobel Prize for his discovery of the inert gas (He, Ne, Ar, Kr, and Xe) in air, and his determination of their place in the periodic table.
- Cleveite was the first known terrestrial source of helium, which is created over time by alpha decay of U/Th and trapped within the mineral.
- Massive quantity of He gas was first found along with natural gas at Dexter, Kansas in 1903.

Helium Liquefaction in 1908

July 10, 1908



Heike Kamerlingh Onnes

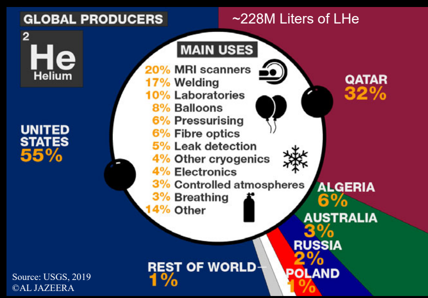
Nobel Prize, 1913

The first experiment had produced 60 ml of liquid helium.

©Leiden Institute of Physics

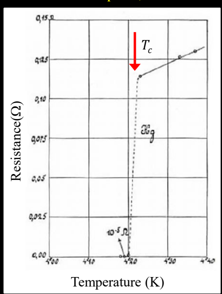
7

Total Production of LHe in 2019



The Discovery of Superconductivity

R = 0 on April 8, 1911



Heike Kamerlingh Onnes

Nobel Prize, 1913

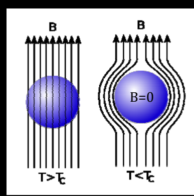
"Door meten tot weten"
(Knowledge through measurement)

H. Kamerlingh Onnes, *Commun. Phys. Lab. Univ. Leiden. Suppl.* **29** (Nov. 1911).

9

Meissner effect, 1933

- Superconductors are found to be perfect diamagnets in 1933.



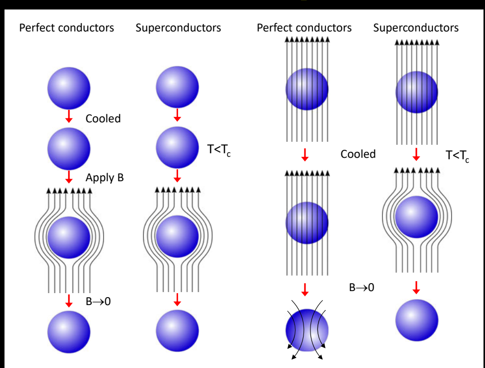
Walther Meißner Robert Ochsenfeld

©PTB Berlin Institute

- What's the difference between a superconductor and a perfect conductor?

10

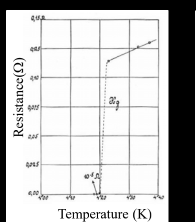
Perfect Conductors vs Superconductors

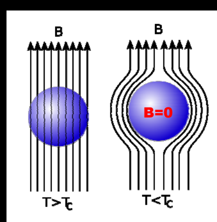


11

Basic Properties of Superconductors

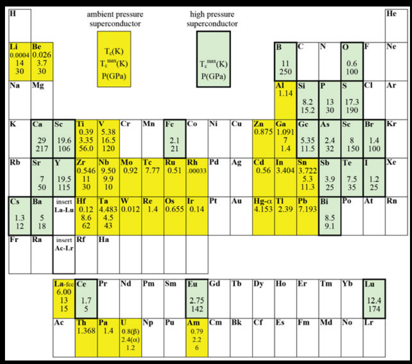
Zero electrical resistivity + Meissner effect





12

Superconducting elements

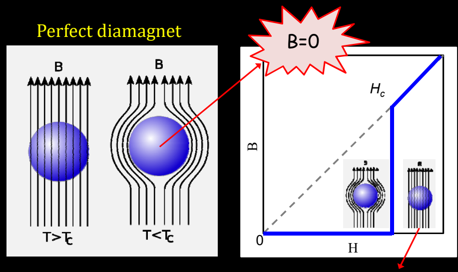


M. Debessai *et al.*, J. Phys.: Conf. Series 215, 012034 (2010).

13

The Meissner Effect, 1933

Perfect diamagnet

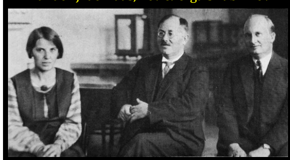


Onnes found that superconductivity was destroyed at a very low critical field Hc of ~500 gauss in 1914.

H.K. Onnes , Commun. Physical Lab., Univ. Leiden 13 (139f), 65 (1914).

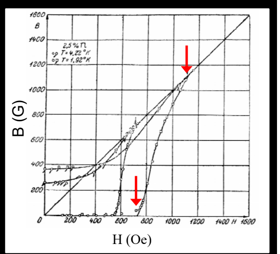
Type II Superconductor : Missed Opportunity

Wander J. de Haas, Lev & Olga Shubnikov



© Leiden Institute of Physics

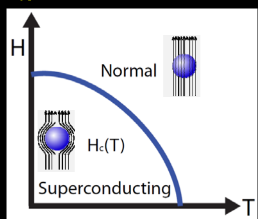
Shubnikov "found" type-II SC in Pb-Tl alloy around 1935 but was executed in 1937.



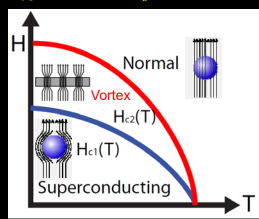
J. M. Kasimir-Jonker and W. J. De Haas, Physica 2, 943 (1935).
L.V. Shubnikov *et al.*, Zh. Eksper. Teor. Fiz. 7, 221 (1937)

Type I & II Superconductors

Type I : Al, Pb…



Type II : Nb, NbTi, Nb_3Sn and HTSC

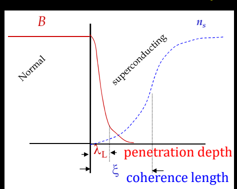


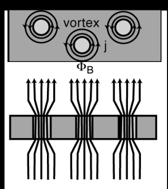
J. N. Rjabinin, L.W. Schubnikow, Physikalische Zeitschrift der Sowjetunion 7, 122 (1935)

16

Type II Superconductor and Vortices

Abrikosov used the G-L theory to derive the existence of a "mixed-state".





Alexei A. Abrikosov
Nobel Prize 2003

A. A. Abrikosov, Doklady Akademii Nauk SSSR 86, 489 (1952)
A. A. Abrikosov, Sov. Phys. JETP 5,1174 (1957)

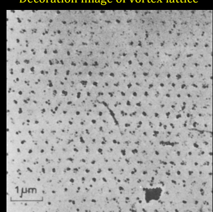
17

Vortex States in Type II Superconductors

- For type II superconductors, surface energy between S and N is negative, "domain" formation is favored! → Abrikosov lattice of flux.
- First confirm by neutron scattering measurements

D. Cribier, B. Jacrot, L. M. Rao and B. Farnoux, Phys, Lett. **9**, 106 (1964).

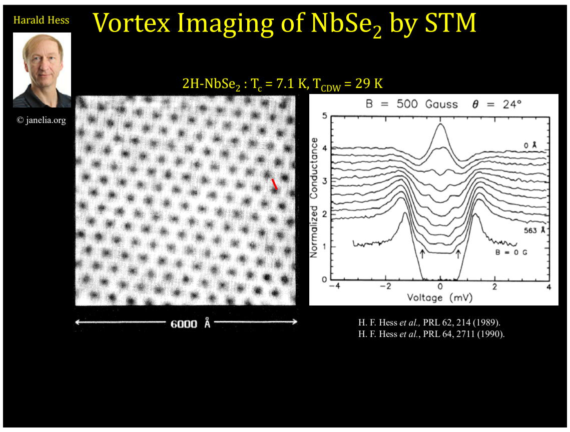
- Vortex in SC has a core, circled by supercurrent.
- Inside the core: normal electrons. Outside the core are Cooper pairs.
- Decoration image of vortex lattice

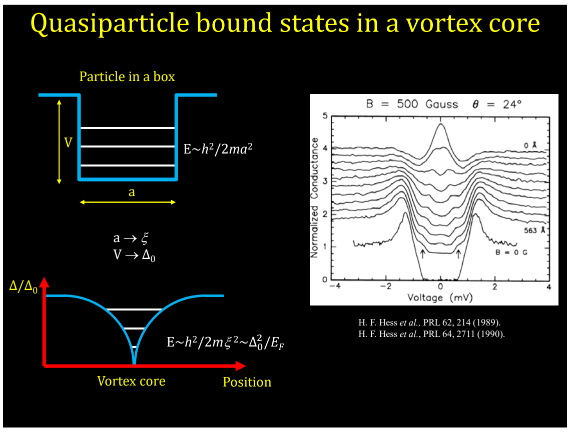


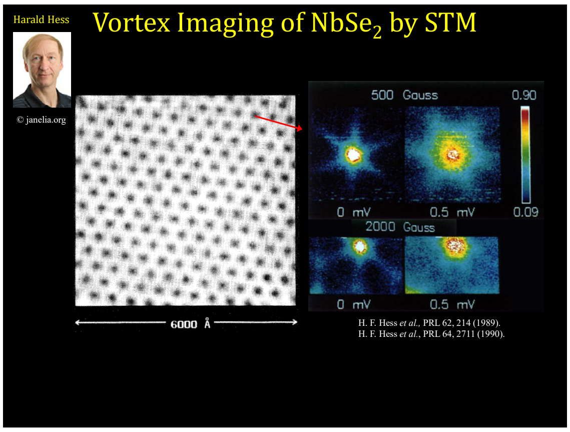
Tonomura et al. (1986), p. 93

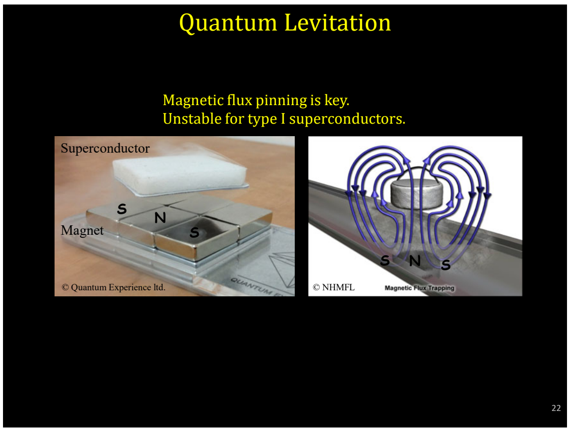
U. Essmann and H. Trauble, Physics Letters 24A, 526 (1967)

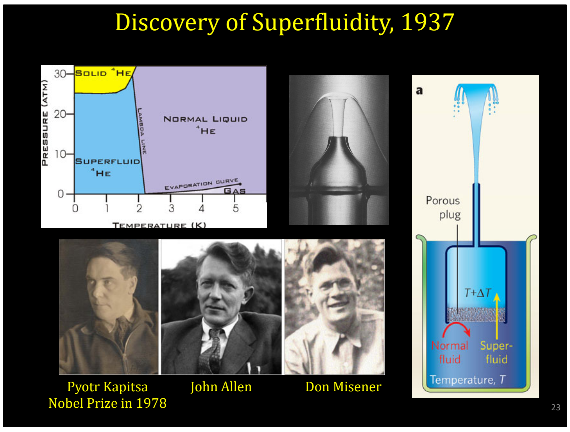
18

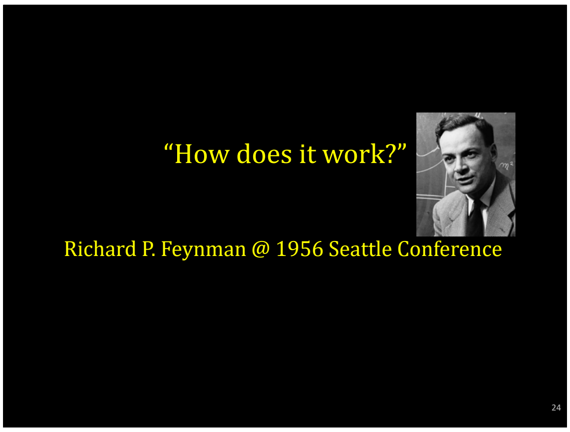

Harald Hess
© janelia.org
Vortex Imaging of NbSe2 by STM
2H-NbSe2 : Tc = 7.1 K, TCDW = 29 K
6000 Å
B = 500 Gauss θ = 24°
Normalized Conductance
Voltage (mV)
0 Å
563 Å
B = 0 G
H. F. Hess et al., PRL 62, 214 (1989).
H. F. Hess et al., PRL 64, 2711 (1990).


Quasiparticle bound states in a vortex core
Particle in a box
V
a
E~h²/2ma²
a → ξ
V → Δ0
Δ/Δ0
E~h²/2mξ²~Δ0²/EF
Vortex core
Position
B = 500 Gauss θ = 24°
Normalized Conductance
Voltage (mV)
H. F. Hess et al., PRL 62, 214 (1989).
H. F. Hess et al., PRL 64, 2711 (1990).


Harald Hess
© janelia.org
Vortex Imaging of NbSe2 by STM
6000 Å
500 Gauss
0.90
0 mV
0.5 mV
0.09
2000 Gauss
0 mV
0.5 mV
H. F. Hess et al., PRL 62, 214 (1989).
H. F. Hess et al., PRL 64, 2711 (1990).


Quantum Levitation
Magnetic flux pinning is key.
Unstable for type I superconductors.
Superconductor
Magnet
S
N
S
© Quantum Experience ltd.
© NHMFL
22


Discovery of Superfluidity, 1937
Solid ⁴He
Normal Liquid ⁴He
Superfluid ⁴He
Lambda line
Evaporation curve
Gas
Pressure (atm)
Temperature (K)
a
Porous plug
T+ΔT
Normal fluid
Super-fluid
Temperature, T
Pyotr Kapitsa
Nobel Prize in 1978
John Allen
Don Misener
23


"How does it work?"
Richard P. Feynman @ 1956 Seattle Conference
24

The London Equation and Penetration Depth, 1935

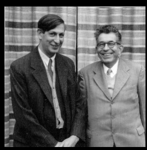
Correct theoretical descriptions of the SC phenomenon:

- In 1935, London brothers propose two equations for E and H; results in the concept of penetration depth.
- Starting from the classical Drude model : $m\dot{\vec{v}} = e\vec{E} - m\frac{\vec{v}}{\tau}$

  but adapts to account for the *perfect conductivity*:

  $$\vec{E} = \frac{m}{n_s e^2}\frac{\partial \vec{J_s}}{\partial t} \qquad (1)$$

- Stationary currents in superconductors are possible even when E=0.


Heinz and Fritz London
© Duke University

25

The London Equation and Penetration Depth, 1935

- Take curl of (1) and with Faraday's Law $\nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}$:

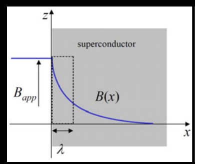
  $$\nabla \times \vec{J_s} = -\frac{n_s e^2}{mc}\vec{B}$$

  Meissner's Effect included!

- Combine London Equations with Ampère's law $\nabla \times \vec{H} = \frac{4\pi}{c}\vec{J}$:

  $$\rightarrow \nabla^2 \vec{B} = \frac{\vec{B}}{{\lambda_L}^2} \quad ; \lambda_L \equiv \sqrt{\frac{mc^2}{4\pi n_s e^2}}$$

  $$B_Z(x) = B_Z(0)\exp(-x/\lambda_L)$$



- B is exponentially screened over a length, λ_L , which explains Meissner effect.
- The penetration depth λ_L is also the characteristic depth of the supercurrent on the surface of the material (due to Ampère's law)

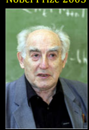
26

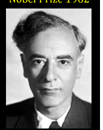
Ginzburg-Landau Theory, 1950

Correct theoretical descriptions of the SC phenomenon:

- The Limitation of London theory: only valid when
  1. The penetration depth is the dominant length scale : λ >> ξ_0 (coherent length)
  2. The field is small and can be treated as a perturbation.
  3. n_s is nearly constant everywhere.
- The first theory to properly take into account the quantum nature of superconductivity.
- Introducing the superconducting order parameter:

  $$\psi(\vec{r}) \equiv \psi_0 e^{i\phi(\vec{r})} \text{ where } \psi_0 = \sqrt{n_s(\vec{r})}$$

Vitaly L. Ginzburg
Nobel Prize 2003

©NY Times

Lev Landau
Nobel Prize 1962

© Nobel Foundation

27

Ginzburg-Landau Theory, 1950

- Landau expansion of free energy:

  $$F = F_n + \int \left(\frac{\hbar^2}{4m}\left|\left(\nabla - i\frac{2e}{\hbar c}\vec{A}\right)\psi\right|^2 + \propto |\psi|^2 + \frac{\beta}{2}|\psi|^4 + \frac{\vec{B}^2}{8\pi}\right)dV$$

  Quantum mechanics — 2nd order phase transition

- Introducing coherence length, ξ

  $$\propto = \frac{\hbar^2}{2m\xi^2} \qquad |\psi|^2 = -\alpha/\beta$$

- GL theory yields $\vec{J} = \vec{J_s} = \frac{e\hbar n_s}{2m}\left(\nabla\emptyset - \frac{2e}{\hbar c}\vec{A}\right)$

  In the absence of magnetic field : $\vec{J_s} = e n_s v_s$

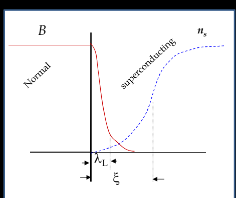
- Also $\left(\nabla^2 - {\lambda_L}^{-2}\right)\vec{J_s} = 0$
- Connection of BCS to GL Theory by Lev Gor'kov in 1958.

V.L. Ginzburg and L.D. Landau, Zh. Eksp. Teor. Fiz. 20, 1064 (1950)

28

Coherence Length

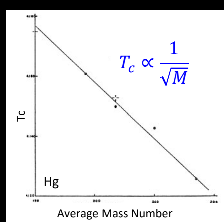
- First introduced by Brian Pippard for the non-local generalization of the Londons' equation concerning electrodynamics in superfluids and superconductors. Later confirmed by BCS theory.
- The DOS, n_s of the Cooper pairs decreases to zero near a superconducting /normal interface, with a characteristic length ξ (coherence length).
- ξ and λ_L are both functions of temperature.



29

The Isotope Effect, 1950

- Lattice vibration is a part of the superconducting process.
- A crucial step to a microscopic theory of superconductivity!



Emanuel Maxwell

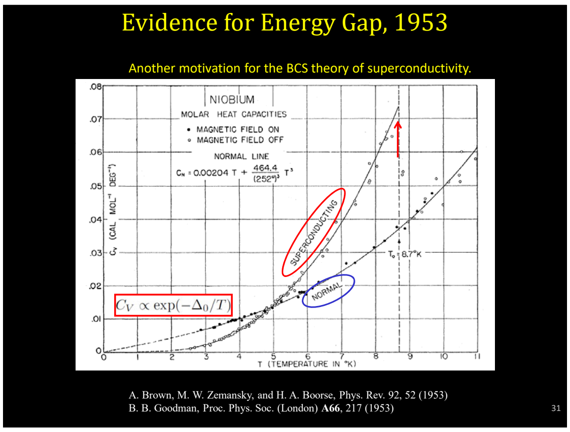
© MIT

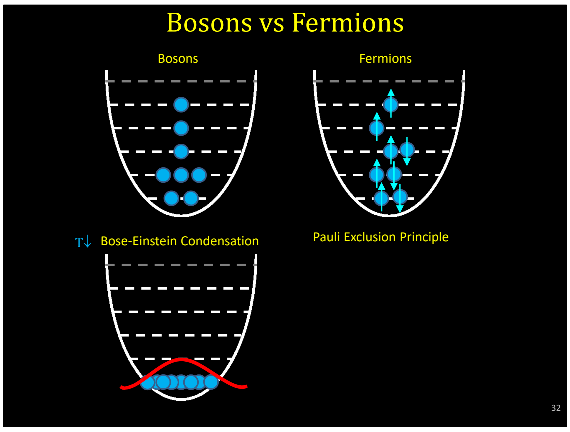
Bernard Serin & Charles Reynolds

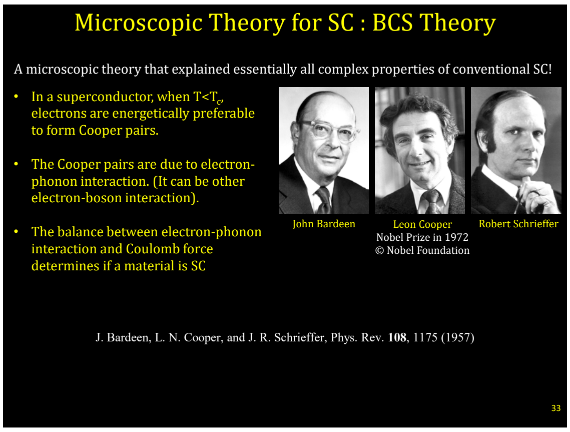
© Rutgers University

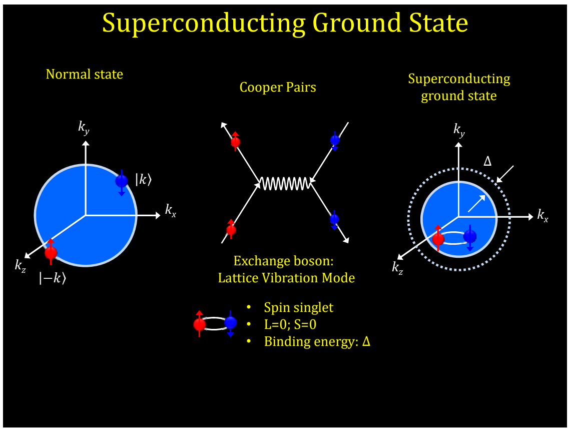
Emanuel Maxwell, Phys. Rev. 78, 477 (1950)
C.A. Reynolds et al., Phys. Rev. 78, 487 (1950)

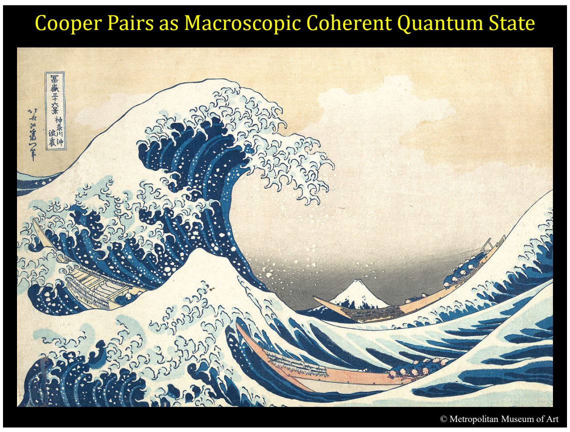
30

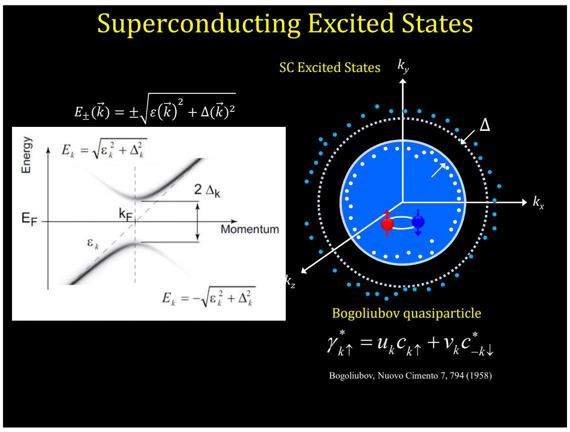

Evidence for Energy Gap, 1953
Another motivation for the BCS theory of superconductivity.
NIOBIUM
MOLAR HEAT CAPACITIES
MAGNETIC FIELD ON
MAGNETIC FIELD OFF
NORMAL LINE
SUPERCONDUCTING
NORMAL
$C_V \propto \exp(-\Delta_0/T)$
T (TEMPERATURE IN °K)
A. Brown, M. W. Zemansky, and H. A. Boorse, Phys. Rev. 92, 52 (1953)
B. B. Goodman, Proc. Phys. Soc. (London) **A66**, 217 (1953)
31

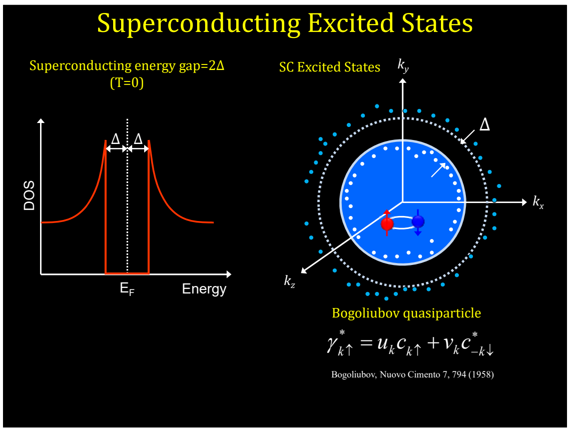

Bosons vs Fermions
Bosons
Fermions
Bose-Einstein Condensation
Pauli Exclusion Principle
32

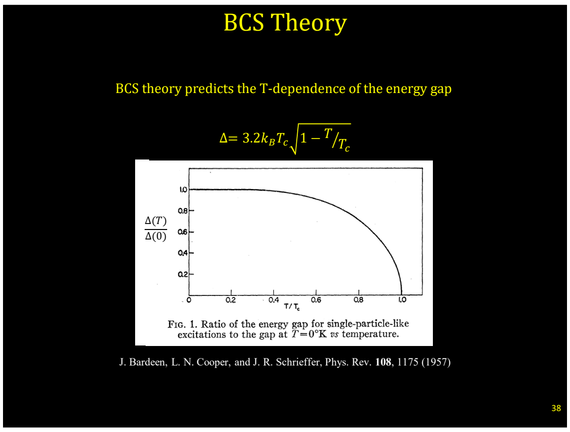

Microscopic Theory for SC : BCS Theory
A microscopic theory that explained essentially all complex properties of conventional SC!
In a superconductor, when $T<T_c$, electrons are energetically preferable to form Cooper pairs.
The Cooper pairs are due to electron-phonon interaction. (It can be other electron-boson interaction).
The balance between electron-phonon interaction and Coulomb force determines if a material is SC
John Bardeen
Leon Cooper
Robert Schrieffer
Nobel Prize in 1972
© Nobel Foundation
J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. **108**, 1175 (1957)
33

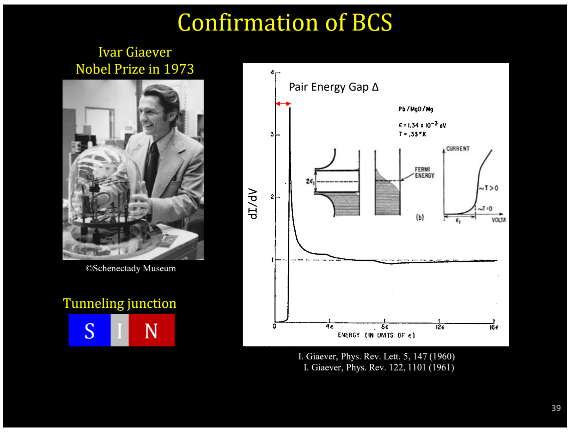

Superconducting Ground State
Normal state
Cooper Pairs
Superconducting ground state
k_y
k_x
k_z
$|k\rangle$
$|-k\rangle$
Δ
Exchange boson: Lattice Vibration Mode
Spin singlet
L=0; S=0
Binding energy: Δ

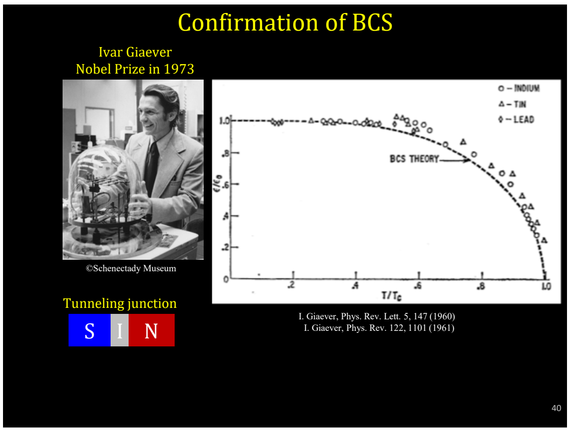

Cooper Pairs as Macroscopic Coherent Quantum State
© Metropolitan Museum of Art

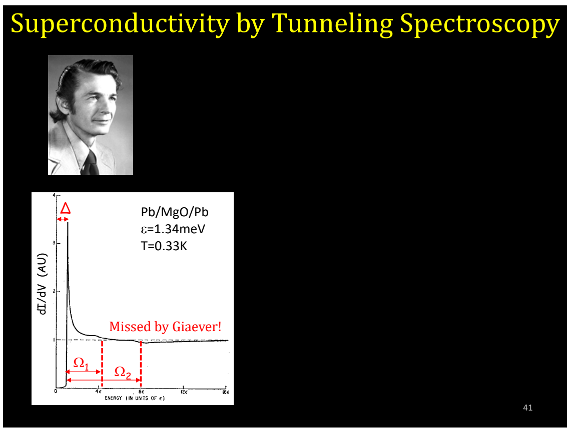

Superconducting Excited States
SC Excited States
$E_\pm(\vec{k}) = \pm\sqrt{\varepsilon(\vec{k})^2 + \Delta(\vec{k})^2}$
Energy
$E_k = \sqrt{\varepsilon_k^2 + \Delta_k^2}$
$2\,\Delta_k$
E_F
k_F
Momentum
ε_k
$E_k = -\sqrt{\varepsilon_k^2 + \Delta_k^2}$
k_y
k_x
k_z
Δ
Bogoliubov quasiparticle
$\gamma^*_{k\uparrow} = u_k c_{k\uparrow} + v_k c^*_{-k\downarrow}$
Bogoliubov, Nuovo Cimento 7, 794 (1958)

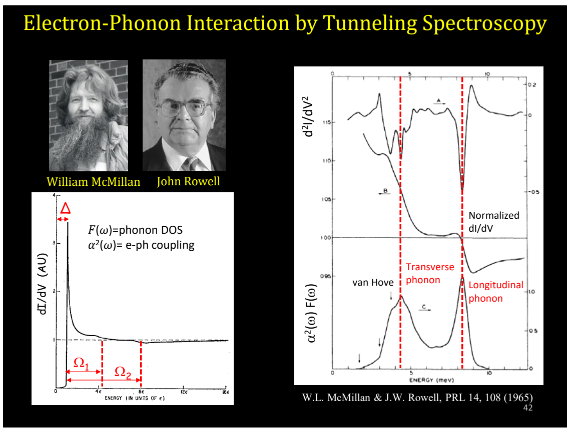

Superconducting Excited States
Superconducting energy gap=2Δ
(T=0)
DOS
Δ Δ
E_F
Energy
SC Excited States
k_y
k_x
k_z
Δ
Bogoliubov quasiparticle
$\gamma^*_{k\uparrow} = u_k c_{k\uparrow} + v_k c^*_{-k\downarrow}$
Bogoliubov, Nuovo Cimento 7, 794 (1958)


BCS Theory
BCS theory predicts the T-dependence of the energy gap
$\Delta = 3.2 k_B T_c \sqrt{1 - T/T_c}$
$\frac{\Delta(T)}{\Delta(0)}$
T/T_c
FIG. 1. Ratio of the energy gap for single-particle-like excitations to the gap at T=0°K vs temperature.
J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. 108, 1175 (1957)
38


Confirmation of BCS
Ivar Giaever
Nobel Prize in 1973
©Schenectady Museum
Tunneling junction
S I N
Pair Energy Gap Δ
dI/dV
Pb/MgO/Mg
CURRENT
FERMI ENERGY
ENERGY (IN UNITS OF ε)
I. Giaever, Phys. Rev. Lett. 5, 147 (1960)
I. Giaever, Phys. Rev. 122, 1101 (1961)
39


Confirmation of BCS
Ivar Giaever
Nobel Prize in 1973
©Schenectady Museum
Tunneling junction
S I N
○ – INDIUM
Δ – TIN
◊ – LEAD
BCS THEORY
T/T_c
I. Giaever, Phys. Rev. Lett. 5, 147 (1960)
I. Giaever, Phys. Rev. 122, 1101 (1961)
40


Superconductivity by Tunneling Spectroscopy
Δ
Pb/MgO/Pb
ε=1.34meV
T=0.33K
dI/dV (AU)
Missed by Giaever!
Ω1
Ω2
ENERGY (IN UNITS OF ε)
41


Electron-Phonon Interaction by Tunneling Spectroscopy
William McMillan
John Rowell
Δ
F(ω)=phonon DOS
α²(ω)= e-ph coupling
dI/dV (AU)
Ω1
Ω2
d²I/dV²
Normalized dI/dV
van Hove
Transverse phonon
Longitudinal phonon
α²(ω) F(ω)
ENERGY (meV)
W.L. McMillan & J.W. Rowell, PRL 14, 108 (1965)
42

Flux Quantization, 1950

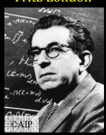
* We note that in order for Ψ to be a single-valued function, as required by quantum mechanics, it is necessary that the moduli of χ fulfill a kind of quantum condition:

$$<x> = \oint \bar{p}_s \cdot ds = Kh$$

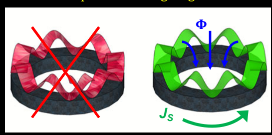
where K must be an integer. This means that there exists a universal unit for the fluxoid:

$$\Phi_1 = h c / e \simeq 4 \cdot 10^{-7} \text{ gauss} \cdot \text{cm}^2$$

Fritz London



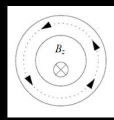
Superconducting ring



Superfluids, Macroscopic Theory of Superconductivity, Structure of Matter Vol. 1 (Wiley, New York, 1950)

Flux Quantization

- From Ginzburg-Landau theory: $\vec{J} = \vec{J_s} = \frac{e\hbar n_s}{2m}(\nabla\emptyset - \frac{2e}{\hbar c}\vec{A})$
- Take $\oint \vec{J} \cdot d\vec{l} = 0$ around a closed contour within a superconductor.

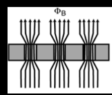


1st term: $\oint \nabla\emptyset \cdot d\vec{l} = \Delta\emptyset = 2n\pi$, n is integer

2nd term:
With Stoke's theorem ->

$$\int \vec{A} \cdot d\vec{l} = \int \nabla \times \vec{A} \cdot d\vec{S} = \int \vec{B} \cdot d\vec{S} = \Phi$$

- Thus, flux quantum $|\Phi| = n\frac{h}{2e} = n\Phi_0$ *where* $\Phi_0 = 2.07 \times 10^{-15} Tesla - m^2$
- One flux quantum in each vortex. The density of vortices in the superconductor is determined by the magnitude of the applied field.



Superfluids, Macroscopic Theory of Superconductivity, Structure of Matter Vol. 1 (Wiley, New York, 1950)

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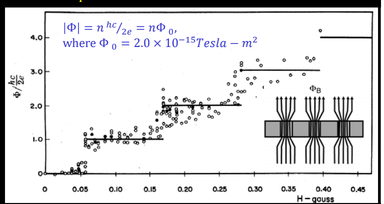
Flux Quantization Experiments in 1961

One of the most compelling evidence for the validity of the description of superconductors by a complex order parameter

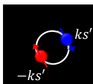


This also shows that q=2e (pairs) in superconductors!

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

45

Pairing Symmetry



Order parameter : SC gap function, $\Delta^{\ell}_{ss'}(k) \propto |\Psi_{kss'}|^2$

Pair wave function : $\Psi_{kss'} = \langle\Psi_{BCS}|c_{-ks'}c_{ks}|\Psi_{BCS}\rangle = g_\ell(k)\,\chi_{ss'}$

Spin part : $\chi_{ss'}$
- $(\uparrow\downarrow - \downarrow\uparrow)$ singlet, $S = 0$
- $(\uparrow\uparrow, \uparrow\downarrow + \downarrow\uparrow, \downarrow\downarrow)$ triplet, $S = 1$

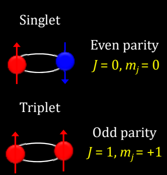
Orbital part : $g_\ell(k) = \sum_{m=-\ell}^{\ell} a_{\ell m}(k) Y_{\ell m}(\hat{k})$, where $\hat{k} = k/k_F$

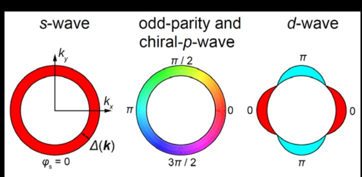
$\ell = 0$: s wave (conventional SC)
$\ell = 1$: p wave (superfluid ^{3}He)
$\ell = 2$: d wave (cuprate SC)

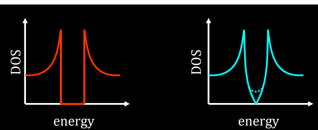
If $\ell > 0$, $\psi(0) = 0$ → { repulsive interaction; $\Delta(k)$ must change its sign }

Spin	Orbital
anti-symmetric (S = 0)	symmetric (s, d, …)
symmetric (S = 1)	anti-symmetric (p, f, …)

Symmetry of the Order Parameter



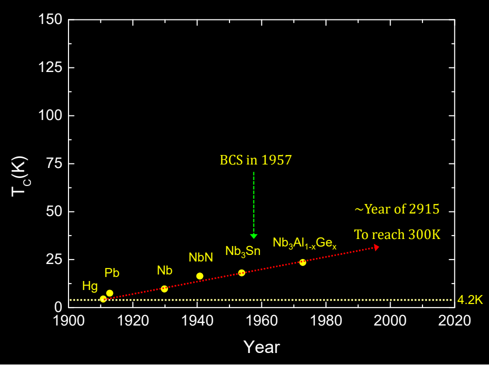




Shingo Yonezawa, Condens. Matter 4, 2 (2019)

47

History of Conventional Superconductors



Matthias's Rules for Searching High TC SC

Bernd Matthias
By Joel Broida©

1. Stay away from insulators; transition metals are better.
2. There are favorable electron/atom ratios.
3. High symmetry is good; cubic symmetry is best.
4. Stay away from Oxygen
5. Stay away from magnetism
6. Stay away from theorists.

W. E. Pickett , Physica B **296**, 112 (2001)
I. I. Mazin, Nature **464**, 183 (2010)

49

The Beginning of High T_c Superconductors (HTS)

Possible High T_c Superconductivity in the Ba – La – Cu – O System

J.G. Bednorz and K.A. Müller
IBM Zürich Research Laboratory, Rüschlikon, Switzerland

Received April 17, 1986

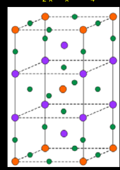
Z. Phys. B – Condensed Matter 64,189 (1986)

Nobel Prize in Physics 1987

J. Georg Bednorz

K. Alex Müller

$La_{2-x}Ba_xCuO_4$

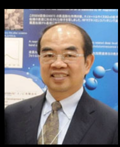


T_c~30K

50

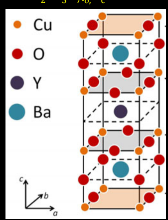
Superconductivity above 77K

C.W. Paul Chu



Maw-Kuen Wu

$YBa_2Cu_3O_{7-\delta}$, T_c~93K



CuO chain
BaO
CuO plane

Note!
LN_2 ~ 30 NTD/L
Taiwan Beer ~ 76 NTD/L

M. K. Wu *et al.*, PRL **58**, 908 (1987)

51

Woodstock of Physics - March Meeting 1987

"The stores and the bars were all 'Physicists welcome,' " said Paul M. Grant, who headed the superconductivity research at I.B.M.'s Almaden Research Center in San Jose. He recalled a discotheque in Chelsea with a long line of people waiting to get in. "The bouncers took anybody that had a physical society badge on to the front," Dr. Grant recalled, "and we got in gratis. Can you imagine what a culture shift? We had a hell of a good time." – NY Times

©American Institute of Physics

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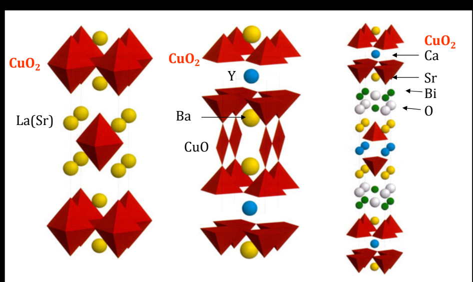
The Cuprates HTS Family



$La_{2-x}Sr_xCuO_4$ (LSCO) (T_c^{max} ~ 40 K)

$YBa_2Cu_3O_y$ (YBCO) (T_c^{max} ~ 93 K)

$Bi_2Sr_2CaCu_2O_y$ (Bi2212 or BSCCO) (T_c^{max} ~ 95 K)

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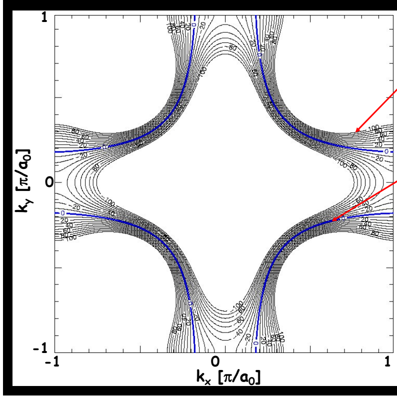
Normal State Band Structure

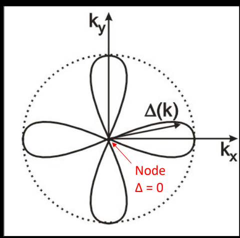


CEC (E): The location in *k*-space of states with energy E

Fermi Surface CCE(0)

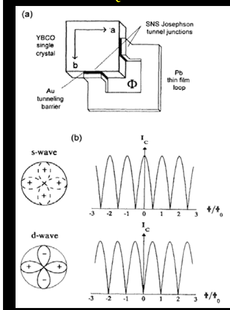
Superconducting State : $d_{x^2-y^2}$ Pairing Symmetry

The SC energy gap, $\Delta(\boldsymbol{k})$ has four nodes.



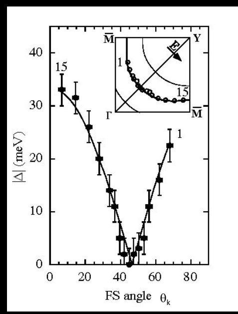
Superconducting State : $d_{x^2-y^2}$ Pairing Symmetry

DC SQUID



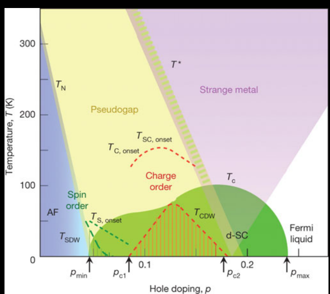
D. A. Wollman *et al.*, PRL 71, 2134 (1993)
D. A. Wollman *et al.*, PRL 74, 797 (1995)

ARPES



H. Ding *et al.*, PRB 54, 9678 (1996)
J. Mesot *et al.*, PRL 83, 840 (1999)

Cuprate Phase Diagram

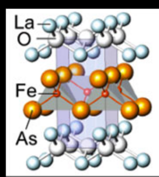


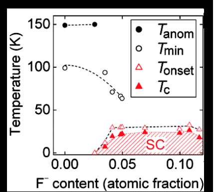
B. Keimer *et al.*, Nature 518, 179–186 (2015).

The Discovery of Fe-based High T_c Superconductors

2006 : $LaFeP(O_{1-x}F_x)$, T_C~5K
2007 : LaNiPO, T_C~3K
Feb 23, 2008 : $LaFeAs(O_{1-x}F_x)$, T_C~26K

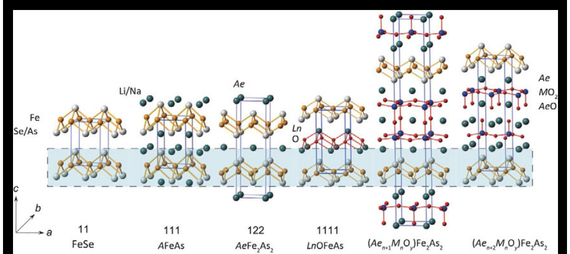
Hideo Hosono





Y. Kamihara *et al.*, JACS. **128**, 10012 (2006)
T. Watanabe *et al.*, JACS. **46**, 7719 (2007)
Y. Kamihara *et al.*, JACS. **130**, 3296 (2008)

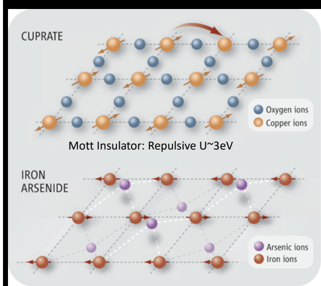
The Fe-based HTS Family

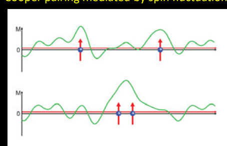


Y. Kamihara *et al.*, JACS **130**, 3296 (2008)
F.C. Hsu *et al.*, PNAS 105, 14262 (2008)
X.H. Chen *et al.*, National Science Review 1: 371–395 (2014)

FeSC vs Cuprates : Superconducting Layer

Cooper pairing mediated by spin fluctuation ?





A. Cho, Science **320**, 870 (2008)

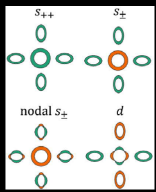
FeSC: Unconventional Superconductivity

1. The electron-phonon coupling is too weak to account for such high T_C.
L. Boeri *et al.*, PRL 101, 026403 (2008)

2. Isotope effect on some materials shown to be negligible.
P.M. Shirage *et al.*, PRL 105, 037004 (2010)

3. Everything seems to work – doping / pressure / different structures

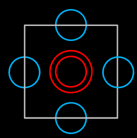
Possible pairing symmetries

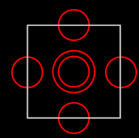


FeSC: Candidates for Pairing Mechanism

SDW suppression leads to SC
→ AF Spin Fluctuation Exchange.
→ S± OP symmetry
I. I. Mazin *et al.*, PRL 101, 057003 (2008)
K. Kuroki *et al.*, PRL 101, 087004 (2008)
K. Seo *et al.*, PRL 101, 206404 (2008).

Orbital Fluctuation → S++ OP symmetry
H. Kontani *et al.*, PRL **104**, 157001 (2010)

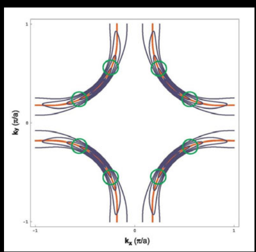




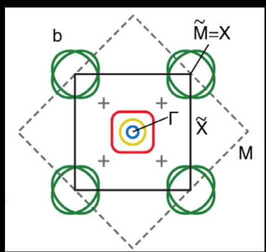
Gap symmetry?
Phase sensitive measurements required!

CuSC vs FeSC : Fermi Surfaces

Cuprates



Fe-based HTS



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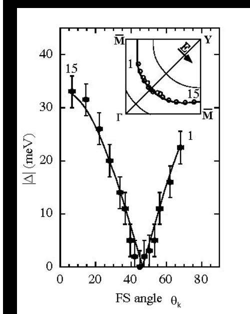
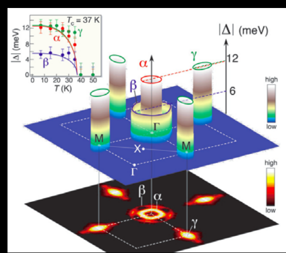
CuSC vs FeSC : Gap Structures

d-wave gap



H. Ding *et al.*, PRB 54, 9678 (1996)
J. Mesot *et al.*, PRL 83, 840 (1999)

Possible s±-wave gap



H. Ding *et al.*, EPL, 83, 47001 (2008)

65

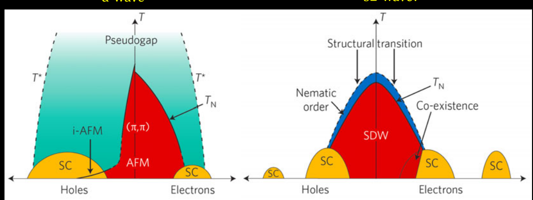
Cuprates vs FeSC : Phase Diagrams

Cuprates

d-wave

FeSC

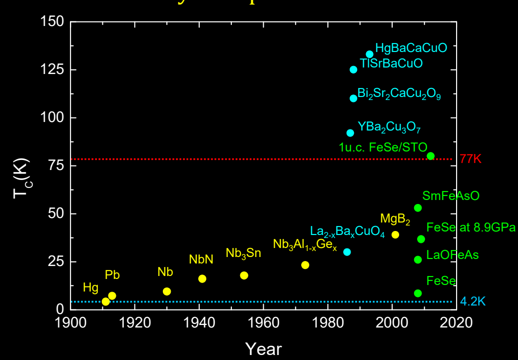
s±-wave?

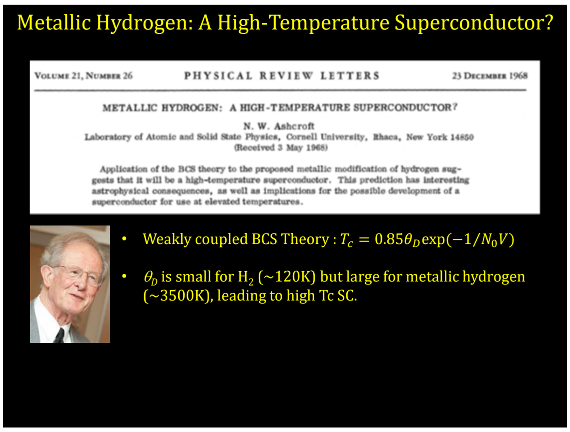


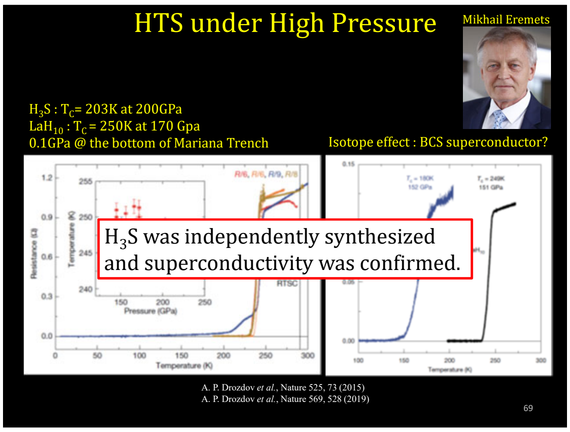
D.N. Basov *et al.*, NPhys **7**, 272 (2011)

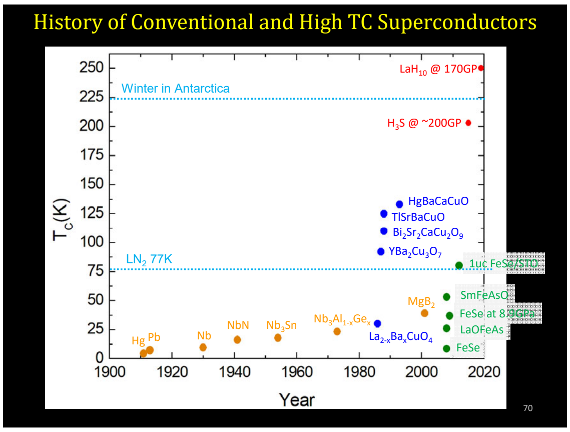
66

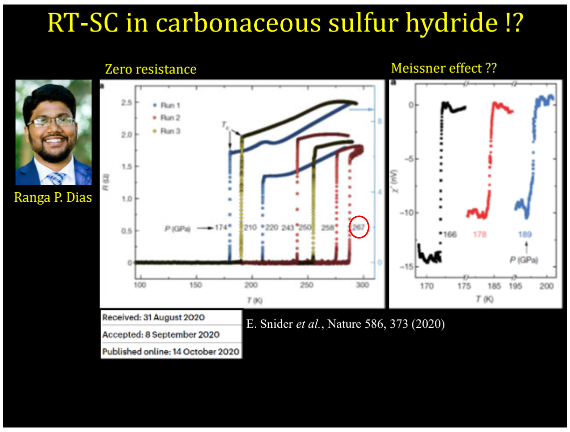
History of Superconductors

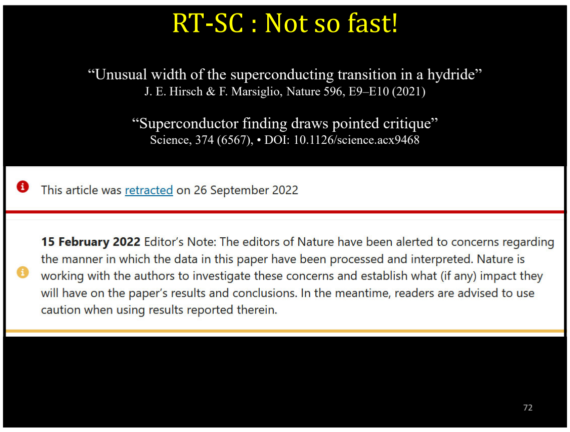


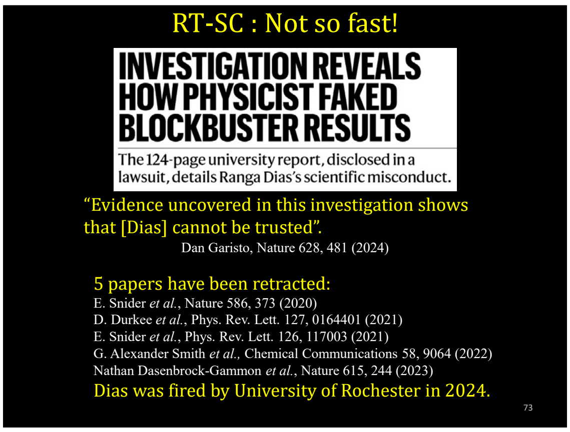

Metallic Hydrogen: A High-Temperature Superconductor?
VOLUME 21, NUMBER 26 PHYSICAL REVIEW LETTERS 23 DECEMBER 1968
METALLIC HYDROGEN: A HIGH-TEMPERATURE SUPERCONDUCTOR?
N. W. Ashcroft
Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York 14850
(Received 3 May 1968)
Application of the BCS theory to the proposed metallic modification of hydrogen suggests that it will be a high-temperature superconductor. This prediction has interesting astrophysical consequences, as well as implications for the possible development of a superconductor for use at elevated temperatures.
• Weakly coupled BCS Theory : $T_c = 0.85\theta_D \exp(-1/N_0V)$
• θ_D is small for H_2 (~120K) but large for metallic hydrogen (~3500K), leading to high Tc SC.


HTS under High Pressure
Mikhail Eremets
H_3S : T_c= 203K at 200GPa
LaH_{10} : T_c= 250K at 170 Gpa
0.1GPa @ the bottom of Mariana Trench
Isotope effect : BCS superconductor?
H_3S was independently synthesized and superconductivity was confirmed.
A. P. Drozdov et al., Nature 525, 73 (2015)
A. P. Drozdov et al., Nature 569, 528 (2019)
69


History of Conventional and High TC Superconductors
LaH_{10} @ 170GP
Winter in Antarctica
H_3S @ ~200GP
HgBaCaCuO
TlSrBaCuO
$Bi_2Sr_2CaCu_2O_9$
$YBa_2Cu_3O_7$
LN_2 77K
1uc FeSe/STO
SmFeAsO
FeSe at 8.9GPa
LaOFeAs
FeSe
MgB_2
$Nb_3Al_{1-x}Ge_x$
$La_{2-x}Ba_xCuO_4$
Hg Pb
Nb
NbN
Nb_3Sn
T_c(K)
Year
70


RT-SC in carbonaceous sulfur hydride !?
Zero resistance
Meissner effect ??
Ranga P. Dias
Received: 31 August 2020
Accepted: 8 September 2020
Published online: 14 October 2020
E. Snider et al., Nature 586, 373 (2020)


RT-SC : Not so fast!
"Unusual width of the superconducting transition in a hydride"
J. E. Hirsch & F. Marsiglio, Nature 596, E9–E10 (2021)
"Superconductor finding draws pointed critique"
Science, 374 (6567), • DOI: 10.1126/science.acx9468
This article was retracted on 26 September 2022
15 February 2022 Editor's Note: The editors of Nature have been alerted to concerns regarding the manner in which the data in this paper have been processed and interpreted. Nature is working with the authors to investigate these concerns and establish what (if any) impact they will have on the paper's results and conclusions. In the meantime, readers are advised to use caution when using results reported therein.
72


RT-SC : Not so fast!
INVESTIGATION REVEALS HOW PHYSICIST FAKED BLOCKBUSTER RESULTS
The 124-page university report, disclosed in a lawsuit, details Ranga Dias's scientific misconduct.
"Evidence uncovered in this investigation shows that [Dias] cannot be trusted".
Dan Garisto, Nature 628, 481 (2024)
5 papers have been retracted:
E. Snider et al., Nature 586, 373 (2020)
D. Durkee et al., Phys. Rev. Lett. 127, 0164401 (2021)
E. Snider et al., Phys. Rev. Lett. 126, 117003 (2021)
G. Alexander Smith et al., Chemical Communications 58, 9064 (2022)
Nathan Dasenbrock-Gammon et al., Nature 615, 244 (2023)
Dias was fired by University of Rochester in 2024.
73

LK-99 in 2023

The claim: the First room-temperature ambient-pressure superconductor.
Sukbae Lee, Ji-Hoon Kim and Young-Wan Kwon, arXiv:2307.12008 (2023)

The hints of SC seen in LK-99 were caused by Cu_2S impurities
Prashant Jain, J. Phys. Chem. C 2023, 127, 37, 18253–18255

Origin of correlated isolated flat bands in copper-substituted lead phosphate apatite
Sinéad M. Griffin, arXiv: 2307.16892 (2023)
But the result is not correct because the incorrect structure is used.

74

There is *STILL* a new hope…..

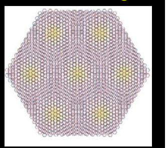
75

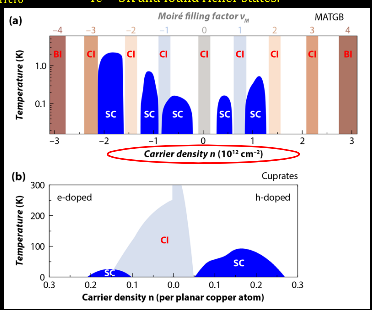
Twisted bilayered graphene @ magic angle

Allan MacDonald Pablo Jarillo-Herrero

Tc ~ 3K and found richer states.

Moiré lattice of BLG @ 1.1°





R. Bistritzer & A. H. MacDonald, PNAS. 108, 12233 (2011)
Y. Cao *et al.*, Nature 556, 43–50 (2018)
Y. Cao *et al.*, Nature 556, 80–84 (2018)
X. Lu *et al.*, Nature 574, 653 (2019)

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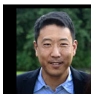
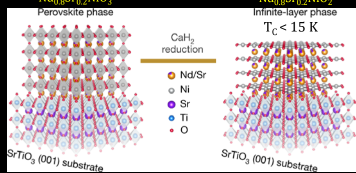
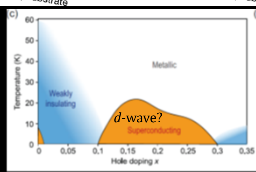
Nickelates superconductors



Harold Y. Hwang

$Nd_{0.8}Sr_{0.2}NiO_3$ $Nd_{0.8}Sr_{0.2}NiO_2$





D. Li *et al.*, Nature 572, 624 (2019)
Wang *et al.*, Annu Rev Conden Matt Phys 15, 305 (2024)

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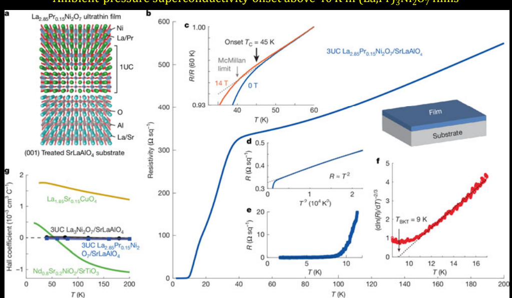
Nickelates superconductors

Ambient-pressure superconductivity onset above 40 K in $(La,Pr)_3Ni_2O_7$ films



Zhou *et al.*, Nature 640, 641 (2025)

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Applications of Superconductivity

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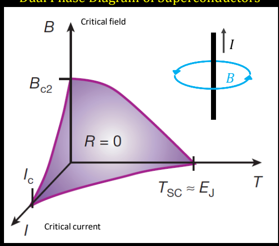
Superconductors for applications

- Critical magnetic field and critical current of superconductor are intimately related.
- Type II SC exhibits higher B_c and I_c.

Dual Phase Diagram of Superconductors



Vortex-Current Interaction

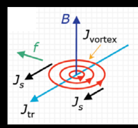
- Lorentz force on J_S due to the interaction between J_S and B.

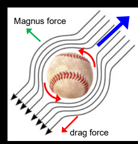
$$f = \int J_S \times B\, d^2r = J_{tr} \times \int B\, d^2r = J_{tr} \times (\phi_0 \hat{B})$$

- Vortex motion implies that the vortex is subject to a power input per unit volume of vortex of characteristic radius r_B

$$P = \frac{f\,v}{\pi r_B^2} = J_{tr}\frac{\phi_0}{\pi r_B^2}v = \underbrace{J_{tr} B}_{\text{Lorentz force per unit volume}} v$$

- Vortex motion leads to dissipation! R≠0 !
- Vortex pinning is crucial for applications.





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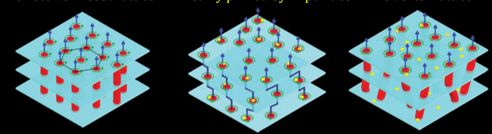
SCs for applications : vortex interaction

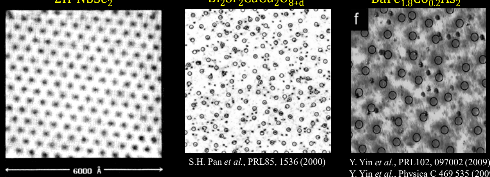
No pinning. Perfect Abrikosov lattice

Weak coupling. Weakly pinned by impurities.

Strong pinning. No vortex lattice.



$2H\text{-}NbSe_2$ | $Bi_2Sr_2CaCu_2O_{8+d}$ | $BaFe_{1.8}Co_{0.2}As_2$



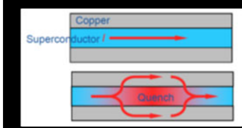
H. F. Hess *et al.*, PRL 62, 214 (1989)

S.H. Pan *et al.*, PRL85, 1536 (2000)

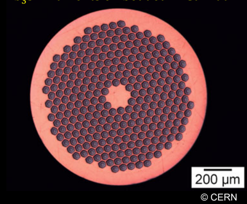
Y. Yin *et al.*, PRL102, 097002 (2009)
Y. Yin *et al.*, Physica C 469 535 (2009)

Superconducting Wire

Cu offers cooling, quench protection and mechanical stability.



Nb_3Sn filaments embedded in Cu matrix.



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Conductors from Cu to Nb3Sn

For a strand with diameter = 0.85mm,

Cu	NbTi	Nb_3Sn
J_e~ 5 A/mm²	J_e~ 600 A/mm²	J_e~ 600 A/mm²
I ~ 3 A	I ~ 300 A	I ~ 300 A
B = ~ 2 T	B = ~9 T	B = 12~16 T

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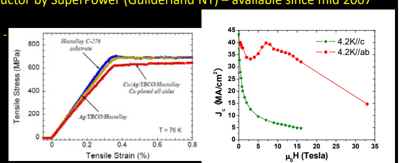
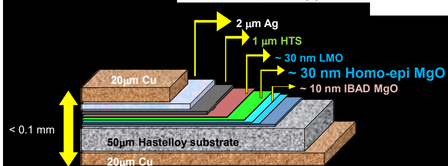
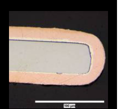
High Tc Superconducting Cables

YBCO Coated conductor by SuperPower (Guilderland NY) – available since mid 2007

- Phenomenal Jc in the YBCO - ~20 x 10⁶ A/cm² at 25T
  - YBCO is ~1% of cross-section
  - 50% is high strength superalloy







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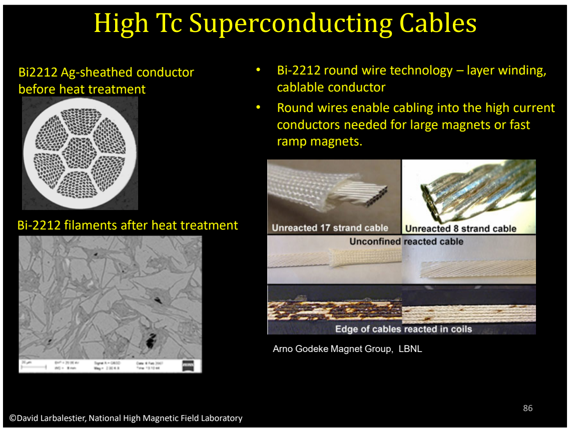

High Tc Superconducting Cables
Bi2212 Ag-sheathed conductor before heat treatment
Bi-2212 filaments after heat treatment
• Bi-2212 round wire technology – layer winding, cablable conductor
• Round wires enable cabling into the high current conductors needed for large magnets or fast ramp magnets.
Unreacted 17 strand cable
Unreacted 8 strand cable
Unconfined reacted cable
Edge of cables reacted in coils
Arno Godeke Magnet Group, LBNL
©David Larbalestier, National High Magnetic Field Laboratory
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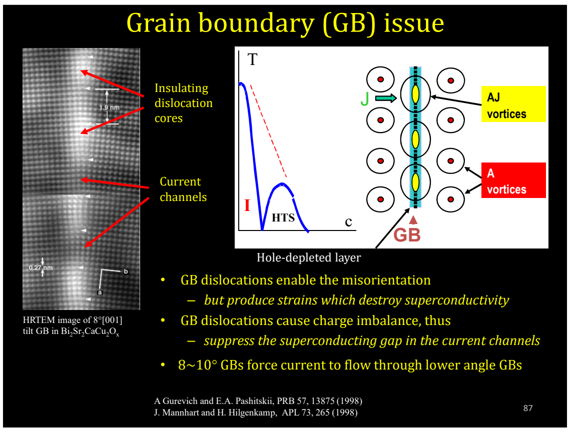
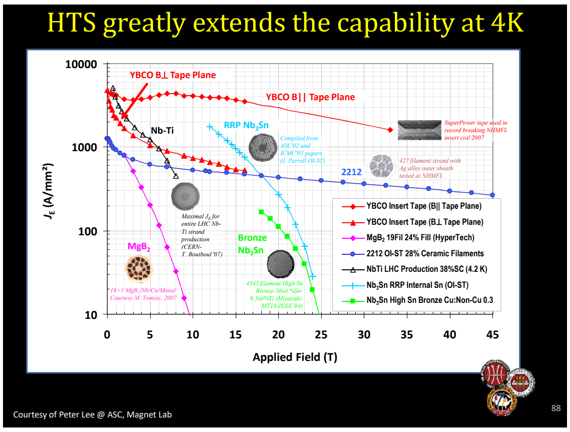


Grain boundary (GB) issue
Insulating dislocation cores
Current channels
HRTEM image of 8°[001] tilt GB in $Bi_2Sr_2CaCu_2O_x$
T
J
AJ vortices
A vortices
I
HTS
c
GB
Hole-depleted layer
• GB dislocations enable the misorientation
– but produce strains which destroy superconductivity
• GB dislocations cause charge imbalance, thus
– suppress the superconducting gap in the current channels
• 8~10° GBs force current to flow through lower angle GBs
A Gurevich and E.A. Pashitskii, PRB 57, 13875 (1998)
J. Mannhart and H. Hilgenkamp, APL 73, 265 (1998)
87



HTS greatly extends the capability at 4K
J_E (A/mm²)
10000
1000
100
10
0
5
10
15
20
25
30
35
40
45
Applied Field (T)
YBCO B⊥ Tape Plane
YBCO B|| Tape Plane
Nb-Ti
RRP Nb_3Sn
2212
MgB_2
Bronze Nb_3Sn
SuperPower tape used in record breaking NHMFL insert coil 2007
Compiled from ASC'02 and ICMC'03 papers (J. Parrell OI-ST)
427 filament strand with Ag alloy outer sheath tested at NHMFL
Maximal J_E for entire LHC Nb-Ti strand production (CERN-T. Boutboul '07)
18+1 MgB_2/Nb/Cu/Monel Courtesy M. Tomsic, 2007
4543 filament High Sn Bronze-16wt.%Sn-0.3wt%Ti (Miyazaki-MT18-IEEE'04)
YBCO Insert Tape (B|| Tape Plane)
YBCO Insert Tape (B⊥ Tape Plane)
MgB_2 19Fil 24% Fill (HyperTech)
2212 OI-ST 28% Ceramic Filaments
NbTi LHC Production 38%SC (4.2 K)
Nb_3Sn RRP Internal Sn (OI-ST)
Nb_3Sn High Sn Bronze Cu:Non-Cu 0.3
Courtesy of Peter Lee @ ASC, Magnet Lab
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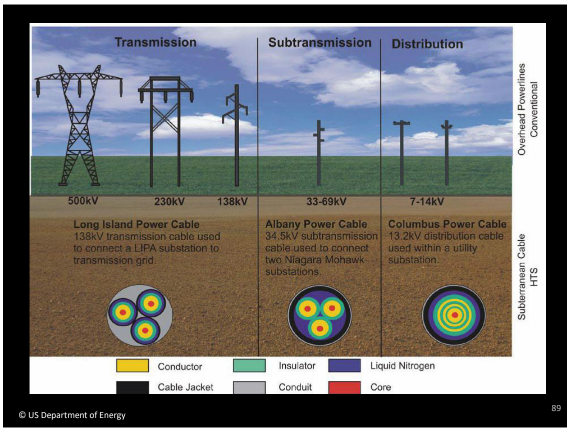

Transmission
Subtransmission
Distribution
Overhead Powerlines Conventional
500kV
230kV
138kV
33-69kV
7-14kV
Long Island Power Cable
138kV transmission cable used to connect a LIPA substation to transmission grid.
Albany Power Cable
34.5kV subtransmission cable used to connect two Niagara Mohawk substations.
Columbus Power Cable
13.2kV distribution cable used within a utility substation.
Subterranean Cable HTS
Conductor
Insulator
Liquid Nitrogen
Cable Jacket
Conduit
Core
© US Department of Energy
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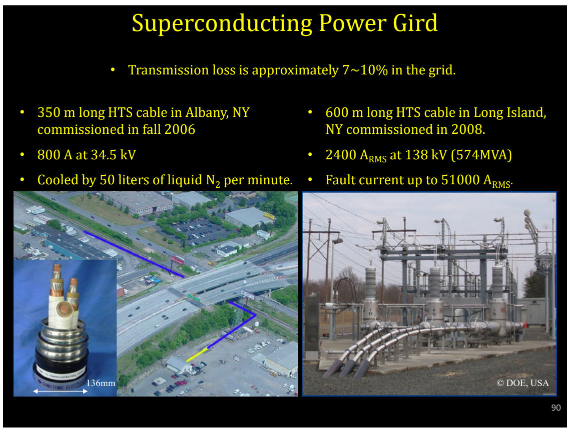
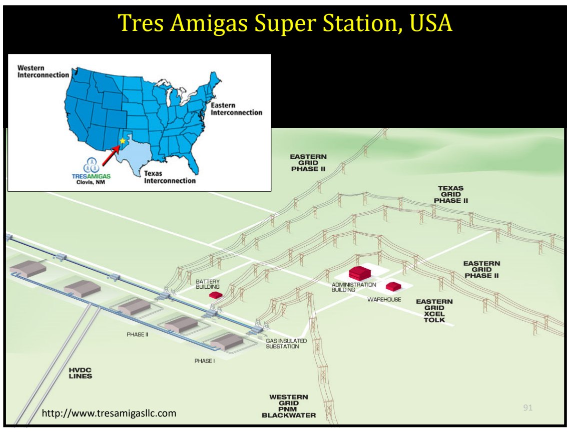


Superconducting Power Gird
• Transmission loss is approximately 7~10% in the grid.
• 350 m long HTS cable in Albany, NY commissioned in fall 2006
• 800 A at 34.5 kV
• Cooled by 50 liters of liquid N_2 per minute.
• 600 m long HTS cable in Long Island, NY commissioned in 2008.
• 2400 A_{RMS} at 138 kV (574MVA)
• Fault current up to 51000 A_{RMS}.
136mm
© DOE, USA
90



Tres Amigas Super Station, USA
Western Interconnection
Eastern Interconnection
Texas Interconnection
TRESAMIGAS
Clovis, NM
EASTERN GRID PHASE II
TEXAS GRID PHASE II
EASTERN GRID PHASE II
EASTERN GRID XCEL TOLK
BATTERY BUILDING
ADMINISTRATION BUILDING
WAREHOUSE
PHASE II
PHASE I
GAS INSULATED SUBSTATION
HVDC LINES
WESTERN GRID PNM BLACKWATER
http://www.tresamigasllc.com
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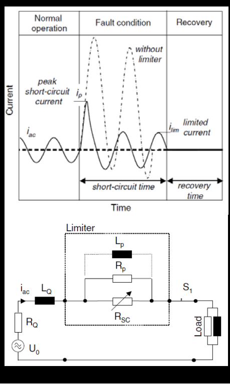
HTS Fault-Current Limiters



- A fault current is the current flow during a short circuit.
- In the power grid system, the fault current is thousands of ampere.
- Dangerous due to large magnetic force and high heat.

Review paper: M. Noe & M. Steurer, https://doi.org/10.1088/0953-2048/20/3/R01

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